DEVELOPMENT OF A COMPREHENSIVE DATABASE AND SELECTION MODEL FOR OPTIMUM RETAINING WALL. CONSTRUCTION, COST AND PRODUCTION

by

FERNANDO PIZARRO QUINTANAR

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Abstract

DEVELOPMENT OF A COMPREHENSIVE DATABASE

AND SELECTION MODEL FOR OPTIMUM

RETAINING WALL. CONSTRUCTION,

COST AND PRODUCTION

Fernando Pizarro Quintanar

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Supervising Professor: Mohammad Najafi

Retaining walls are earth retention structures that are essential in the majority of the construction projects for the overall project’s engineering performance, as well as its budget and schedule. These elements constitute a key role in urban development, industrial facilities and civil projects as evidenced by the more than 170 million of square feet being constructed per year in the United States. The current market conditions, as well as the advances in the technology and knowledge associated to these elements, determine the need for accurate decision making processes that lead to optimum retaining walls in terms of applicability, cost and production rates.

More than 50 types of retaining walls are currently available in the market, having each one of them further subdivisions depending on the materials and configurations being used. Thus, properly developed databases and decision models are highly important to make accurate selections.

Each type of retaining wall present a unique set of advantages and disadvantages, construction processes, equipment and material needs as well as limitations. These

particular features of each are identified and analyzed in order to determine those factors driving the selection of each type.

Literature references in retaining wall design and construction are extensive and complete. However, no single source provides a comprehensive guideline for the analysis of the different types of retaining walls in order to make a comparative analysis that can lead to a selection decision. This lack of references is greater in regards to unit costs, production rates and construction issues mostly caused by the commercial implications of disclosing them. Specialized references consider field observation and record keeping as the most adequate approach to determine accurate costs and production rates.

Previous studies have attempted to develop wall selection models that use previous experiences to determine the most appropriate retaining wall type for a specific set of needs and constraints. However, these references failed to include three key factors such as direction of construction, unit cost and production rates. The selection model developed in this research follows an Imperialist Competitive Algorithm (ICA), based on a knowledge database and incorporating specific decision driving parameters for each wall type.

Successful experiences in previous projects do not ensure proper outcomes in the future ones and therefore only a project specific analysis can provide the basis for the reduction of the risk associated with the wall selection. This research analyzes and present those considerations that determine the adequacy of each type of wall and the factors that affect their performance during and after construction.

The results from the literature review, analysis of previous experiences, surveys and interviews to expert subjects are supplemented with field observations of heavy civil construction Projects in the DFW area to determine typical unit costs, production rates and construction issues. While the identified construction issues can serve as the base for the developments of specially tailored QA/QC programs, the unit costs and production rates can be used as a database for future preliminary studies and are built into the decision model developed in this research. The model is validated using four known walls as input in order to compare the solutions returned by the model against the real-world constructed ones in terms of wall type. Additionally, subject experts are used to further validate the accuracy of the model to replicate expert reasoning process.

The data obtained during the different collection phases, as well as the analyses performed can serve as a starting point for future preliminary studies. The selection model developed ins this research can be used to determine the most adequate retaining wall for a specific set of constraints, where limited information is available.

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Chapter 1

Introduction

Retaining wall design and construction has evolved and been developed greatly in the last decades due to the increasing need of optimizing the space and reducing the material consumption. ASCE (2013) calculated that the current earth retaining market of the US exceeds 170 million square feet per year. Additionally, this has been catalyzed by the need of reducing the environmental impact of construction projects. Based on an ASCE Seminar (2013), there are over 50 different retaining systems. However, each type of wall involves different advantages and disadvantages that need to be evaluated when deciding the wall type for a particular set of conditions and constraints. A proper selection of the type of retaining wall to be used is key for the overall success of any construction project.

Wall types vary among different categories, having unit costs spanning from less than $20 to in excess of $250/sq. ft. Selecting the most technically appropriate and cost-effective system is often critical to project cost and schedule. An incorrect wall system selection can lead to delays and/or cost overruns. Most Engineers, contractors and construction management personnel lacks the required specialized knowledge to select the most appropriate wall for an intended location. (ASCE, 2013)

During the design and construction process of the retaining walls, mostly for nailed and mechanically stabilized earth walls, different companies and agents interact between the different phases. Coordination and consistency among them is essential to achieve the desired retaining wall built. Also, production and cost control is key for the overall output of the project where the walls are constructed and therefore, they will be analyzed in this Report.

The equipment involved in the construction of some of the types of retaining walls constitutes the highest cost incurred and determines the production rate to be achieved. Some of this machinery is very specific and operating them properly requires a deep understanding of the process and the optimization of the cycles of work. Production cost and rates will be analyzed and discussed for the different types of retaining walls reviewed.

The privileged position where the author finds himself while developing this thesis will be used to obtain data from retaining walls under construction, expert designers, construction companies, specialized subcontractors, developers and public owners. Currently participating in a heavy civil transportation project, some of the walls being constructed in the DFW area will be used as a data pool for both input for the decision model and also as a check for the trials runs to be executed with it. By introducing the parameters for these walls in the model, the returned wall type will be compared with the one executed to determine the accuracy and applicability of the selection process.

1.1 Topic

The proposed Thesis will focus on retaining wall construction. Starting with a research effort to identify the different types of retaining walls used on civil construction and transportation projects, the main ones will be selected. Then, a comparison will be performed, in terms of applicability, advantages and disadvantages. Additionally, standard cost and production ratios will be developed based on field observation, reference analysis, interviews and surveys to personnel from specialized companies.

By analyzing and comparing all the data obtained in these previous phases, a wall selection guideline and a retaining wall database will be developed. This model will consist in a “wall selection matrix” that guides the selection process in a flowchart with Yes/No questions, leading to the optimum type of wall for a given set of constraints.

1.1.1 Scope and Limitations

Three main phases will be completed during the development of this Thesis.

- First an extensive research will be performed in order to identify not only which types of retaining walls are currently available for civil construction projects but also which ones are the most common, selecting these for the next phases of the Thesis. This will include not only a literature research but also an analysis of real projects.
- Second, these selected walls will be analyzed in order to determine their advantages and disadvantages under certain conditions, their applicability under the different design parameters, their unit cost and production rates. A retaining wall database will be developed.
- Lastly, all this information will be built into a decision model that will later be evaluated by using three know existing retaining walls.

This study will include the review of the majority of the types of retaining walls being available for heavy civil construction under permanent conditions. However, it will focus on those main types being used such as cantilever reinforced concrete, tie back, rock/soil nails, drill shafts and mechanically stabilized earth. Although some of the wall types are both used as permanent and temporary walls, only permanent construction will be considered.

Specific needs and locations might require sequences of different retaining walls such as land developments or landfills. In those cases where the height to be retained is excessive and space is available, multiple level retaining walls can constitute a viable solution with no more than three tiers under normal circumstances (Jalla, 1999).

Plenty of documentation and reference is available regarding wall design and construction. However, production rates and unit costs are parameters where the commercial interests pose an obstruction for their public distribution. In order to counteract against this trend, research, investigation, surveys and observations will be performed in this research in order to develop these rates. Although every project requires an specific cost and productivity analysis, the values presented here can serve as a starting point for those engineer in need during preliminary or feasibility studies.

1.2 Need Statement

Determining the most appropriate retaining wall to be constructed in a particular location or project is a complicated task that involves a thorough and educated decision process. Several considerations are required to be comprehensively analyzed in order to achieve the desired result in terms of safety, quality, budget and schedule.

The unfavorable current market conditions and the reduced work available for the construction companies, create a difficult environment where the competition between companies is harder than in previous decades. Project owners benefit from these conditions, via reduced bids, PPP (Public-private-partnership) or concessions. Therefore, proper selection of the wall type and an optimized construction process is essential for any Engineer involved in the current construction market where the room for inefficiencies and corrections has been reduced to inexistent.

Current heavy civil construction projects include a combination of the different types of retaining walls, each one of them determined due to its specific location or use. Temporary or permanent use, space available for their construction, rate of production needed and loads to be withstood determine the best type of wall to use (Hess and Adams, 1995).

Retaining wall design and construction has been optimized in all phases of the process due to the scientific and technological developments. This was partly triggered by an increasing need of reducing the space and material consumption. In addition to this, the increasing efforts towards more sustainable civil construction, forced engineers and builders to develop new systems and configurations that reduce the construction impact. Despite the developments, each type of wall involves a complicated set of advantages and disadvantages that need to be evaluated in order to identify the best wall for a particular set of conditions and constraints. A proper selection of the type of retaining wall to be used is instrumental for the final success of any civil construction project, especially in the transportation field.

A comprehensive guide and database of retaining walls does not currently exist as evidenced by the literature review. The research performed shows that most wall type selections are performed based on subjective previous experience (Hancher et al. 1992). The development of a scientifically based database of those features that affect in the wall selection is a necessary step towards more optimized studies in preliminary studies and feasibility analyses.

Every designer and/or developer needs to evaluate which type of retaining wall is most appropriate for a particular use or location. Based on the references investigated in Section 2, there is no comprehensive guideline tool to help making this determination. Currently, most fields of retaining wall design and construction have been widely investigated, and publications are available in all formats such as books, papers, journals, thesis and dissertations. However, each one of these documents focus are individually focused in design, construction, monitoring, evaluation, production or cost. Decision models, with or without expert systems, are not available for the general use (Yang, 2004).

Only an extensive experience, supplemented with multidisciplinary design teams can gather the required information to determine which wall is the most adequate for a particular need. Irrespectively of the degree of experience of an engineer, it is always required to receive input from other engineers. Thus, a pre-constructed selection model appears as a good tool to provide the engineers with more information and help during the decision process (Yang et. al 2003).

Literature and previous experiences and developments in regards to the retaining wall selection process have been researched. No single source has been identified to provide a sufficiently comprehensive system that is adapted to current needs and that is available to the general engineering practice. Although expert systems have been used in the past for selection and preliminary design of retaining walls (Lee 1989, Ikoma 1992 and Yang 2003), these research documents were developed at least 10 years ago, thus losing the potential of current programming methods and technology evolution.

All the previous experiences consisted in computer based models. These required of an extensive knowledge of programming language and database development. Most engineers in need of determining a certain type of wall would not have the time nor the skills required to make use of these tools.

Additionally, none of the methods identified during the literature research included three of the most important factors in the retaining wall decision process: cost, production rate and direction of construction (upward or downward). Just by the use of these three parameters, the available options can be drastically reduced, therefore easing the process of selecting among fewer potential types.

Previous references have established the need of developing knowledge-based systems in order to better determine the most adequate solutions for the different project needs. Both Hancher et. al (1992) and Chong (2005) concluded that rather than relying on pure experience or improperly appraised historical records, a comprehensive research would lead to more accurate data and decision making processes. Yang (2004) research showed that some construction problems cannot be represented nor resolved with the use of conventional scientific algorithms, thus the need of different systems and approaches. Although experience-oriented problems represent a suitable alternative where solutions are obtained by previous experiences, Hess and Adams (1995) indicated that the majority of the engineers tend to restrict themselves to select retaining wall types that they have experience with.

Following these references as a starting point, the present research will gather information from multiple sources such as literature, field observations, expert surveys and interviews to combine them into a knowledge based database and a decision model.

1.3 Research Objectives

The goal of this research is to perform a comprehensive analysis of the current “state of the art” in retaining wall construction, focusing on those configurations that are most used in civil construction. Based on this analysis, the main types are to be selected for further study and identification of their unit cost and production rates under normal circumstances. Lastly, based on all information obtained from the literature research, and additional collected data, a wall selection model and a retaining wall database will be developed.

Five main objectives are established to be accomplished at the completion of the Thesis:

- Analyze the currently available retaining wall types in heavy civil construction, identifying their applicability, advantages and disadvantages.
- Identify the main types of retaining walls for the aforementioned heavy civil construction and transportation projects based on the previous analysis,
- Collect accurate information regarding limiting heights, construction issues, driving parameters, cost and production rates by performing observations, research, interviews and surveys that can serve as a starting point for retaining wall selection and preliminary studies, therefore developing a database of retaining wall information.
- Develop a comprehensive database that provides adequate information for use in preliminary studies and for the determination of the most suitable wall type for a certain project needs, including limiting heights, specific features, frequent construction issues, unit costs and production rates.
- Develop a set of guidelines for retaining wall selection based on a given set of constraints, by constructing a sequential decision model based on a flowchart structure.

At the completion of this Thesis, the developed model will allow a designer or construction engineer to identify the optimum retaining wall type to fulfill his/her needs based on the particular set of conditions of the wall at hand.

1.4 Expected Outcome

The final result of the work to be performed during the completion of this Thesis will be a comprehensive decision model and a retaining wall database that includes unit costs, production rates, advantages and disadvantages for each type. The model will result in a user-friendly set of guidelines that by means of a flowchart can be used by any Engineer to determine which retaining wall type is the most suitable for a certain location.

The data presented in the database will serve as an starting point for preliminary studies and feasibility analysis where limited information is available and few references are available to obtain typical values for each wall type.

This model will be based a series of questions/answers that will guide the decision process to the optimum solution. These questions will be developed based on the information sources that will be utilized such as literature review, background studies, observations, surveys and interviews. The thinking process followed by experienced geotechnical designers and retaining wall builders will be implemented into the model so it can be used by other engineers in need.

These wall selection guidelines will serve as a preliminary filter for those engineers that face the problem of which wall to design in detail for a particular location. Current market conditions do not allow engineers to pre-dimension 15 wall types to determine the optimum solution, thus the usefulness of the proposed model which can reduce the feasible options to 1 or 2 types of wall.

Although the model does not intend to substitute the engineering judgment required to determine the best wall for a particular need, it will help on reducing the types being considered, identifying those more adequate.

1.5 Thesis Organization

Chapter 1 introduces the associated problems with retaining wall selection, as well as those factors that affect the need for proper decision models. It includes the scope and limitations of the research, the support for its need, the purpose of the different chapters and the expected outcome.

Chapter 2 reviews the literature and references available in regards to retaining wall construction, advantages and disadvantages or each wall type. Additionally, literature references are researched for data regarding selection models, construction operations, equipment and materials required for each type. References for wall construction unit costs and production rates are also included in this chapter as well as an analysis of four known walls to determine their main features and the costs/rates obtained during their construction.

Chapter 3 describes the process followed to collect the information necessary to fulfill the objective of developing a database and selection model. Field observations, surveys to expert personnel and interviews to experienced engineers are included in this chapter. The results of the data collection is organized and analyzed in order to determine typical values and considerations for use in the database and selection model development.

Chapter 4 provides the results for the previous work regarding the development of a retaining wall database and the selection model. The results include limiting height, typical unit cost and production rates for the different types of walls analyzed. Additionally, the completed Retaining Wall Selection Model (RWSM) is presented and analyzed in this chapter.

Chapter 5 summarizes the results of the evaluation and model verifications performed over the RWSM described in Chapter 4. The four known wall and two subject experts were used in order to validated the accuracy of the selection model to resolve real world solutions. Additionally, an analysis of the retaining wall database developed is included in this Chapter.

Chapter 6 includes the summary and conclusions for the work performed in this research and its results. Future research recommendations in order to further develop and improve the results from this study are also included in this chapter.

The completed forms the surveys and interviews as well as the complete selection model are included in the different appendixes included a the end of the report.

A list of the references used to support and develop this research work is included at the end of this report.

Chapter 2

Background and Literature Review

2.1 History of Retaining Walls

Retaining walls have been present in human civilizations since the development of the first societies. Some walls are dated several centuries before Christ, for example, the Apadana Persepolis walls constructed under the reign of Darius I (Darius the Great - reigned 522–486 B.C.) or the Norte Chico city Caral in the Supe Valley, Peru, dated 2627 B.C.

Figure 2-1: Layout of the Eastern Stairway of Apadana

(http://realhistoryww.com/world_history/ancient/Misc/Elam/Persepolis.html)

Human establishments have increased their need for more conglomerated urban constructions throughout the centuries. This triggered the development of new and more optimized types of retaining walls. Also, building and temple construction in sloped areas required the development of these ancient walls. Military and religious constructions have traditionally provided an advance research in the construction technology.

Ancient constructions were typically made of stone, wood, mud and other natural materials. Walls were constructed as a functional element for defense, storage, containment or to protect valorous objects or food.

The knowledge of wall construction was transmitted from individual to individual, creating trends of construction specific to the society or geographical areas considered. This transmission of construction knowledge and the availability of certain materials determined the configuration of the retaining wall to be constructed. Extreme examples of this are the ice walls built by the Inuit in Lappland or the houses built by the Muhimba tribe, made of a mixture of soil and cow excrements.

Figure 2-2 (a) Inuit building igloo in Lappland and (b) Angolan muhimba child in traditional house (www.windows2universe.org)(www.flickr.com)

Retaining walls constitute a cornerstone of the human development, as they satisfy primary needs of the human being such as protection from weather, enemies or wild animals, storage of foods and goods, or to construct religion related temples.

2.2 Literature Research and Background Review

"A researcher cannot perform significant research without first understanding the literature in the field" (Boote and Beile, 2003). It is commonly accepted that dissertations that include a poorly literature review often result in a generally poor dissertation (Mullins and Kiley, 2002). By researching, analyzing and evaluating the available sources of information in the matter at hand, not only will the need for this dissertation be questioned, but also the previous developments by different authors will be used as a reference and a foundation for the studies performed in this Thesis.

In this chapter, a review of the different types of retaining wall, their advantages and disadvantages, cost and production rates and the selection methods available will be discussed. The information presented in this chapter was collected from journals, books, conference proceedings, dissertations, existing projects and other research project reports.

Additionally, due to the practical nature of this Thesis, it has been deemed necessary to perform a thorough study of those activities, materials and equipment involved in the construction of the main types of retaining walls constructed in heavy civil and transportation projects.

Any model needs to be checked against known solutions to evaluate its performance. For the verification of the selection model developed in this dissertations, four known walls will be analyzed in order to identify their main parameters. These will be used as input to the model so the returned outputs can be compared with the real-world types determined by professional designers..

2.2.1 Retaining Wall Types, advantages and disadvantages

Retaining walls are separated into distinctive categories based on differential parameters of comparison. Regarding the structural behavior and configuration of the retaining walls, these are generally classified as gravity, semi-gravity (or conventional), non-gravity cantilevered, mechanically reinforced and anchored (Caltrans 2004 and Das 2011).

Table 2.1. Classification of Retaining Walls by Configuration and Materials

DIVISION BY STRUCTURAL CONFIGURATION	DIVISION BY MATERIALS / ELEMENTS
Gravity Walls and Semi-Gravity	Masonry
	Blocks
	Mass concrete
Cantilever Walls	**Cast-in-place concrete**
	Precast concrete
Anchored Walls	**Soil/Rock Nails**
	Tie Back Nails
Pile Walls	**Drill shaft walls**
	Slurry walls
	Sheet pile
	Soldier pile
Mechanically reinforced earth	Geotextiles
	Metallic reinforcement
	Wire mesh walls

A separate classification can be developed introducing the main type of materials being used in their construction (TDOT 2012 and Das 2011). This second classification is presented below:

1. Cast-in-place (CIP) Concrete
    a. Gravity Walls
    b. Cantilever
    c. Counterfort
    d. Buttressed
2. Concrete Crib Walls
3. Bin Wall
4. Gabion Wall
5. Dry rubble
6. Segmental, Precast Facing and Block Mechanically Stabilized Earth (MSE) Wall (geogrids, metallic, polymers, etc.)
7. Wire Mesh Walls
8. Anchored Wall
9. Nailed Wall
10. Drill Shaft Wall
11. Diaphragm Wall
12. Sheet pile walls
13. Slurry Wall
14. Ground freezing wall

Each type of wall presents a separate set of advantages and disadvantages, as well as “no-go” conditions. These “no-go” conditions trigger the rejection of the considered type of wall if the particular project constraints include one of these “no-go” parameters. An example of “no-go” conditions would be a rock nail type for upward construction or a drill shaft wall constructed with a total cost under 20 $/sf.

Just by the analysis of the direction of construction of the retaining wall, the different types can be separated as fill walls and cut walls (TDOT 2012). Once this separation has occurred, the remaining divisions gather wall types that are more comparable. For example, an anchored wall and an MSE wall would never be compared as the applications and configurations of each type are entirely different.

Current heavy civil construction projects include a combination of different types of retaining walls, each one of them determined due to its specific location or use. Temporary or permanent use, space available for their construction, type of soil, unit cost, rate of production needed or loads to be withstood determine the best type of wall to use.

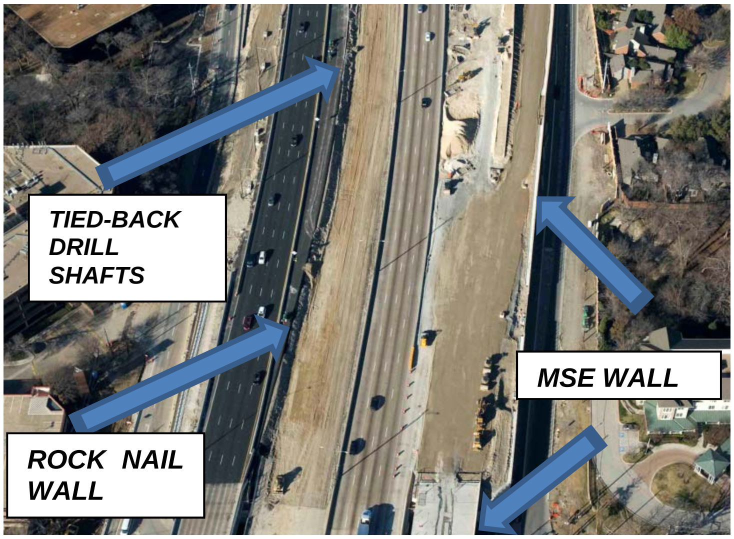


Figure 2-3 Aerial Picture of LBJ Project. March 2013

However, not all the aforementioned types of walls are commonly used in transportation projects, therefore, only the main ones are included in this analysis. Cantilever, tie-back, nailed, pile and mechanically reinforced earth retaining walls are the most common. Each type of wall included pros and cons depending on the specific features of the project where they are intended to be built.

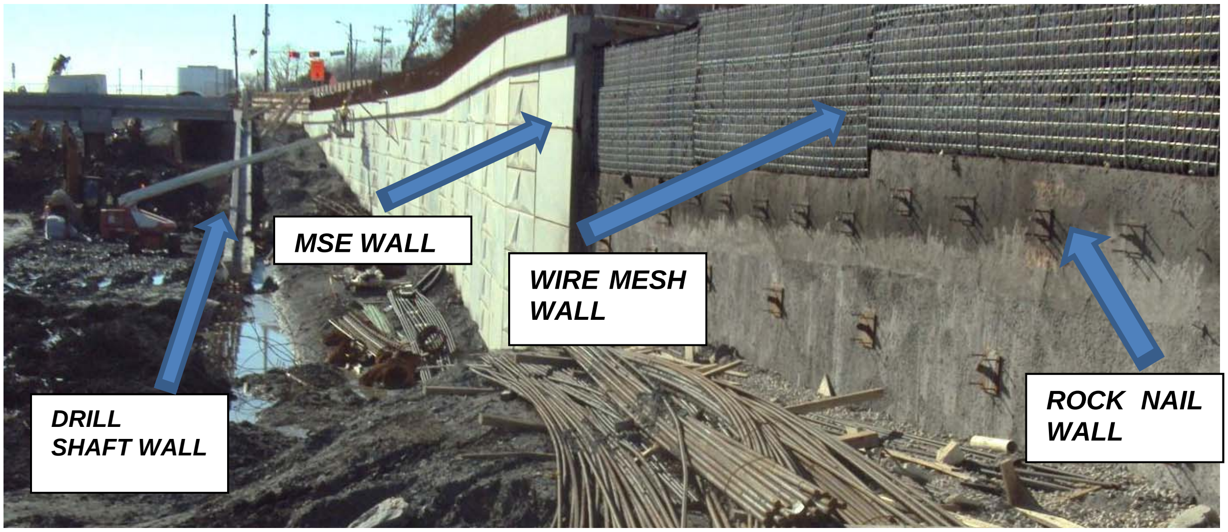


Figure 2-4 Different types of wall constructed in an specific location. Wire mesh, rock nail, drill shaft and MSE Walls coexist in a very tight area. Each one is determined by specific needs and constraints. (Courtesy of Mr. Azofra)

A brief description of the retaining wall types highlighted in Table 2.1 is presented here to provide a basis for the literature review and background research. These 5 types of walls will constitute the core of the detailed analysis to be performed in this Thesis.

2.2.1.1 Cantilever Reinforced Concrete

These walls are constructed of a combination of concrete and reinforcement steel. The structural principle for these walls is the transformation of the lateral pressure into vertical load to the concrete footing, resisting the overturning by the weight of backfill mass over the footing heel (Babu and Basha, 2008). Additional lateral resistance can be achieved with the implementation of base keys which mobilize the passive resistance of the soil under the footing (California Building Code, 2007). Cantilevered walls are the most optimized geometry among the cast in place concrete walls (Das, 2011). These walls are easy to design; do not require highly specialized materials, equipment of craftsmanship. On the other hand, the horizontal space required to construct these walls is considerable and there are limitations of height both due to economic and structural considerations. Under normal circumstances, retaining walls higher than 25 feet are more economical to be constructed as MSE than concrete cantilever type (Das, 2011). Design and specifications literature is extensive and readily available; therefore these constraints do not constitute a limitation on the specialization for the design and construction of these walls.

2.2.1.2 Mechanically Stabilized Earth (MSE)

An MSE wall is a composite structure that is composed of backfill material, reinforcement, foundation and facing (Elias et al. 2001). The global behavior of the entire wall is highly dependent on the interaction between all these components, especially between the reinforcement material and the backfill (Desai and El-Hoseiny, 2005). These walls can be constructed easily, quickly, by non-expert workmanship and can be located in flood areas and retain substantial heights and loads when upward construction is needed. However, these are flexible walls that can present considerable horizontal movement even failures if all parameters are not strictly controlled (Elias et al. 2001). Special care must be taken when developing the Specifications, quality control, performance monitoring, backfill materials, drainage, corrosion of reinforcement and construction damage (Hossain et al. 2012). For example, Kibria et al (2014) analyzed an MSE wall in Lancaster, Texas that accumulated horizontal movements between 300 and 450 mm during the years 2004–2009 due to primarily inadequate reinforcement lengths. As in the case of the cantilever walls, design and specifications literature is also wide and the need for specialized knowledge is not a constraint for this type of wall.

2.2.1.3 Drill Shafts

A drill shaft wall is a structure composed by a sequence of closely spaced reinforced concrete cylinders drilled in the ground. These shafts Different configurations of spacing, size, length and reinforcement can be designed depending on the groundwater conditions, soil type, height and loads to support (Bierchwale et al. 1981). These walls appear as an appropriate solution where deep excavations require a strict movement and groundwater control due to close-by structures, such as in urban environments as evidenced by Long (2001). Based on the studies and observations performed by Long (2001), although the current design practices may be excessively conservative, these walls are highly affected by the over excavation and therefore excessive cantilevered stresses can lead to unacceptable movements. This is of critical importance when retaining sensitive infrastructure elements. These walls have a high cost, low production rate and require of specialized machinery and workmanship as well as design processes and thus, are not used unless the rest of types are not feasible (TDOT, 2012).

2.2.1.4 Soil/Rock Nail

Soil and Rock nail walls have been widely used during the last two decades throughout the world (Su et al. 2008, Sheahan and Ho 2003) for both temporary and permanent applications. Soil and rock nails rely on small ground displacements to mobilize their reinforcing stresses which then alter the mechanics near failure surfaces in the soil/rock masses (Sheahan and Ho 2003). This earth retention system is based on the use of steel bars inside “near-horizontal” drilled holes that are later filled with cementitious grout over the exposed face of the cut (Hayward Baker, 2013). These walls are constructed downward under normal circumstances. A drainage system is placed over the exposed soil cut in order to collect and evacuate the groundwater behind the wall. Steel plates and nuts retain the steel bars inside of the ground, therefore providing a passive resistance (Hayward Baker, 2013). The final step is the coverage of the exposed face and drainage strips by application of a layer of pneumatically placed concrete (shotcrete) and/or precast concrete panels. These steps are sequentially repeated down until the planned bottom of excavation is achieved.

Current design methods focus in the limit state and the existing specification. Statistical data and design background is limited, especially for the application of the reliability-based design and LRFD over ASD (Babu and Shing, 2011). This is evidenced by the fact that FHWA Manual (2003) did not include LRFD parameters, although the FHWA did include it in the previously published Design Manual (1998). Based on the findings of Babu and Shing (2011) and Lazarte et al. (2003), LRFD for soil nailing shall be based on load and resistance factors calibrated using reliability analysis. Developments in quicker and more advanced testing techniques will result critical in the future of this type of retaining wall (Tan et al. 2008) as well as a better definition of the parameters involved in the design (Su et al. 2008, Chu and Yin 2005). In opposition to the previous wall types, soil nail design and specifications literature and experiences are not that extensive and therefore the design and construction of a soil/rock nail wall requires of specialized designers, subcontractors and field inspectors.

2.2.1.5 Tie Back

Soil reinforcement can be advanced by the use of anchors, also called tie backs. These systems were not fully developed until 1979, when the FHWA authorized a demonstration project in order to promote the use in the different states, as well as to gain experience to develop a set of guidelines

(FHWA, 1988 and 1999). This system transfers the tensile loads to the ground, increasing the retention action, by means of a configuration of pre-stressing steel, anchorage head and grout (PTI, 2004). These anchors are used for building lower levers, slope stabilization, against uplift, bridge abutments or walls for civil construction (FHWA, 1999 and Druss, 1994).

The external end of the tieback is anchored in the wall face by steel plates, nuts or anchor chucks. The other end is anchored to the ground in a similar way than the nails as the grout bulb created resist the load based on the friction exerted to the ground. The holes are drilled with specialized equipment to ensure proper inclination and length. Grout is then pumped under pressure into the tieback anchor holes so that the rods can utilize soil resistance to prevent tieback pull-out and wall destabilization. These tiebacks are tensioned once the injected grout has attained enough strength. This extra tension provides the wall with an extra capacity to resist the lateral forces applied to it, but also requires an increased level of wall monitoring. Loads vary depending on the wall but values between 50 and 150 kips per tie backs are commonly used for tensioning (Sabatini et al. 1999; Weatherby, 1998).

As described for the soil/rock nails, the current understanding of tie back service and long term behavior is not fully complete, this might be due to either the limited information obtained to date from experiments or numerical models (Costopoulos, 1988). Nevertheless, the needs for higher walls and more efficient space consumption has promoted developments in both the knowledge and technology involved in the design and construction of these walls. The last decade joint effort of FHWA and ASTM has led to improved sets of rules and regulations for materials, design and construction (PTI, 2004). Tie back walls can reach considerable heights in excess of 80 feet, with irregular shapes and differential wall movement control. However, the level of expertise required for the design, construction, inspection and monitoring exceeds all the previous types of walls analyzed in this section. The impact of groundwater and soil corrosion over the tie backs has a direct effect on their retention capacity, thus protection and drainage systems resulting critical for the long term performance of the anchors (Strom and Ebeling, 2001).

2.2.1.6 Summary of Retaining Wall Features

The Tennessee Department of Transportation (2012) issued its Transportation Earth Structures Manual which included a list of parameters that determine which wall out of nine available types is the most adequate. Additionally, a matrix of advantages and disadvantages for each type was included in order to allow state Engineers make a proper selection of the most adequate types of wall for each need. These matrices were divided in fill and cut walls because just by analyzing the direction of the wall construction, some types can be discarded as not applicable.

Table 2.2 Matrix for Fill Walls (From TDOT, 2012)

SYSTEM SELECTION CHART FOR FILL WALLS						
Wall Type	**Permanent**	**Temporary**	**Cost Effective Height Range**	**Cost ($/sf face of wall)**	**Required ROW (from face of wall)**	**Differential Settlement Tolerance**
Concrete Gravity Wall	x		3-10	25-35	0.5-0.7H	1/500
Concrete Cantilever	x		6-30	25-60	0.4-0.7H	1/500
Concrete Counterforted	x		30-60	25-60	0.4-0.7H	1/500
Concrete Crib	x		6-35	25-35	0.5-0.7H	1/300
Metal Bin	x		6-35	25-35	0.5-0.7H	1/300
Gabion	x		6-26	25-50	0.5-0.7H	1/50
MSE (precast facing)	x		10-65	22-35	0.7-1.0H	1/100
MSE (modular facing)	x		6-23	16-26	0.7-1.0H	1/200
MSE (geogrid, wire face)	x	x	6-50	15-35	0.7-1.0H	1/60

Wall Type	**Advantages**	**Disadvantages**
Concrete Gravity Wall	Durable	Deep foundation support may be necessary
	Requires less select Backfill than MSE	Long construction time
	Concrete can meet aesthetic requirements	
Concrete Cantilever	Durable	Deep foundation support may be necessary
	Requires less select Backfill than MSE	Long construction time
	Concrete can meet aesthetic requirements	
Concrete Counterforted	Durable	Deep foundation support may be necessary
	Requires less select Backfill than MSE	Long construction time
	Concrete can meet aesthetic requirements	
Concrete Crib	Does not require skilled labor or specialized equipment	Difficult to make height adjustments in field
	Rapid Construction	
Metal Bin	Does not require skilled labor or specialized equipment	Difficult to make height adjustments in field
	Rapid Construction	Subject to corrosion
Gabion	Does not require skilled labor or specialized equipment	Need adequate source of stone
		Construction of wall requires significant labor

Table 2.2 Continued		
Wall Type	**Advantages**	**Disadvantages**
MSE (precast facing)	Does not require skilled labor or specialized equipment	Requires use of select backfill
	Flexibility in choice of facing	Subject to corrosion in aggressive environment
MSE (modular facing)	Does not require skilled labor or specialized equipment	Requires use of select backfill
	Flexibility in choice of facing	Subject to corrosion in aggressive environment
	Blocks are easily handled	Positive reinforcement connections to block is difficult to achieve
MSE (geogrid, wire face)	Does not require skilled labor or specialized equipment	Facing might not meet aesthetical requirements
	Flexibility in choice of facing	Geosynthetic reinforcement is subject to degradation in some environments
		Vegetated soil face requires high maintenance

Table 2.3. Matrix for Cut Walls (From TDOT, 2012)

SYSTEM SELECTION CHART FOR CUT WALLS					
Wall Type	**Permanent**	**Temporary**	**Cost Effective Height Range**	**Cost ($/sf face of wall)**	**Required ROW**
Sheet Pile Wall	x	x	Up to 16 ft.	15-40	None
Soldier Pile/Lagging Wall	x	x	Up to 16 ft.	/10-35	None
Slurry (Diaphragm wall)	x	x	/20-80	/60-86	None
Tangent pile wall (drill shaft wall)	x	x	/20-80	/40-75	None
Secant Pile Wall	x	x	/20-80	/40-75	None
Anchored Wall	x	x	/16-65	/15-75	0.6H + bond length
Soil Nailed Wall	x	x	/10-65	/15-56	0.6H-1.0H
Micropile Wall	x		30	/75-125	None
Wall Type	**Lateral Movements**	**Water tightness**	**Advantages**	**Disadvantages**	
Sheet Pile Wall	Large	Fair	Rapid Construction	Difficult to construct in hard ground or obstructions	
			Readily Available		
Soldier Pile/Lagging Wall	Medium	Poor	Rapid Construction	Difficult to maintain vertical tolerance in hard ground	
			Soldier piles can be drilled or driven	Potential for ground loss at excavated face	
Slurry (Diaphragm wall)	Small	Good	Can be constructed in all soil types or weathered rock	Requires specialty contractor	
			Watertight	Significant spoil for disposal	
			Wide range of stiffness	Requires specialized equipment	
Tangent pile wall (drill shaft wall)	Small	Fair	Adaptable to irregular layout	Difficult to maintain vertical tolerance in hard ground	
			Can control wall stiffness	Significant spoil for disposal	
				Requires specialized heavy equipment	

Table 2.3 Continued					
Wall Type	**Lateral Movements**	**Water tightness**	**Advantages**	**Disadvantages**	
Secant Pile Wall	Small	Fair	Adaptable to irregular layout	Significant spoil for disposal	
			Can control wall stiffness	Requires specialized heavy equipment	
Anchored Wall	Small-Medium	N/A	Adaptable to variable site conditions	Requires highly specialized labor and equipment	
			Can resist large horizontal pressure	Anchors may require permanent easements	
Soil Nailed Wall	Small-Medium	N/A	Rapid Construction	Nails may require permanent easements	
			Adaptable to irregular wall alignment	Difficult to construct and design below water table	
Micropile Wall	Small	N/A	Does not require excavation	Requires specialty contractor	

Focusing on the particular problems of the downward construction of retaining walls in Taiwan, Yau et al. (1997) developed a summary chart that included the advantages and disadvantages of each type of wall considered, with emphasis on groundwater control.

Table 2.4. Retaining Wall Systems in northern Taiwan (From Yau et al. 1997)

TYPE OF RETAINING WALL SYSTEM	**GROUND CONDITIONS**	**EXCAVATION DEPTH**	**REQUIREMENTS FOR WATERPROOFING**	**ADVANTAGE**	**DISADVANTAGE**
H-Section steel pile	Excluding extremely soft ground	Up to 25 meters below ground	No special requirements	Simple and low cost	Lack of water stop functions
Open Excavation	No special requirements	Depends on site conditions	Needs water stoppage	Simple construction	Needs large site area
Retaining Column	Gravel, pebble	Up to 13 meters below ground	No special requirements	Easy construction	Valid for certain soils, slow construction
Row Pile	Soft ground with heavy water boil	Up to 30 meters below ground	Needs water stoppage	Allows various stiffness for design	Spacing between piles requires serious attention
Driven Pile	Soft ground	Up to 15 meters below ground	Needs water stoppage	Simple construction	Noise pollution
Auger Boring Pile	Soft ground	Up to 50 meters below ground	Needs water stoppage	No pollution, economic for deep excavations	Unsuited for sandy gravel
Steel Rail Pile	Loam, clay, sand	Up to 5 meters below ground	No special requirements	Simple and low cost	Low strength, only for simple retaining works
Full Casing Pile	Soft ground unsuited for sandy soil	Up to 20 meters below ground	Needs water stoppage	No pollution, simple construction	Construction process requires serious attention

Table 2.4 Continued

TYPE OF RETAINING WALL SYSTEM	GROUND CONDITIONS	EXCAVATION DEPTH	REQUIREMENTS FOR WATERPROOFING	ADVANTAGE	DISADVANTAGE
Steel Sheet Pile	Soft ground with heavy boil	Up to 15 meters below ground	Needs water stoppage	Simple waterproof wall method	Noise pollution, heavy vibration and complex joint work
Slurry Wall	Soft ground with heavy boil	Up to 40 meters below ground	Needs water stoppage	No settlement	Long duration, high cost

2.2.2 Retaining Wall Construction: Phases, Equipment and Materials.

Retaining wall construction requires specialized personnel, materials and equipment that need to be carefully selected and utilized in order to achieve acceptable safety, quality, cost and production outputs. Furthermore, some types of retaining wall can only be built if custom-made machinery and materials are utilized to complete certain activities or elements. For the types analyzed in this Thesis, based on increasing needs for specialized personnel, equipment and materials, we can organize them as shown below:

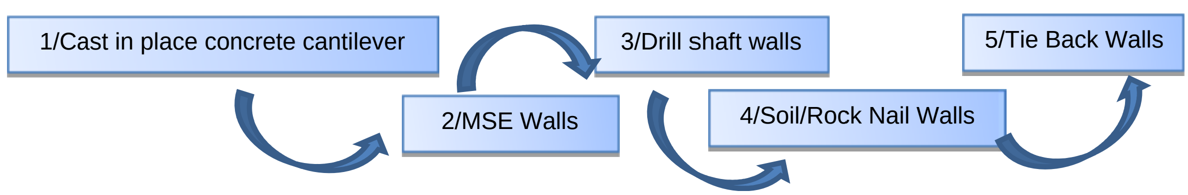


Figure 2-5 Retaining wall categories organized by increasing needs for specialized equipment and materials

Therefore, the selection process must account for the availability of specialized personnel and equipment, increasing costs and requirements in regards to level of supervision needed.

The development of unit costs and production rates for the different types of retaining walls require of an analysis of the different phases involved in the construction processes. Despite the specific features of each type of walls, some of these phases are common to various types. Certain departments of transportation develop guidelines based on the experiences and record keeping obtained in the different projects throughout the State. For example, the Texas Department of Transportation released a summary of parameters for the retaining walls constructed in Texas highways between August 1, 2006 through June 20, 2007 (Galvan, 2007).

Table 2.5. Retaining Wall distribution for TxDOT Projects from August 1 to July 2007 (Galvan, 2007)

WALL TYPE	AREA (sq.ft)	% TOTAL BUILT	UNIT COST ($/sq.ft)
MSE	2,000,000	85.1%	35
Concrete Block	150,000	6.4%	26
Cantilevered Drill Shaft	100,000	4.3%	70
Soil Nailed	70,000	3.0%	65
Tied-Back	20,000	0.9%	95
Spread Footing	10,000	0.4%	85

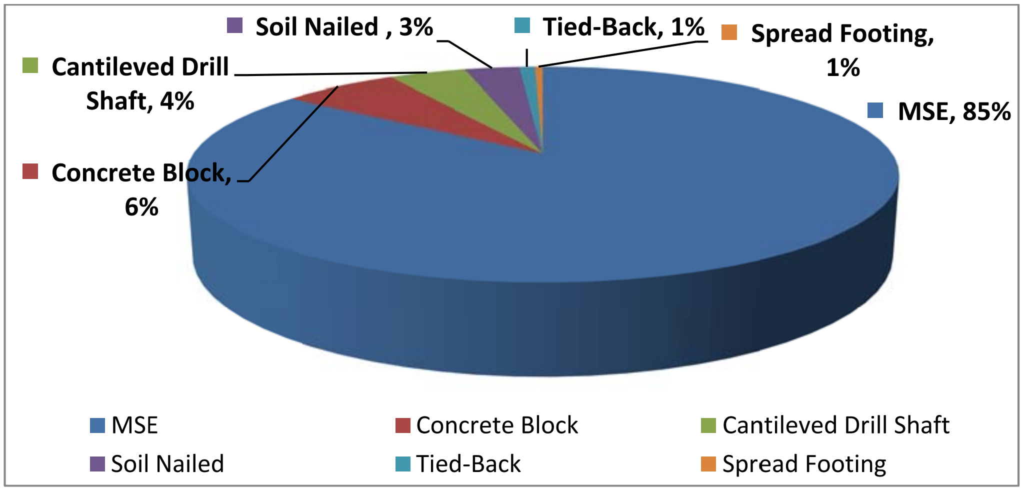


Figure 2-6 Retaining wall use distribution for TxDOT Projects from August 1 to July 2007 (Galvan, 2007)

Although the concrete block wall constituted the second highest percentage, this type is almost only used for small walls where heights are reduced. The applicability of this wall to heavy construction and highway projects is very limited. If analyzed for highway projects only, this percentage is reduced to under 1% (Galvan, 2007).

The operations involved in the retaining wall construction can be divided into six different categories as some of them are common for various types of retaining wall. Small specific operations such as filter fabric placement, drainage strips, underdrains, coping, cleaning, safety devices or dewatering are not included as they generally do not constitute a main source of expenses or time consumption during the construction of the walls. Also, each wall encompasses different miscellaneous works so neglecting these parameters is justified.

These main categories are:

1. Excavation
2. Drilling
3. Reinforcement placement
4. Concrete, grout and shotcrete placement
5. Backfilling
6. Stressing

In order to calculate the cost involved in the construction of each type of wall, not only is necessary to determine the equipment involved but also the characteristics of the materials required. Equipment requirements are mainly a matter of performance and capabilities and not the compliance with Specifications. On the other hand, the set of requirements that the different materials need to comply with is vast, variable and location-dependent. Although the requirements to be met by the different materials being used during the wall construction differ depending on the Agency or Owner in the particular project location, the ASTM codes are the main reference in most cases. For example, TxDOT Standard Specification Item 440 regulates the requirements in regards to reinforcement steel. This Item requires the rebar to meet the requirements of the DMS-7320 (Department Material Specifications) which includes most requirements directly from ASTM A615 (TxDOT, 2004 and 2012).

An analysis of the main phases involved during the retaining wall construction, as well as the equipment and materials is included below. The review of the costs and production rates will be analyzed at the end of the section.

2.2.2.1 Excavation

Every type of wall considered involves excavation processes either to bring the natural ground to subgrade elevation (cast in place cantilever and MSE Walls), to expose the soil/rock face before drilling for nail/tie back placement or to provide the space for concrete and rebar placement (drill shafts). This excavation process involves both digging and hauling equipment for the excavated material.

The equipment used to perform this excavations vary depending on the specifics of the location and wall considered, but for most cases, regular or modified hydraulic hoes are used to excavate while trucks haul the excavated material to the designated dump site.

Figure 2-7 Preparatory excavation process for (a) Rock Nail and (b) cantilever wall

(personal pictures archive 2013 and www.excavationpcouture.com)

As an initial preparatory step, for cast in place concrete cantilever and MSE Walls, subgrade needs to be properly conditioned before starting the wall construction. Compaction and/or soil replacement is commonly performed to improve the bearing capacity of the soil where the wall will be supported. This is performed prior to the construction of the known Wall #1 as described in Section 2.4.1.

Figure 2-8 Underdrain for MSE Wall drainage and subgrade preparation (personal archive 2013)

2.2.2.2 Drilling

Soil/Rock nail and Tie back walls require of drilling operations to create the holes where the reinforcement steel and grout will be later placed to create the retention system. The sensitivity of the system require that the holes are drilled with tight tolerances in regards to drilled hole length and inclination otherwise the design parameters would not be achieved.

The equipment used to perform this drilling operation are custom-made hydraulic hoes where the boom is tailored to incorporate a drilling rig with inclination controlled by a series of digital levels that self-adjust any deviation of the drill as it is executed. The drill rig is composed of continuous fight auger mounted in an hydraulic arm. These machines are normally track mounted to allow more movement flexibility in rough terrain and improved stability during the drilling operations. These machines offer a high degree of flexibility, being able to drill at high elevations, with skewed angles and inclined holes both upwards and downwards.

Figure 2-9 (a) Drilling operation for Tie Back and Rock Nail walls. (b) Detail of drilled holes prior to reinforcement placement and grout injection. (personal pictures archive 2013)

Figure 2-10 (a) Drilling operation for Rock Nail walls and (b) Detail of drilled holes inclination check prior to reinforcement placement and grout injection. QA/QC is essential. (personal pictures archive 2013)

Drill shaft walls require also drilling operations but of a different kind. Vertical drilling is required to execute the holes where the reinforcement steel cage and the concrete will be later placed to create each individual pile composing the wall. These machines, yet very specialized, are more common than the drilling rigs required for the nail/tie back walls. Plumb and length of the holes drilled are normally controlled by the operators supervising the operations. The material being drilled must be carefully examined to ensure the geotechnical parameters assumed in the design match the actual soil conditions encountered in the field for end bearing and skin friction.

Shaft drilling processes are normally regulated by the Agency responsible of the Project, for example TxDOT Specifications Item 416 (TxDOT, 2004).

Figure 2-11 Drilling operation for drill shaft walls. (a) drill shaft wall executed in front of a nail wall and (b) protective cage for the operator. (personal pictures archive 2012)

As in the case of the nail/tie backs, the machinery used to perform this drilling operation is custom-made hydraulic excavators where the boom is modified to incorporate a vertical mast where the drilling auger is mounted. The drill rig is composed of continuous or discontinuous fight auger. These machines are also track mounted to allow more movement flexibility in rough terrain and improved stability during the drilling operations.

Auxiliary equipment is required for all reviewed drilling operation to load, haul and dispose the spoils resulting of the drilled holes. Loaders, highway dump trucks and dozers are commonly used.

Figure 2-12 Hydraulic hoe loading spoils in a rigid frame dump truck. (logansitework.com)

No specific requirements are applicable to the materials as excavation processes are mainly an equipment based operation. However, compliance with the environmental and administrative regulations during the excavation, drilling, hauling and disposal of materials is of critical importance. Improper practices during the dumping of materials, groundwater and contamination management or equipment operations can result not only in delays and over costs but also considerable fees, penalties and violation processes (Dallas EMS, 2005).

2.2.2.3 Reinforcement Placement

The reinforcement placed in each type of walls differs from one type to another as shown below. In the following list, details are provided for each type of reinforcement used in the wall types considered:

- Cast-in-place concrete walls are reinforced with steel bars that provide the stem and footing additional resistance to withstand the tensile stresses that concrete cannot resist. Drill shaft walls are composed of a series of individual shafts that are made of cast in place concrete poured into a drilled hole where a reinforcement steel cage is placed in advance. This rebar provides the shaft with additional resistance against the tensile stresses that only concrete will not support. These piles are normally tied together by reinforced concrete capping beams where rebar is also a main component.

Figure 2-13 (a) Rebar cage in drill shaft prior to concrete placement. (b) Rebar placement for cantilever cast in place wall stem. (personal pictures archive 2011)

- MSE walls can be reinforced by several different materials but the most commonly used are series of metallic galvanized strips that support the facing panels based on the friction between them and the granular backfill (Elias et al. 2001). These strips are designed to provide satisfactory factors of safety against both pullout and breaking of the strips.

Figure 2-14 Galvanized straps placed over the granular backfill for reinforcement (www.dot.state.oh.us)

The reinforcement steel being used for both the cast in place cantilever, drill shaft, MSE precast panels and shotcrete facing needs to comply with the specific requirements of the Owner/Agency where the walls is built but generally, ASTM A615 is the referenced code.

- Soil/Rock nail walls are reinforced with steel bars, normally epoxy coated for corrosion protection and durability. These are encased in grout so the friction between this grout and the surrounding soil is such that the bars can develop their allowable stress to retain the wall. Welded wire mesh reinforcement is also commonly used to provide tensile resistance for the external shotcrete facing. Nuts, plates and studs are also steel-made elements necessary for the system to perform.
- Tie Back walls are reinforced with either high strength steel bars or low relaxation steel cables following ASTM 722 or 416 respectively. These bars/cables are placed in the holes and develop their allowable stress following a similar process than the nails as detailed in point b above. Corrosion protection is provided with epoxies, greases, grouting or sheeting. As for the previously described case of soil/rock nails, welded wire mesh reinforces the shotcrete layer sprayed over the exposed soil face. Wedges, nuts, washers, plates, chucks, studs and anchor heads are also steel-made elements necessary to be accounted for.

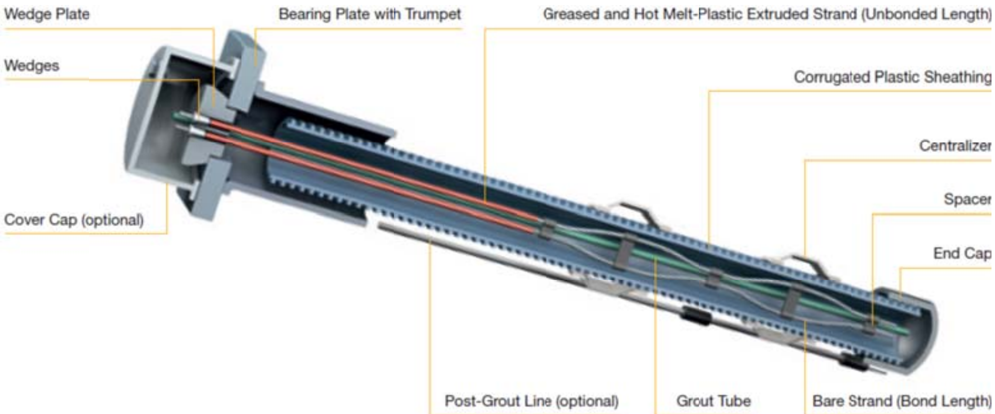


Figure 2-15 Commercial tie back anchor system (DSI USA Geotechnical Product Guide)

With the exception of the rebar cage for drill shafts that require a crane to be introduced in the drilled holes, the rest of the reinforced elements included above are normally placed manually by the construction personnel involved in these operations. In the case of the drill shafts, although normally of certain complication, the rebar cages can be preassembled outside of the drilled hole so the rebar placement is a quick operation that does not limit the overall production rate.

2.2.2.4 Concrete, grout and shotcrete placement

Hydraulic cementitious materials are widely used in the current construction industry and retaining walls are no exemption to the trend. Different types of materials are used as part of the retaining walls analyzed in the present report. Concrete, grout and shotcrete are used in different parts or these walls:

- Grout: This mixture of hydraulic cement and water which can include fine aggregate and is used to fill the holes where the nails or tiebacks are placed. The grout provides the transmission of the friction between the bar and the soil. Water cement of the grout mix designs used in retaining wall construction vary from 0.3 to 0.5 ratio.

  Grout can be either fabricated in an outside plant and delivered in concrete trucks or on-site mixed. In both cases is then injected in the holes by special pressure pumps until rejection is observed at the top of the hole to ensure no voids are present around the reinforcement. Batch plants, mixers, special pumps, concrete trucks, hoses, purges and pressure injectors are used to place the grout in the holes.

Figure 2-16 Grout mixer system used to on-site grout production (www.chemgrout.com)

- Shotcrete: This material is a variation of concrete where no coarse aggregate is used. The use of chemical admixtures creates a highly sticky mixture that adheres to the excavated face to provide an extra support and protection of the exposed rock/soil face. The shotcrete is pneumatically placed with nozzle machines under dry or wet conditions. Dry conditions refer to the case that pumps a dry mix and the water is added at the tip of the nozzle. Wet placement is the one where the mix incorporates the water before entering the pump. Batch plants, special pumps, concrete trucks, hoses and nozzles are used to produce, deliver and spray the shotcrete over the excavated face of the nail/tie back walls. A special set of ASTM regulations exist for the control of the shotcrete fabrication, placement and testing such as C1385, C1436, C1140 and C1604.

Figure 2-17 Nozzle operator placing shotcrete in rock nail wall (wet) (personal archive 2013)

- Concrete: Hydraulic cement is mixed with aggregates and water to create a fluid material that later hardens to form different elements. Cantilever wall stems and footings, MSE precast wall panels as well as the drill shafts are constructed with this material. Batch plants, concrete trucks, pumps, buckets and tremie tubes are used to produce, deliver and place the concrete inside the formwork or the holes in the cantilever or drill shaft walls respectively.

Due to the specifics of the precast panel construction, the details of it will not be analyzed in detail as these elements are fabricated off-site and delivered to the Project. Thus, the production rate of the panels do not impact the ones for the wall if the delivery is properly scheduled. Cost for the panels will be considered as a fixed cost for cost calculations.

Figure 2-18 (a) Concrete placed in cantilever wall with bucket and (b) drill shaft with hopper (personal archive 2013)

Figure 2-19 (a) Detail of tremie tube inside of rebar cage to place the concrete (avoid segregation and soil intrusion) and (b) concrete Batch Plant (personal archive 2011 and www.gulfatlanticequipment.com)

The cement being used in the grout, concrete and shotcrete production is normally Portland cement in compliance with ASTM C150 requirements. Aggregates production need to comply with different regulations from the environmental perspective but as far as materials are concerned, the main applicable requirements are detailed in ASTM C33. Additional regulations apply for the production such as ASTM C94 for the production of Ready-Mix concrete (Obla and Lobo, 2006). The secondary products used in the fabrication of the hydraulic cement mixes are also regulated by ASTM codes. A summary of these is included below (Obla and Lobo, 2006):

- ASTM C 618 Class F fly ash
- ASTM C 989 Ground granulated blast furnace slag
- ASTM C 1240 Silica fume
- ASTM C 260 Air entraining admixture
- ASTM C 494 Water reducing admixture

2.2.2.5 Backfilling operations

Rock/Soil Nails, tie back and drill shaft walls are based on a "downward cut" configuration, where the material in front of the wall is excavated before (nails and tie backs) or after its execution (drill shaft). The material in the back of the wall is the existing soil/rock that remains retained by the wall.

On the other hand, cast in place cantilever and MSE Walls follow a "upward fill configuration" where the wall is backfilled with borrowed material to complete the wall section. In the case of the MSE walls this is even more critical as the ability of the wall to resist the loads is dependent on the friction existing between the reinforcement ties and the granular backfill. The main difference between the cast in place and the MSE Walls is the fact that the latter is continuously backfilled once each row of panels and reinforcement strips are placed. Cast in place are entirely built and then backfilled once the concrete has attained sufficient compressive strength and the drainage measures are in place.

Although general regulations exist at both the national, state and local levels, the requirements for the materials used for the backfill are highly dependent on the particular location of the wall being constructed. A summary of the different constraints and the consequential requirements is included below (FHWA, 2009):

Table 2.6. Summary of Constraints and Resulting requirements for backfill

CONSTRAINT	RESULTING REQUIREMENT
Flooded area	Gravelly granular material
Insufficient space for straps (MSE)	Increased friction angle and unit weight
Soft foundation	Reduced unit weight
Need for drainage	Limited passing #200 sieve
Use of metallic reinforcement	Controlled PH and resistivity

As shown above, although the general requirements specified in the contract Specifications are satisfied by most non-cohesive soils and crushed aggregates, design constrains can determine additional parameters that need to be met. These may increase the cost and complication of the aggregate production, therefore increasing the overall wall unit cost and reducing the production rate. An example of Specifications would be the TxDOT Item 423 where a specific gradation, PH, and resistivity need to be met in order to use a certain backfill in an MSE wall (TxDOT, 2004).

Figure 2-20 Backfilling operation in MSE Wall. (personal pictures archive 2013)

Specific drainage measures are to be implemented in the walls. Filter fabrics, bituminous paints, waterproof joints, weep holes and shear keys are normally used in these walls to ensure that no material is washed from the runoff events and that no undesired water pressure will build up in the retained backfill.

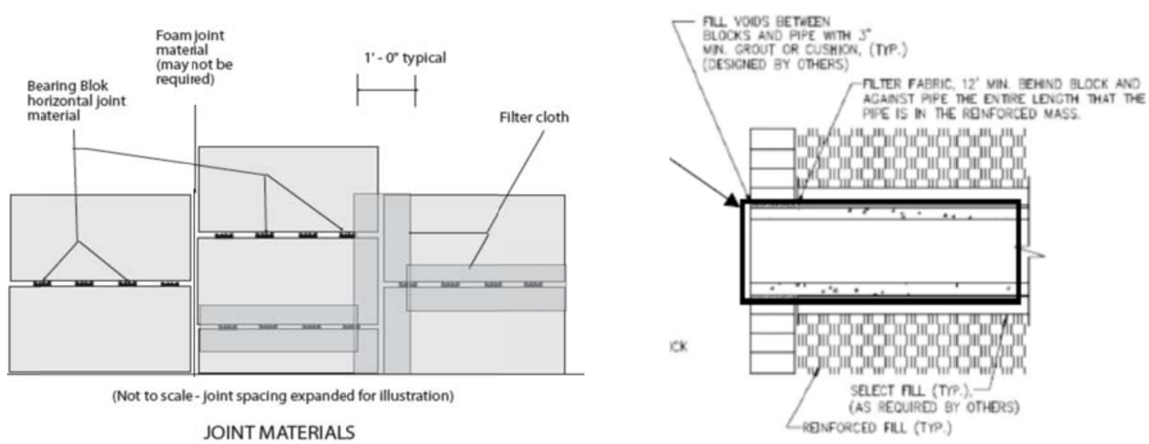


Figure 2-21 (a) Joint materials and (b) detail of weep-hole device to install in MSE Walls (Reinforced Earth Company. Large Panel Construction Manual and FHWA MSE Wall D&C Manual)

The equipment used to perform this operations is commonly available in almost project. Loaders, hydraulic backhoes, dump trucks, dozers and compactors are used to perform these operations. The compaction of the area closer to the panels need to be carefully executed using tamping plates or smaller compactors to avoid excessive loads that may induce a “lean forward” in the recently placed wall.

2.2.2.6 Stressing operations

Tie back walls include an additional step for the stressing of the reinforcement steel both for threaded bars and cables. Once the bars or cables are placed and the hole is grouted, a certain amount of time is required to allow the grout cure and achieve the design required compressive strength. Once an independent laboratory has confirmed this sufficient strength, the tie backs can be pulled to the design specified strength (Strom and Ebeling, 2001).

Soil/Rock nails are also stressed during the proof and performance testing that is performed in a certain percentage to evaluate the actual parameters and to identify any potential deviation from the design expected performance. This stressing does not contribute to the structural behavior of the wall as these nails are de-tensioned after the test is completed (FHWA, 2003).

Figure 2-22 Stressing operation for (a) threaded bar tie back wall and (b) low relaxation steel strands (personal archive 2012)

The bars or cables are stressed using hydraulic jacks that are previously calibrated to obtain the relationship between the pressure in the jack gauge and the force exerted in the tie back (see figure 2.36). The values of the elongations on the tie backs are recorded and compared with the expected values in order to evaluate the actual performance of the soil-grout bonding and the real resistance of the tie back wall to resist the acting loads. Cell pressures and creep monitoring devices are also installed in certain structures where the elements being retained are critical assets (gas lines, hospitals, dams…).

Highly specialized equipment and personnel are involved during stressing operations. These not only provide the tie backs of their required load but also verify that the assumed geotechnical performance is indeed achieved. This phase is of critical importance in both soil/rock nails and anchored walls and as such, the costs and durations associated need to be considered when developing unit cost and production rates. The subcontractors specialized in geotechnical solutions such as nail or anchor walls generally own the necessary equipment to perform the stressing and testing operations so they include these as part of their unit rates.

2.2.3 Retaining Wall Construction Cost and Production Rates

The phases, materials and equipment involved in the construction of the 5 types of retaining walls were researched and the results were presented in Section 2.2.2. Similarly, in order to develop an accurate set of unit costs and production rates, it is necessary to investigate the available experiences and literature.

An accurate forecast of the construction durations and costs result of key importance when planning, bidding, managing and controlling the construction projects (Mubarak, 2010). Although the scheduling and estimating knowledge and tools have evolved greatly in the last decades, avoidable social costs, delays and budget overruns are not uncommon in current highway construction (Chong, 2005).

Production rates and unit cost estimation cannot be considered an exact science. Although certain databases are commercially available in the market, most agencies and companies rely in their own historical data as well as proprietary programs. For example, TxDOT obtains most of the information during the contracting and design stages from their expert senior staff, subcontractor input, RS Means database and the Contract Time Determination System (Chong, 2005 and Hancher, et al. 1992). It is important to note that although RS Means was developed as a unit cost database, it is being used by several schedulers to determine the production rates for the construction activities during the planning and design stages (Chong, 2005). It is during the application of the site specific factors that make these unit rates and prices accurate where the expertise of the engineer is put to the test

The consequences of an improper estimation of project costs and durations can have not only economic implications but also social, political, security or even legal repercussions (Pratt, 2011). Let us picture a critical example; there are dozens of companies building the infrastructures required for the XXXI Olympic Games in Rio de Janeiro, Brazil. Should these works incur in project delays, Brazil will not only face multimillion dollar revenue losses but also liquidated damages from the Olympic Committee, heavy pressure from the international community, loss of a platform for projection as an economical power, great image damage as well as potential financial impact due to investor's loss of confidence.

Although there is what appears to be an industry-wide effort towards developing a more reliable set of production rates, unit costs remain carefully kept within the boundaries of each company (Chong, 2005). In reality, the commercial interests preclude these improvements to occur. A superior record-keeping system can determine a success in future bidding processes where competing companies propose to (Mubarak, 2010). Current duration estimation and unit costs development processes are based on "expert guesses" and adaptation of general rates by the application of job specific factors.

The unit costs and production rates associated to the construction of any retaining wall is very complex in nature. Not only do these rates involve several different materials but also equipment, labor, subcontractors and overhead (Pratt, 2012). Under some circumstances, two equally adequate walls for a certain location will be ranked just by the comparison of their unit costs and production rates (TDOT, 2012). Therefore, the author's focus is to develop unit costs and production rates that can be used to evaluate "competing" wall types but also to serve as a database for future preliminary studies. The next sections present an analysis of those factors that can have the biggest impact on these values and literature references for unit costs and production rates.

2.2.3.1 Retaining Wall Construction Cost

Pricing a certain retaining wall would not only include the construction of it but also the design, maintenance, rehabilitation and replacement costs. This would be the life cycle cost of the retaining wall (Penn and Parker, 2012). This analysis would result outside of the scope of this thesis defined in Section 1.1.1 where only construction costs are compared.

The literature available in regards to unit costs of retaining wall construction is limited and of questionable applicability to real world needs. This is due to the commercial interests of the construction companies to not to disclose their unit prices for future bidding. Additionally, previous studies used methodologies that could have taken a better suited approach in the author's opinion. For example, despite the concise work performed by Petaja (1999), the results are ranked by cost per linear feet. This unit of measurement neglects the height of the wall as well as equals the different types so the unit costs are not properly compared. Petaja (1999) distributed the walls by categories and ranked them by unit cost. This approach does not consider the higher applicability of certain types under some of these ranges, therefore not allowing a proper comparison when heights required span over two or more of these ranges. The influence of the wall height is deep and of critical importance when comparing different retaining wall types for a certain need. Particularly, the cost of the different processes, equipment and certain materials required to construct a certain wall are increased exponentially when the wall height increase. Petaja (1999) analyzed the changes of steel, concrete and formwork cost for different cast in place cantilever walls. Although the cost of steel was deemed constant, formwork and concrete increased its cost for the extreme heights, both at the high and low levels.

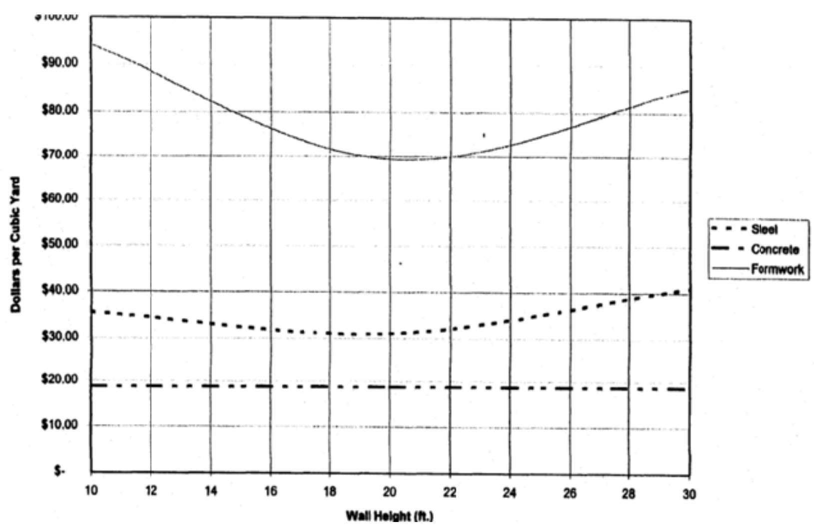


Figure 2-23 Steel, formwork and concrete labor cost per CY Vs. Wall Height (from Petaja, 1999)

The data shown above neglects the increase of cost in both specialized labor and equipment required to place the materials when height increases. This would have definitely increased the slope of the cost increase for heights over 20 ft. in all three categories considered.

Not only the considerations of the wall location or materials have an influence on the wall unit cost (Poubarba, 2012). For example, as shown in the graph below, there is a deep influence of the factor of safety used during design on the unit cost of a certain wall. Additional cost affections can be caused by construction permits, procurement, market fluctuations or raw materials cost. The findings of the analysis performed by Poubarba et al (2012) by use of an imperialist model are included below:

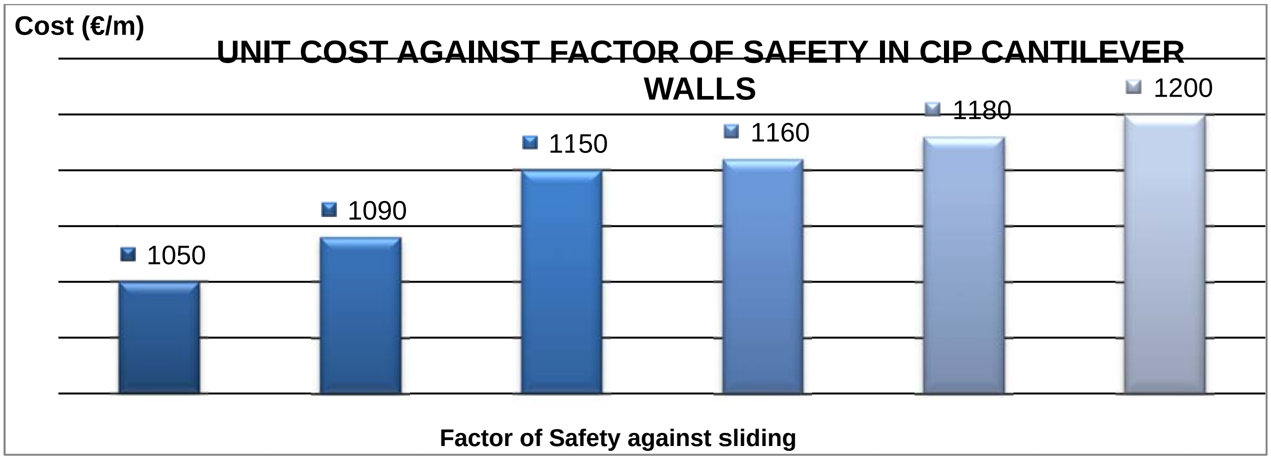


Figure 2-24 Influence of design sliding Safety Factor in Cantilever wall unit costs (from Poubarba, 2012)

The results of the different unit costs identified in literature references for the main types of retaining walls are included in Table 2.14, under Section 2.2.6.

Based on the literature review performed, there is a profound lack of applicable reliable sources or previous references for retaining wall unit costs. Therefore, a different approach is adopted in the present Thesis where these rates will be obtained first hand from the personnel currently designing and constructing hundreds of square footage of the retaining walls types being analyzed in the DFW area. This data collection is based on surveys, interviews and field observations. The methodology and the results of this data collection campaign are included in Section 3. The developed unit rates will be analyzed and later used as a comparison parameter among the different types of wall.

2.2.3.2 Retaining Wall Construction Production Rates

Productivity could be informally defined as "how much work can I do with these many resources". A more formal definition would be the general one adopted by Thomas and Kramer (1988): "ratio of output divided by input".

One of the first coordinated efforts performed to investigate and develop tools and systems to accurately estimate construction duration time was undertaken by the Transportation Research Board in 1981 and 1995 (NCHRP, 1981; Herbsman et al. 1995). The results for the Herbsman (1995) were more definite and concluded that "realistic production rates are the key in determining reasonable contract times”. Hancher et al. (1992) performed a series of surveys to further collect evidence among expert engineers to support the general belief that in most cases, the input for retaining wall selection came from past experiences. The results of their work are shown below:

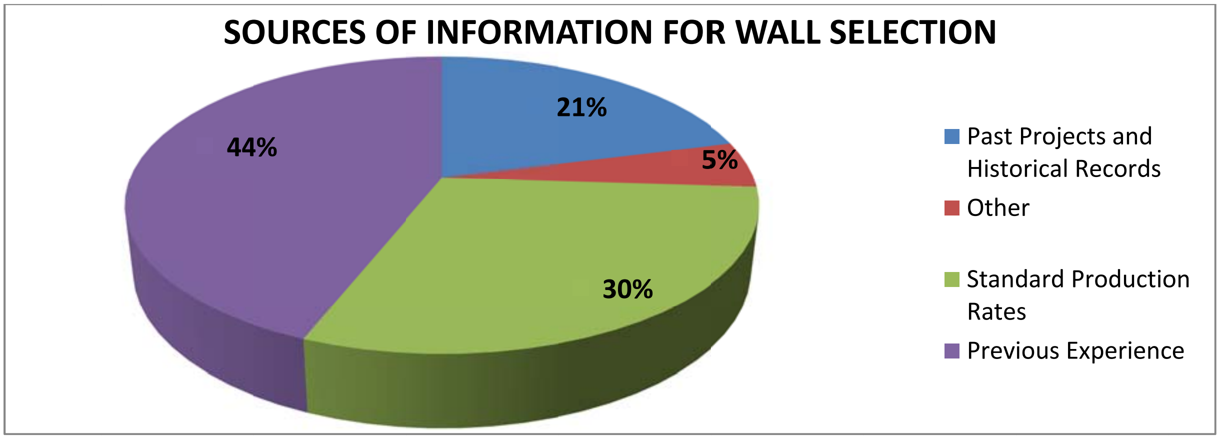


Figure 2-25 Sources of Information for Wall selection (from Hancher et al. 1992)

Despite the high percentage and common use, obtaining the production rates from just past experiences of the staff involved is risky in nature. These parameters are subjective, non-verified and far from being error-free, irrespectively of the subject’s experience. Site specific conditions, as well as the production drivers are essential to be considered in order to accurately forecast the actual durations. Later work such as the one developed by Chong (2005) shifted towards specific production rates that were no longer based on uncontrolled historical records mixed with subjective experiences. Chong (2005) rather focused in the development of production drivers and unreliable resource removal. Results showed that despite promising correlation, research was still necessary to develop the knowledge database and factors such as weather or workforce (Chong, 2005).

Several factors can have an impact on the production rates of the construction of each type of wall. Based on the classification developed by Murawski (2001), these factors are categorized by:

- Uniqueness of Projects
- Labor
- Varied Locations.
- Dependence on the Economy
- Weather and Seasonality
- Risk of Worker Accidents
- Disruptions and material supply
- Traffic and accessibility
- Advancement in technology
- Effect of learning curves

Based on the literature review performed, most references concur regarding the difficulties to accurately forecast production rates for a certain construction work (Chong, 2005; Murawski, 2001). Independently from the records of past activity, the analysis can only be performed under a probabilistic approach where best case and worst case are analyzed to determine the most probable outcome for a certain set of constraints (Murawski, 2001).

As described for the unit costs, and due to the lack of applicable reliable sources or previous references, these rates will be obtained first hand from the personnel currently designing and constructing hundreds of square footage of the retaining walls types being analyzed in the DFW area. This data collection will be performed by surveys, interviews and field observations where the results are included in Sections 3.2, 3.3, 3.4 and 3.5. These production rates will be analyzed and later used as a comparison parameter among the different types of walls.

2.2.4 Retaining Wall Selection Process

The complicated process of determining the optimum wall type for a certain location involves the analysis of different needs in terms of safety, economics, constructability, schedule, material or equipment availability, procurement and pollution prevention (Yang, 2004).

After an extensive research in regards to the currently available decision models for retaining wall selection, very few references have been located, where most of them used Expert Systems (ES). Expert Systems are currently one of the most successful, practical, and recognizable subsets of classical Artificial Intelligence. The ability to supply decisions or decision-making support in a specific domain has seen a vast application of expert systems in various fields such as healthcare, military, business, accounting, production, and human resources (Giarratano, 2004).

Some construction problems cannot be represented nor resolved with the use of conventional scientific algorithms, thus the need of different systems and approaches arise (Yang, 2004). Experience-oriented problems represent a suitable alternative where solutions are obtained by previous experience solutions. Due to the variety of agents and participants in the design and construction process, the structure that surrounds the wall construction processes is undefined and unorganized in nature. As defined by Yang (2004) “previous cases involving construction engineering and management also play important roles in solving problems since they show how decisions are made”. Using experienced knowledge from domain experts and previous examples of successful decisions, can lead to acceptable solutions. Thus, experience-oriented results as a powerful tool to imitate previous known decision cases where the solution converged to a successful outcome (Yang, 2004).

2.2.4.1 Retaining Wall Selection Models

Initially, Lee (1989) developed a dissertation regarding the use of expert systems to select and design retaining walls (1989). This knowledge based expert system (KBES) was based on a OPS5 programming language that returned the most appropriate type of wall and its main parameters based on the input data. Lee (1989) presents a model where nine types of walls are compared by using computer programmed logic. For the particular case of temporary retaining walls, Ikoma (1992) also used an expert system but supplemented it with fuzzy set theory for improved solution convergence.

Further research and development led to more refined models that were based not only in expert systems but logic regression analysis (Choi, 2010). These were the rule induction knowledge systems (Yang, 2003) and case-based reasoning (Yau et al. 2002). Most of these studies were based on a limited source of information such as Wuhan City (Yang, 2003) or Taiwan (Yau et al. 2002).

An additional factor was presented by Hess and Adams (1995) which indicated that the majority of the engineers tend to restrict themselves to select retaining wall types that they have experience with.

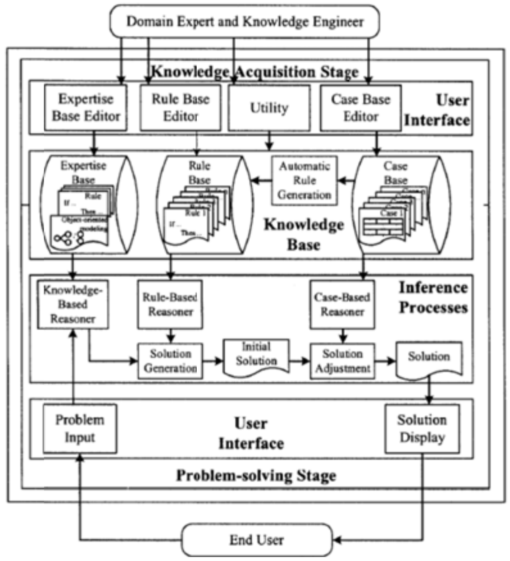


Figure 2-26 Retaining Wall Selection System (RWSS) developed by Yang (2004)

Yau et al (2002) developed a model based on induction rules (RI) that depending on the input parameters, their software was able to return the most appropriate wall type for deep excavations in Taiwan. Although the research, methodology and algorithm reasoning are thorough and useful for our goals, the scope is restricted to Taiwan's downward construction and dedicates excessive effort in temporary structures.

If Groundwater < 0.550
And Soil_Type is Sandy_Gravel
And Excavation_Depth >= 6.500
Then Retaining_Wall_System is Auger_Boring_Pile
If Groundwater < 0.550
And Soil_Type is Rock
Then Retaining_Wall_System is Auger_Boring_Pile
If Groundwater >= 0.550
And Soil_Structure_Solid is Yes
And Soil_Structure_V_Soft is Yes
Then Retaining_Wall_System is Auger_Boring_Pile
If Groundwater >= 0.550
And Soil_Type is Sandy_Gravel
And Soil_Structure_V_Soft is No
And Goundwater <1.625
Then Retaining_Wall_System is Auger_Boring_Pile
Then Retaining_Wall_System is Auger_Boring_Pile

Figure 2-27 Yau's (2002) algorithm for wall selection for deep excavations in Taiwan.

With the goal of implementing the engineer’s experience into a model available to the rest of the profession, Adams et al (1993) used a knowledge based system where by considering four categories, i.e. functional, spatial, behavioral and economical; they were able to discard the non-viable options before selecting the most appropriate ones. Further developments with the use of neural network techniques to reduce uncertainties due to the site conditions returned selection accuracies up to 72% (Sheu, 1996) but the complications of the programming language and algorithm made these models unsuitable for the general use.

The work by Yau (1998) presents a case-based retaining wall selection system (CASTLES) in which the case base consists of 254 previous retaining wall cases in Taiwan. According to the ability of the user's input to accurately describe the characteristics of a new project and a predefined similarity function, CASTLES identifies a set of feasible retaining-wall systems from the case base. Comparing CASTLES with four actual field cases revealed that the case-based reasoning approach is highly promising for selecting retaining wall systems.

Choi (2010) developed a different method based on machine learning techniques. This approach requires thousands of cases to derive a reliable conclusion, but such a large number of excavation cases are very difficult to acquire in the construction domain. There have been efforts to develop retaining wall selection systems using machine learning techniques but based only on a couple of hundred cases of excavation work. The resultant rules were inconsistent and unreliable based on his findings. This paper proposed an improved decision tree for selecting retaining wall systems. The retaining wall systems were divided into three components (wall, lateral support, and optional grouting). A series of logistic regression analyses, analysis of variance (ANOVA), and chi-square tests were used to derive the variables and a decision tree for selecting retaining wall systems. The prediction accuracy rates for the retaining walls, lateral supports, and grouting were 82.6%, 80.4%, and 76.9%, respectively, higher than the prediction accuracy rate (58.7%) of the decision tree built by an automated machine learning algorithm.

Several computer based decision models are currently available, and the increased use of databases will allow investigation in this field. Yang (2002) developed a rule-based knowledge system (RBKS) to support knowledge acquisition. While knowledge acquisition is the main constraint in constructing a rule-based knowledge system (RBKS), rule induction (RI) is one of the fastest means of extracting rule-based knowledge from previous cases. Yang (2002) developed a model that integrates a RI approach, a RBKS, and a database management system to support the aforementioned automated knowledge action. A typical experience-oriented problem in construction domain, selecting a suitable retaining wall system in construction planning stage, was employed to demonstrate how to implement the model.

One year later, Yang (2003) developed a rule-based expert system for selection of both retaining wall types and groundwater control methods in deep excavations in Wuhan city. For this expert system, a new type of generation rule was developed in which one condition is able to be defined with a “third state” that not only contributes directly to reaching the conclusion in a rule, but also factors into calculating the reliability of the conclusion. The traditional backward chaining technique was improved to accommodate the change of a rule type and a fuzzy backward chaining method was established to increase reasoning flexibility. Using backward chaining as a fundamental element was found to be convenient to form a complicated reasoning network in the inference engine. Finally, two knowledge bases were built from more than 100 case histories and other resources, and the new expert system proved to be effective in case studies.

2.2.4.2 State Guidelines for retaining wall selection

Independently from the academic research, the Departments of Transportation of some States have attempted to provide a set of guidelines to perform this selection process by developing manuals. For example, Tennessee Department of Transportation issued its Transportation Earth Structures Manual which included a list of parameters that determine which wall of nine available types is the most adequate. The decision to select a particular retaining wall system for a specific project requires a determination of both technical feasibility and comparative economy (TDOT 2012). These factors were summarized as:

- Cut or fill earthwork situation
- Size of wall area
- Average wall height
- Foundation conditions
- Availability and cost of select backfill material
- Cost and availability of ROW
- Complicated horizontal and vertical alignment changes
- Need for temporary excavation support systems
- Maintenance of traffic during construction
- Aesthetics

None of the models previously described accounted for the economic implications of each type of wall as a differentiating parameter when selecting the most appropriate wall. This cannot only jeopardize the overall cost of the resulting wall but also put the entire decision model in question for practical applications.

2.2.4.3 Optimization and parametric design

There are several references available in scientific publication in regards to methods of optimization and parametric design of a particular type of walls. These models and methods focus on the improvement mechanisms but require that the wall type is predetermined. For example, the work developed by Yepes, Alcala and Perea (2002), focused on the economic optimization of reinforced concrete earth-retaining walls used in road construction by use of simulated annealing algorithm. The formulation of the problem included 20 design variables: four geometrical; four material types; and 12 variables for the reinforcement set-up. The study estimated the relative importance of factors such as the base friction coefficient, the wall-fill friction angle and the limitation of deflections. Finally, the paper presented a parametric study of commonly used walls from 4 to 10 m in height for different fills and bearing conditions returning total costs, pre-dimensioning parameters and rebar consumptions.

In the case of temporary retaining walls, the Metropolitan Expressway Public Cooperation in Japan bases the selection process in the flowchart shown below:

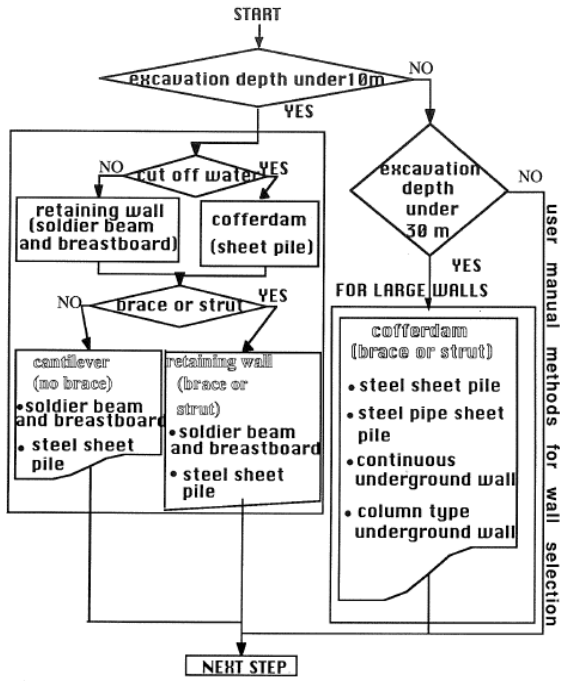


Figure 2-28 Temporary Wall selection process for Metropolitan Expressway Public Cooperation

Although developed for optimum cost design of cantilever cast in place walls, the approach adopted by Poubarba et al. (2012) will be used as a reference for the retaining wall selection model (RWSM) developed in this research. This Chaotic Imperialist Competitive Algorithm considers a system "where the imperialistic competition begins in which any empire (wall type) that is not able to succeed in this competition and cannot increase its power (or at least prevent losing its power) will be eliminated from the competition (selection process). It means that weak empires will lose their power and ultimately will collapse" (Poubarba, 2012). Each wall type will be "facing" all the "adversary" wall types, in such a manner that the last remaining type will be the most adequate among the competing ones (i.e. potential wall types).

2.2.5 Analysis of 4 known walls

In order to determine which parameters are instrumental for each type of wall, the literature research performed in section 2.2.1 and 2.2.2 is supplemented with an analysis of 4 known walls of a current heavy civil construction Project being constructed in the DFW area.

These four walls will also be used as a reference when the decision model is evaluated and validated. The identified input parameters will be used to check if the returned wall type matches the reality. Both matching and differing responses are evaluated to identify which factors affecting the model during the selection process led to each particular outputs.

2.2.5.1 Wall 1

Wall 1 consists on a cantilever wall constructed with reinforced concrete. This wall presents a variable height from 5 to15' with a stem thickness of 1' where the footing width is 11'. A keyway is added to the footing to increase the lateral resistance of the structure, by mobilizing the passive earth pressure of the foundation soil. The concrete type considered in the design is TxDOT Class C 3600 psi with a steel reinforcement of ASTM A615 Grade 60.

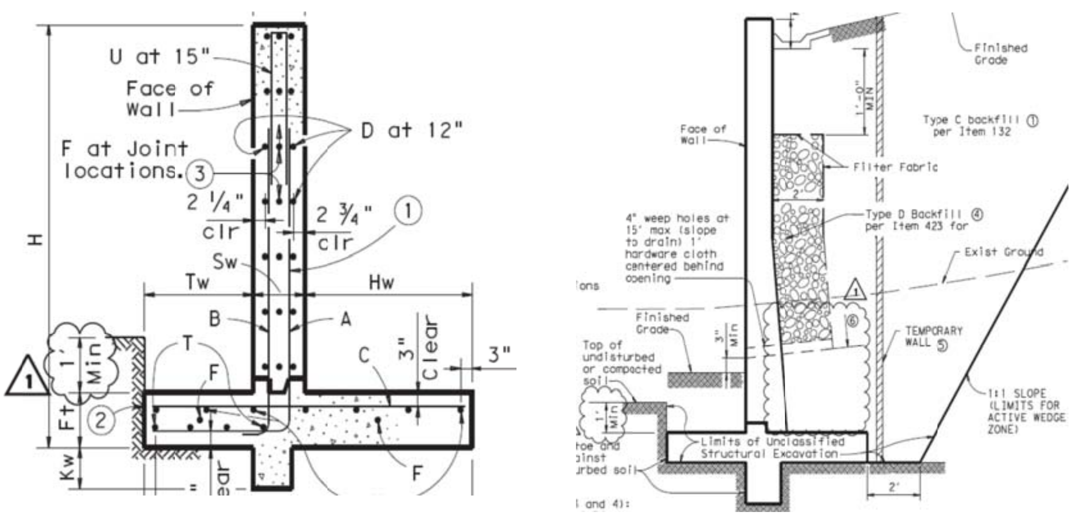


Figure 2-29 Typical sections and wall properties for Wall 1 (Personal archive 2012)

During the geotechnical exploration, deposits of human activities were encountered and due to the organic content, deleterious and anthropic materials, all this underlying soil was removed and replaced with engineering fill. Additionally, seams of stiff clay were required to be removed in the area of wall foundation. When stiff clays experience an increase in water content they swell and expand which can affect the stability of the wall (Jalla, 1999). This imported fill was placed in 8" compacted lifts at least to 98% of the reference Proctor (Tex-114-E), controlled by Nuclear Density Testing (Tex-115-E) over the exposed clayey subgrade. Once the subgrade was prepared, a proof roll confirmed the suitability of the prepared base.

Figure 2-30 (a) Cast in place wall placement and (b) subgrade preparation (archive 2013)

The retaining wall is founded in an over consolidated fat clay (CH) overlying poorly graded sand and gravel over the weathered clay shale formation. The settlement in this location after removal of the loose material was estimated in less than 1 inch, occurring most of the settlement in a period of 6 months.

No drainage conditions were identified in the areas under or behind the retaining wall to be constructed. Additionally, the wall is not located in the 100-yr flood zone identified in the hydrological studies of the Project.

The area were this wall was to be designed to be constructed presented traffic and space constraints and a 1:1 slope was defined to be executed for the temporary excavation. This wall was designed to provide earth retention for a future highway ramp to be constructed in the inside of it, allowing the restoration of the ROW to its original position after the backfilled was complete.

Based on the analysis performed once the construction was completed, the resulting unit cost for Wall 1 is shown below:

Table 2.7. Unit cost distribution for known Wall 1 (self-developed)

WALL 1 UNIT COST	
CONCEPT	**COST PER ft^2**
Equipment	$0.18
Materials	$9.47
Labor/Subcontractor	$47.07
	$**56.73**

The average production rate was identified as 750 sq ft /day based on an extended time period that spanned through 20 days of construction monitoring.

2.2.5.2 Wall 2

Wall 2 differs with Wall 1 in almost every parameter that can be considered prior to determine the most suitable type to design for a specific location. Wall 2 is defined to allow a direct connector from the surface to a lower highway level. This wall is a downward type planned to retain cuts that will support tan and gray limestone. Wall 2 consists in a combination of rock nails and fascia panels, connected with an in place concrete closure pour. The fascia panel cover responded to an aesthetic requirement more than to a pure stability need.

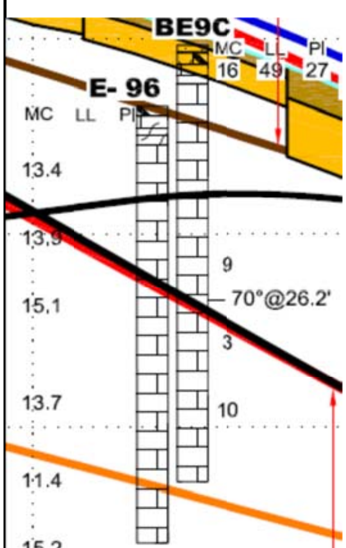
Wall 2 maximum height is 32 feet, where 85% of the exposed height fell in grey unweather limestone. At the point of maximum height, seven rows of nails, separated 4.5' were necessary to stabilize the rock mass against failure once the vertical cut was executed. The good quality of the rock identified in the majority of the wall face allowed the permanent rock nail to be designed and constructed in this area.

The unit weight, effective internal friction angle, and effective cohesion values were generated based on results of direct shear and triaxial shear test results on weathered tan limestone, and gray limestone.

Figure 2-31 Rock Nail drilling and drainage operations (personal archive 2013)

The pullout resistances of clay soils, weathered tan limestone and gray limestone were estimated based on unconfined compressive strengths of intact specimens of the aforementioned materials, coupled with results of recent pullout field tests.

Table 2.8. Recommended nominal factored presumptive pullout resistances or factored bond strengths for rock-nail wall design (Table 5 for LRFD design)

Material 	**Presumptive Nominal Factored LRFD Dry Case Bond Resistance**	**Presumptive Nominal Factored LRFD Wet Case Bond Resistance**
Class 1 Tan Limestone	1300 psf	1625 psf
Class 2 Tan Limestone and Gray Limestone	3750 psf	4690 psf

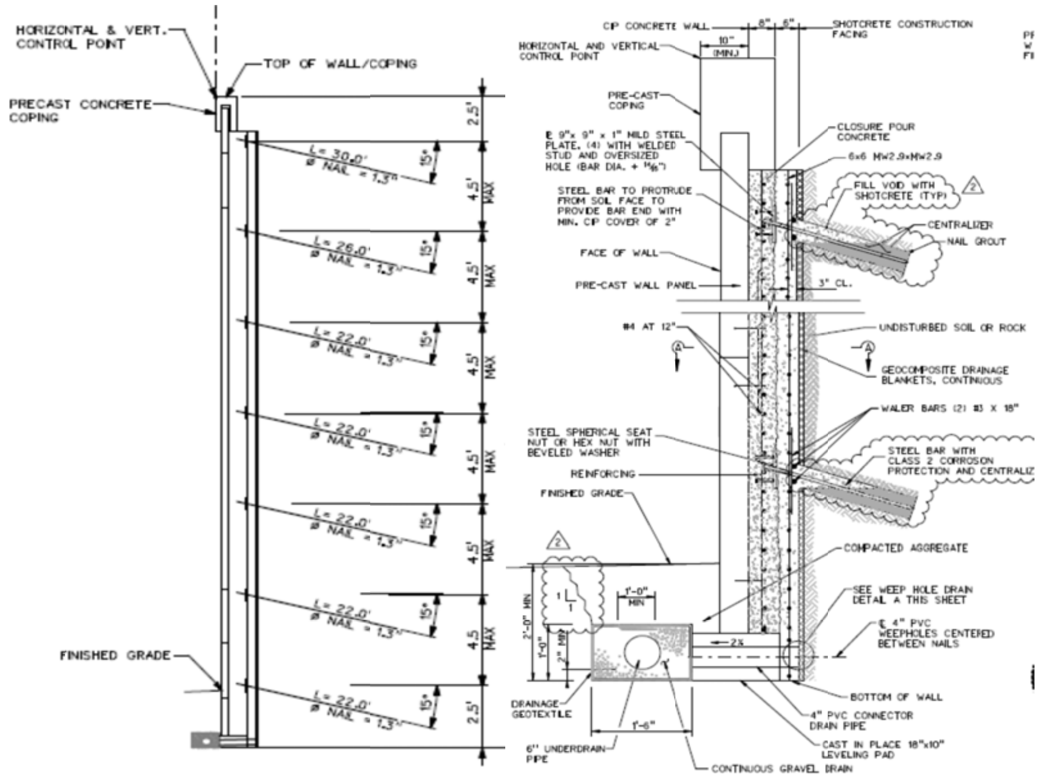


Figure 2-32 Typical sections and wall properties for Wall 2

Although Wall 2 was also located outside the 100-yr flood zones and the geotechnical report did not show groundwater, the drainage conditions of the existing soil face determined the need of specific considerations to be accounted for in both the design and construction. Geocomposite drainage panels or strips were used to provide drainage between nails. These strips were continuous from the top to the bottom of the wall and 36 inches wide. Splices had a minimum of 12 inches overlap to assure that water flow is not impeded.

The construction of a rock nail of this characteristics requires of an specialized subcontractor which not only has the equipment needed but also the knowledge to identify issues during construction that can affect the integrity of the wall being constructed. Wall behavior is highly impacted from the actual rock parameters and therefore, close monitoring and supervision is required. Additionally, an extensive campaign of, proof and performance testing as per FHWA0-IF-03-017, Geotechnical Circular No. 7 was followed to evaluate the actual nail behavior as well as the verification of the soil parameters by performing sacrificial tests performed in extra nails pulled to failure.

Specific considerations were required due to the permanent nature of this wall. The long term durability and stability of this type of wall is highly dependent in the degree of success achieved in the corrosion protection of the steel reinforcement. Rock nails were protected from corrosion by means of fusion bonded epoxy coating and grout protection for Class 2 protection in accordance with FHWA-IF-99-015, Geotechnical Engineering Circular No. 4.

Figure 2-33 Epoxy coated protection for soil/rock nail bars in Wall 2 (archive 2013)

Based on the analysis performed once the construction was completed, the resulting unit cost for Wall 2 is shown below:

Table 2.9. Unit cost distribution for known Wall 2 (self-developed)

WALL 2 UNIT COST	
CONCEPT	**COST PER SF**
Equipment	$14.50
Materials	$36.22
Labor/Subcontractor	$21.74
	$**72.46**

The average production rate was identified as 625 sq ft /day based on an extended time period that spanned through 25 days of construction monitoring.

2.2.5.3 Wall 3

Wall 3 was also a downward construction wall, but in this case located in an area of cohesive soils, with predominance of shaley clays and weathered shale. The soil profile consisted of clays transitioning into shaley clays overlying the Eagle Ford Shale. Both the clays and shaley clays encountered were identified to be very expansive. The Eagle Ford Shale was a soft dark gray to gray clay shale. The shale was highly expansive and contained soluble sulfates, being considered as highly corrosive.

Wall 3 is a drill shaft wall, executed by a sequence of drill shafts spaced between 5 and 6.5 feet, being all of them joined by a reinforced concrete capping beam. These shafts had diameters from 3-1/2' to 5' with a maximum length of 70'. The exposed height of this wall varied between 17 and 35 feet.

Figure 2-34 Wall 3 (a) shaft and (b) capping beam reinforcement (archive 2014)

This high percentage of exposed height determined the wall to behave as a cantilevered wall, therefore requiring some sections to be anchored by means of actively stressed tie backs. The shale weathers rapidly when exposed thus losing both durability and stability if left open for even short periods of time. This determined the need of a strictly monitored effort between the earthwork and tie back subcontractors in order to minimize the exposure of the sensitive shale layers once exposed.

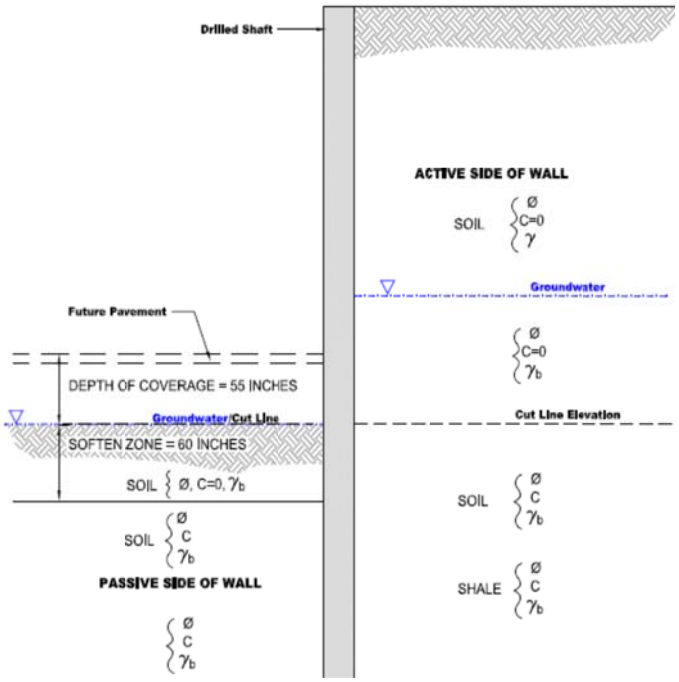


Figure 2-35 Wall 3 geotechnical configuration for calculations (archive 2013)

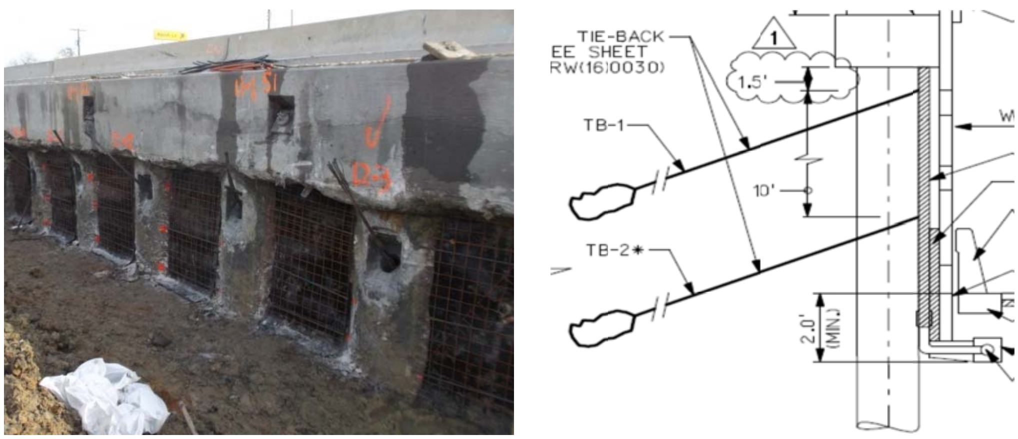


Figure 2-36 (a) Wall 3 drill shafts with tie backs and (b) typical section (personal archive 2014)

As in the case of Wall 2, a tied back drill shaft wall of this characteristics requires of an specialized subcontractor which not only has the equipment needed but also the knowledge to identify those issues during construction that can affect the integrity of the wall being constructed. Both the shafts and tie backs behavior is highly impacted from the actual soil encountered, therefore needing a monitoring system in place during construction.

Additionally, an extensive campaign of, proof and performance testing as per FHWA0-IF-03-017, Geotechnical Circular No. 7 was followed to evaluate the actual tie back behavior as well as the verification of the soil parameters by sacrificial tests performed in extra anchors pulled to failure.

The cables were stressed using hydraulic jacks previously calibrated to obtain the relationship between the pressure in the jack gauge and the force exerted in the tie back. The values of the elongations on the tie backs were recorded and compared with the expected values in order to evaluate the actual performance of the soil-grout bonding and the real resistance of the tie back wall to resist the acting loads.

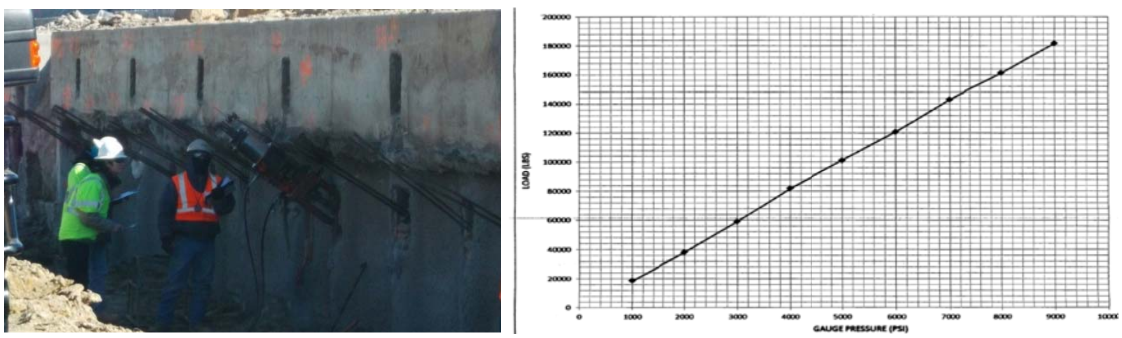


Figure 2-37 (a) Wall 3 anchor testing and (b) load-pressure curve (archive 2014)

As previously described, the shaley materials encountered were highly corrosive and with a significant sulfate content. As defined by the FHWA Geotechnical Circular 4, minimum Class I protection required with multiple barrier layers with at least two levels of protection being pre-grouted poly corrugated tube in both the bond and free-stressing length, centralizers and protective end cap over nut and washer and filled with corrosion inhibiting compound. Additionally, heat shrink sleeves at connections were used for increased protection.

In addition to the type of soil to be contained with the retaining wall, one of the most important factors in Wall 3 was the lack of lateral space available for the construction. This Wall contained a critical high capacity highway, being therefore necessary to execute a wall with zero reduction of the road traffic and no affection to existing infrastructure. Considering the lack of space, clayey soil, continuous support and downward construction, tied back drill shaft wall appeared to be the only viable option.

Based on the analysis performed once the construction was completed, the resulting unit cost for Wall 3 is shown below:

Table 2.10. Unit cost distribution for known Wall 3 (self-developed)

WALL 3 UNIT COST	
CONCEPT	**COST PER SF**
Equipment	38.06$
Materials	68.51$
Labor/Subcontractor	45.68$
	152.25$

The average production rate was identified as 450 sq ft /day based on an extended time period that spanned through 30 days of construction monitoring.

2.2.5.4 Wall 4

The last of the walls analyzed, Wall 4, is a Mechanically Reinforced Earth wall (MSE) consisting in a combination of precast concrete panels and backfill that is constructed with artificial reinforcing. In this particular case, the reinforcement consisted in strips of galvanized steel with lengths between 8 and 16 feet. The maximum wall height was 12 feet.

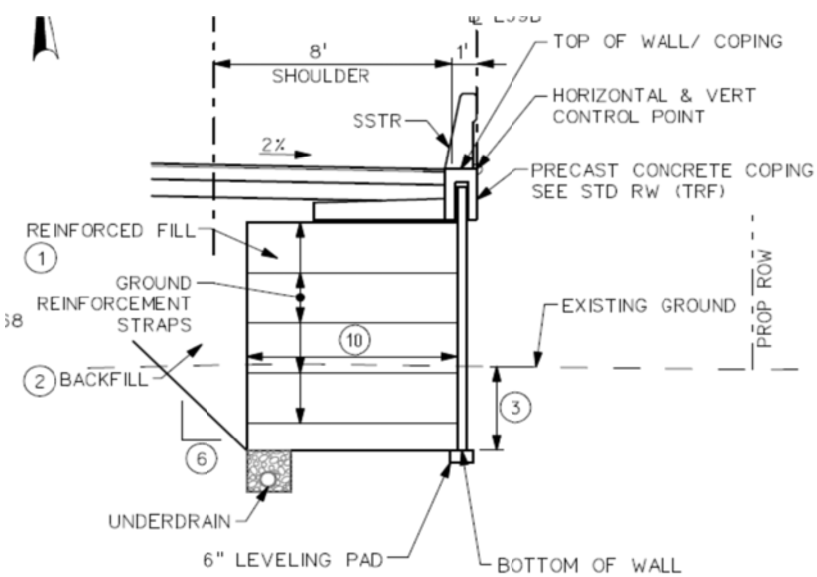


Figure 2-38 Wall 4 MSE Wall Typical section (personal archive 2012)

The wall foundation consisted in both previous embankment fills and existing high plasticity clays (fat clays). These materials were deemed to provide sufficient bearing capacity but required some preparatory work by ripping, conditioning and compaction.

Figures 2.38. Backfilling operation in Wall 4. (a) strip placement over executed lift and (b) loader places backfill over strips to avoid strip damages. (personal pictures archive 2013)

An additional requirement for this wall was the location inside the 100-yr flooded zone due to a close creek. Specific drainage measures were specified in the design consisting in filter fabrics, bituminous paints, waterproof joints and underdrain. These measures were constructed to ensure that no material is washed from the runoff events and that no undesired water pressure will build up in the retained backfill. Not all the height was subject to the potential flooding and therefore TxDOT Item 423, Type B above inundated wall section and Type D below the 100-year flood elevations were defined with a filter fabric to separate the two different fill types.

No specific space constraint was identified in the proposed location for Wall 4, therefore, the temporary slope excavated did not constitute a design constraint. Additionally, it was required to build the wall in a short period of time which determined the adequacy of this type over a cast in place concrete retaining wall. If the wall would have been located outside the flooded zone, the defined type would likely still be an MSE without the Type B backfill and drainage measures. Based on the analysis performed once the construction was completed, the resulting unit cost for Wall 4 is shown in Table 2.11:

Table 2.11. Unit cost distribution for known Wall 4 (self-developed)

WALL 4 UNIT COST	
CONCEPT	**COST PER SF**
Equipment	$4.49
Materials	$28.80
Labor/Subcontractor	$19.18
	$52.47

The average production rate was identified as 1150 sq ft/day based on an extended time period that spanned through 8 days of construction monitoring.

2.2.6 Conclusions and findings of literature research and background review

Most of the selection models being developed to date have been applied to a wide range of decisions and fields. By introducing different parameters into the computer algorithms, the systems can return the optimum solution for the desired reasoning logic. These models, such as the ones proposed by Choi (2010), Yang (2003), Yau (2002) or Lee (1989) require of extensive knowledge information being input in the systems as well as a proficient programming capabilities in the engineer making the decision. The research performed reveals that no software has implemented these models into a user-friendly tool that can be easily used for the engineers in need of determining the most suitable wall for their particular project.

Although not definitive, the fact that no private company has entertained the process to make these tools in software available to the market, casts doubt over their ability to properly select the most appropriate wall based on a certain input. It is almost certain that if commercially profitable, any software company would have already implemented them for profit purposes.

The methods of optimization such as the one presented by Yepes et al (2002) do not present a usable tool for the purpose of wall selection as they focus on the optimization of a particular structure once the type has been predetermined. This focus on the structural and constructability implications of different parameters but do not allow the consideration of different type of wall.

As demonstrated by the work developed by Yang (2004), experience-oriented problems represent a suitable alternative where solutions are obtained by previous experience solution and subject experts input. Due to the difficulties to use these systems by programming algorithms, the development of a simpler model that is based on the same principles that an Expert System (ES) results of particular interest. Previous known experience result of critical importance as the selection process undertaken for them resulted in a successful wall type output and expert subjects already deemed the solution acceptable (Hess and Adams, 1995).

Based on the analysis of the 4 known retaining walls, some considerations have been identified as triggering factors that determine the most appropriate type of wall to construct in a certain location. A summary of the main parameters of the walls analyzed is included below:

Table 2.12. Summary of Constraints and features for the Walls analyzed

	Type of Soil	**Max Height**	**Space Available (Yes/No)**	**Continuous Support (Yes/No)**	**Flooding Area (Yes/No)**	**Need Specialized Subs**	**Include Proprietary Systems**	**Wall Type**
Wall #1	*Clay with anthropic*	*15*	*Yes*	*No*	*No*	*No*	*No*	*CIP*
Wall #2	*Tan/Grey Limestone*	*32*	*No*	*Yes*	*No*	*Yes*	*No*	*Rock Nail*
Wall #3	*Clay and Shale*	*35*	*No*	*Yes*	*No*	*Yes*	*Yes*	*Drill Shafts (+Tie backs)*
Wall #4	*Clay and previous fill*	*12*	*Yes*	*No*	*Yes*	*No*	*Yes*	*MSE*

Table 2.13. Summary of Unit Costs and Production rates for known Walls (*fascia, 48.50 w/o)

	Type of Soil	**Max Height**	**Unit Cost ($/sf)**	**Production rate (sf/day)**	**Wall Type**
Wall #1	*Clay with anthropic materials*	*15*	*56.72*	*750*	*CIP*
Wall #2	*Tan and Grey Limestone*	*32*	*72.46**	*625*	*Rock Nail*
Wall #3	*Clay and Shale*	*35*	*152.25*	*450*	*Drill Shafts (+Tie backs)*
Wall #4	*Clay and previous embankment*	*12*	*52.47*	*1150*	*MSE*

The data shown in Table 2.13 evidences the aforementioned considerations in regards to how differing parameters other than just the geometry and type of soil influence the most suitable type of wall for a particular location.

None of the different methods identified during the extensive literature research includes four of the most important considerations such as direction of construction, height limitation of each type, unit cost per unit of area of wall and nominal production rate. Disregarding these parameters severely handicaps the ability of these models to accurately select the most appropriate wall (Adams et al., 1993).

Based on the results of the literature research, it has been deemed essential to perform field observations, surveys and interviews to collect and gather the required data to build the selection model and comprehensive database. Currently, no single document or publication gathers enough information that allows the engineer in need to determine the most adequate wall for a certain location. Only through a careful balance between calculations, experience and several literature sources, the decision can be taken. The knowledge associated with the educated decision of which wall type results optimum for a certain location is wide in nature, multidisciplinary and affected by several aspects. Only by observing actual field operations, interviewing design and construction experts and performing surveys will the necessary data be obtained (Chong, 2005).

The literature research performed supports the need for a simple model that accounts for production rates and costs during the decision process. Additionally, due to the absence of previous experiences that separate upward and downward construction, this will be one of the basis for the selection model developed in this research. Also, the absence of published rates and costs for wall construction determines the need to perform a specific analysis via interviews, surveys and observations to develop actual unit costs and rates to serve as the starting point for future needs.

Although limited, different sources of unit costs and production rates have been obtained such as TxDOT (2007), TDOT(2012), the known walls included in Section 2.2.5, author's experiences or Chong (2005). After the analysis of all these different parameters for the walls being considered, it results obvious that a project specific analysis is critical for detailed studies. As shown in table below, different sources present greatly different values for the unit costs. The references for production rates publicly published are almost non-existent (Mubarak, 2010 and Pratt, 2012). Using a certain parameter under a set of constraints that does not adapt to the actual ones, can lead to adverse consequences in terms of budget and schedule.

Table 2.14. Comparison between Unit Costs obtained from different sources

UNIT COST OF DIFFERENT TYPES OF RETAINING WALL ($/sf face of wall)					
	Wall Type	**TDOT (2012)**	**TxDOT (2007)**	**SPANISH HIGH SPEED TRAIN (2007-2009)**	**KNOWN WALLS (Section 2.5) (2013-2014)**
UPWARD CONSTRUCTION (FILL)	*Concrete Gravity Wall*	25-35	85	72	N/A
	Concrete Cantilever	25-60	85	75	57
	CIP Counterforted	25-60	85	N/A	N/A
	Concrete Crib	25-35	26	N/A	N/A
	Gabion	25-50	26	65	N/A
	MSE (precast facing)	22-35	35	58	52.5
DOWNWARD CONSTRUCTION (CUT)	*Sheet Pile Wall*	15-40	N/A	N/A	N/A
	Slurry (Diaphragm)	60-86	N/A	115	N/A
	Tangent pile wall (drill shaft wall)	40-75	N/A	108	N/A
	Secant Pile Wall	40-75	70	121	N/A
	Anchored Wall	15-75	95	135	152
	Soil Nailed Wall	15-56	65	95	72.5
	Micropile Wall	75-125	N/A	185	N/A

Due to the high variability of unit costs and rates presented in the consulted literature references, for the present Thesis, it is deemed necessary to develop more accurate rates and unit costs based on field observations, analysis of project-specific constraints, surveys and interviews to expert subjects.

All the data collected will be gathered, compared and analyzed in order to develop a retaining wall database that can serve as a starting point for future reference during preliminary or feasibility studies.

Chapter 3

Methodology

Several methods and sources have been utilized to both obtain the required information as well as to develop and forecast the required parameters for each type of retaining wall. As determined in Chapter 2, the sources available for the selection of the optimal retaining wall type as well as to identify the unit costs and production rates are very limited. Thus, in order to have accurate and useful parameters as input for our selection model, it is necessary to supplement this background information with actual collected data. Additionally, a database will be developed in the present research and therefore the information collected will be compiled, compared and analyzed.

The methodology followed during the research performed for this Thesis is summarized in the next Sections.

3.1 Definition of the research and phases of data collection

The method used during this research responded to the needs identified during the initial conception and literature review phases. In order to determine the data required to be used as input for our decision model, the design process followed for 4 known walls was analyzed jointly with the Engineers responsible for them. This helped to further define which parameters were required to be collected in order to properly develop our selection guidelines. The results of this analysis and the main parameters that determined the type selected for each case are included under Section 2.2.5 and summarized in Tables labeled 2.12 and 2.13.

Literature review was also identified as a critical stage for the research. Neglecting these previous steps from previous professionals would not only be a researching negligence but also a severe handicap for the potential developments to be achieved in this Thesis. The findings of this literature review critically influenced the subsequent stages of research data collection, the database and the wall selection model development.

The identified lack of published comprehensive guidelines for retaining wall selection determined the need of performing a series of surveys, interviews and field observations of retaining wall construction.

This data was then organized, summarized and analyzed in order to identify those critical drivers for each type of retaining wall that determine the adequacy or non-adequacy for a certain set of constraints (direction of construction, soil type, height, cost, schedule, etc.).

In general terms, the research performed consisted in six main phases listed below:

- Perform a research of the existing literature regarding retaining wall construction with emphasis on those parameters that determine the optimum type for the different constraining parameter.
- Analyze the currently available retaining wall types in heavy civil construction, identifying their applicability, advantages and disadvantages.
- Study and analyze a selection of personally known heavy civil projects to identify the most used wall types and configurations.
- Perform surveys and interviews to expert personnel involved in the different phases of the retaining wall definition and implementation. This will include design, bidding, construction and maintenance.
- Observe and monitor the construction processes followed for the selected types of walls with the purpose of obtaining unit costs and production rates for each of them as well as critical parameters to be considered during the selection model development.
- Summarize and analyze all data collected so it allows the development of a sequential decision model that will serve as a selection guideline that returns the optimum wall type with project constraints as input but also serve as a database for future reference.

The methodology followed during this research is summarized in the next page, including the interrelations between the different phases. It is re-emphasized that the results of each phase were used as input for the subsequent steps of the research.

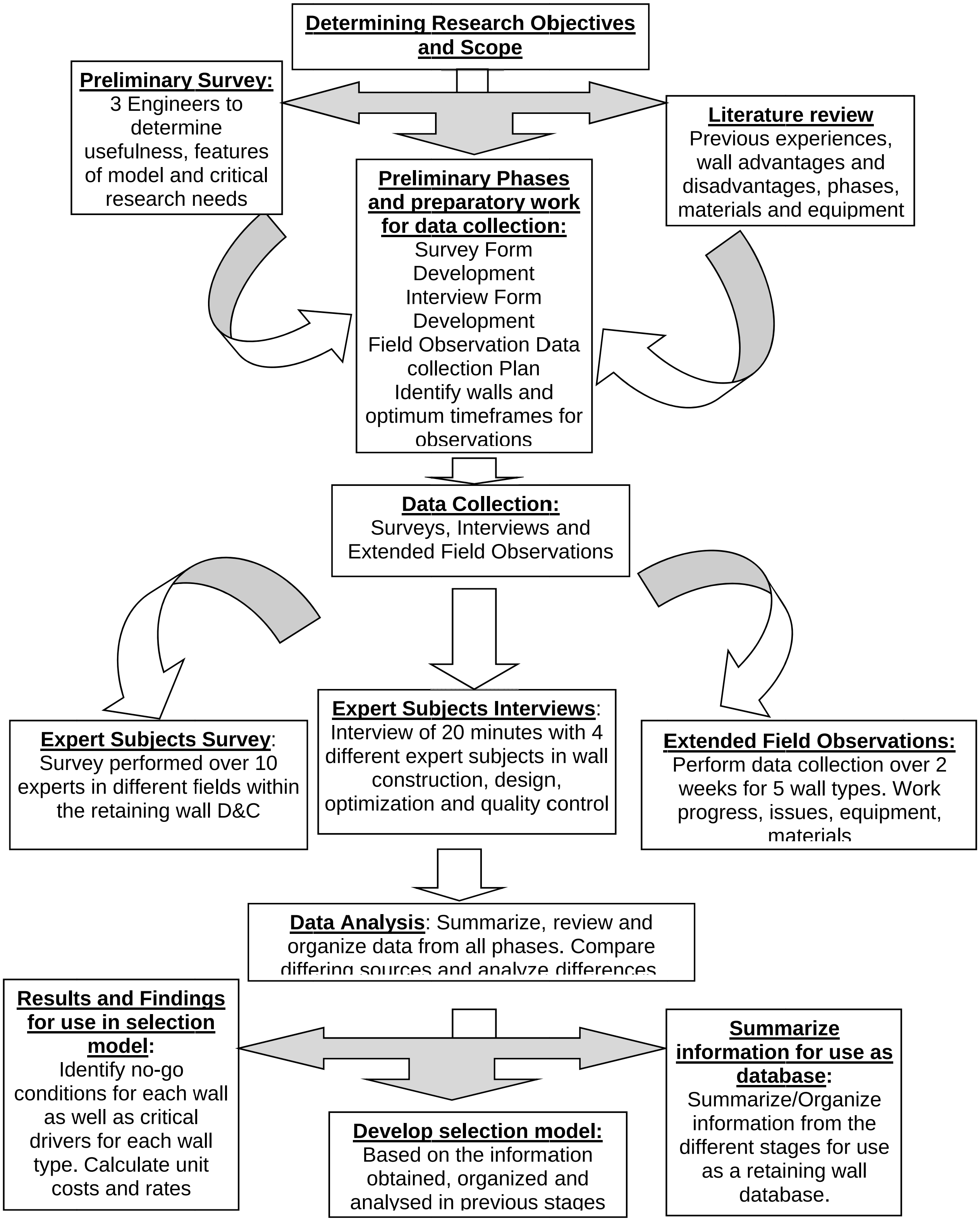


Figure 3-1 Research Methodology Process

3.2 Background and literature review

It is essential for any research to locate, analyze and use the previous references as a base for the future work as well as to support the need for the topic being under consideration. Not only the previous work can be used as the starting point but also can serve to identify those areas in need of additional research, study and developments.

Previous experiences on the academic and professional field were analyzed as well as those previous models developed for selecting the optimum retaining wall type for a certain location or need. These models were complicated in nature and computational in form, therefore requiring an extensive knowledge in programming in order to use them in a real-world application. This determined the need of developing a simpler model that can be quickly used by engineers in need during preliminary or feasibility phases.

During the definition of the construction phases, materials and equipment involved during the construction of the retaining walls, specific technical references from journals, articles, records and books were consulted. Additional input was obtained from the expert personnel interviewed as well as the field observations detailed in Section 2.2.2.

All construction research is highly dependent on previous experiences as well as an accurate record keeping process. The privileged position that the author finds himself allowed an extensive analysis of data from previous projects as well as data collection from on-going wall construction in the DFW area. The data collected included unit costs, production rates, construction issues and decisions taken for existing walls by design engineers.

3.3 Surveys and Interviews to expert subjects

The literature research evidenced a lack of published data in regards to expert decision models for retaining wall construction as well as unit costs and production rates. Additionally, the models available in the literature neglected critical data such as direction of construction, cost or schedule. Thus, it was determined that the expertise from experienced engineers was required in regards to preliminary design, wall advantages and disadvantages, unit costs, production rates, constructability issues and wall selection processes.

As identified by Baker and Edwards (2007), it is highly difficult to identify at the initial steps of the research which questions and individuals are the most adequate to interview and survey. This was resolved by a sequential approach in three different phases:

1. Preliminary survey
2. Detailed interviews
3. Supplementary surveys

Initially, a preliminary survey was performed in order to evaluate the potential usefulness of the model to be developed and its required features in order to be a working tool for professional engineers. Five simple questions were submitted to 3 engineers in different positions within a multinational company. The questions and responses are summarized below:

Table 3.1. Summary of Preliminary Survey performed on 11/15/2013

QUESTION	**Project Manager**	**Structural Design Manager**	**Geotechnical Design Manager**
Which 4 parameters do you consider critical when determining the optimum type of wall?	Cost, schedule, constructability, difficulty for procurement and safety risks.	Soil type, materials required, availability of specialized subcontractors and allowable wall movement	Groundwater, soil type, availability of selected backfill, soil corrosion and allowable settlement.
Would you use a model that require programming?	No	No	No
Do you apply rules when determining the optimum wall for a certain location? (i.e. MSE>30´, CIP<30´)	Yes, to identify potential cost saving options	No, start point in Geotechnical Report with the walls proposed.	Yes
How would you describe in a few words the system you use to determine the most suitable wall for a particular location	Weighted analysis between, cost, schedule, safety, procurement and quality	Pre-dimension all types suggested in Geotechnical Report and compare	Cascade system where non-suitable models are discarded.
Which 3 factors can justify a change of retaining wall type once determined a certain type?	Cost optimization, schedule acceleration need, material/labor/equipment issues	Construction mistake, Optimization, constructability issues	Differing subsurface or surface conditions, lack of backfill, absence of specialized contractors

The results of this simple and quick survey were instrumental in order to not only identify the need for a decision model simpler than the ones developed to date but also to determine that additional data was needed as input for the selection process to supplement geometrical and geotechnical constraints.

The consulted engineers concluded that the proposed model should not include any platform that required language programming from them. Additionally, the responses from these expert colleagues resulted in a series of critical factors to account for when determining the optimal wall type:

Table 3.2. Driving factors identified by the three consulted experts

CONSTRUCTION RELATED	GEOTECHNICALLY RELATED	STRUCTURALLY RELATED	OTHERS
Cost Optimization	Allowable Settlement	Allowable Settlement	Safety risk reduction
Schedule compression	Soil Type	Constructability issues	Environmental Compliance
Procurement issues (material, equipment)	Groundwater	Designer expertise for specialized wall types	Quality of product
Availability of selected backfill	Soil corrosion		
Lack of specialized subcontractors for certain walls	Availability of selected backfill		

The consulted geotechnical engineer suggested a “cascade model” that resembled in its concept to the Chaotic Imperialistic Algorithm developed by Poubarba et al. (2012) where only the “victorious empire” (i.e. wall type) remains after being face with all the “opponents” (i.e. the other potential types). The fusion of these two concepts as well as the introduction of production cost and rates resulted in the baseline for the selection model developed in this research as detailed in Section 4.2 and Appendix D.

In order to collect accurate data that could be compared and processed for use in the model, predetermined survey and interview forms were developed. This forms facilitated the interview and survey processes, not only reducing the time required to complete them but also drives the responses to those parameters most needed for the decision model. Only by analysis of comparable data it is possible to identify driving factors as well as trends, disagreements and/or concurrences among the different professionals.

Interviews and surveys can be satisfactorily combined for research needs (Driscoll, 2011). Interviews are a more comprehensive tool that not only incorporate the subject's responses but also subjective expert considerations and experience examples of great importance. It was determined after the interview process that due to the design related background of the interviewed experts, cost and production information was still in need. This determined the selection of the recipients of the survey. These experts were mainly managers, construction related personnel and geotechnical subcontractors.

3.3.1 Survey to Eight Expert professionals.

As described in the previous section 3.3, once the interviews were completed, a lack of cost and production data was identified. These parameters are mainly numerical and did not require an great level of detail other than the constraints that affects them. Therefore, the most suitable tool to collect them was determined to be a series of surveys (Kelley et al. 2003).

Eight retaining wall construction and management experts were selected to participate in the survey. Two of the initially selected individuals declined to participate and were replaced with two geotechnical engineers from an specialized company.

The recipients of this survey chose to remain unidentified due to the commercial implications of production rates and unit costs. These values were provided as typical, and would not be applicable to every case in general. Only by a detailed analysis where all site specific constraints are analyzed can return accurate cost/production rates (Mubarak, 2010).

The given values do not necessarily belong to the known walls presented on Section 2.2.5 or the field observed ones. An effort to preserve the proprietary nature of the information provided by the participants in the survey was undertaken during the entire research.

A predetermined survey form was developed and provided to all the participants, requesting them to be returned within a week. All participants completed it before the allowed timeframe. The survey form distributed is included in Table 3.3.

Table 3.3. Sample Retaining Wall Selection Survey Form

Name:	Years of experience:
Position:	Date:
Area of expertise:	Country where most experience:
Please list the 3 main factors you consider when developing unit costs for retaining walls in general terms:	
Please list the 3 main factors you consider when developing production rates for retaining walls in general terms:	
Please list the 3 main factors to consider when developing unit costs and production rates for retaining walls for the following types:	
o Cast in place =	o Sheet pile wall =
o Drill Shaft wall (w/o tie backs) =	o Diaphragm wall =
o Drill Shaft wall (w tie backs) =	o Wire mesh wall =
o Tie Back wall =	o MSE Wall =
o Nailed wall =	o Gabion wall =
What wall height would be the limit of economically feasible construction for these walls in your opinion?	
o Cast in place =	o Sheet pile wall =
o Drill Shaft wall (w/o tie backs) =	o Gravity Wall =
o Drill Shaft wall (w tie backs) =	o Wire mesh wall =
o Tie Back wall =	o MSE Wall =
o Nailed wall =	o Gabion wall =
Which typical unit cost do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place =	o Sheet pile wall =
o Drill Shaft wall (w/o tie backs) =	o Gravity Wall =
o Drill Shaft wall (w tie backs) =	o Wire mesh wall =
o Tie Back wall =	o MSE Wall =
o Nailed wall =	o Gabion wall =
Which typical production rates do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place =	o Sheet pile wall =
o Drill Shaft wall (w/o tie backs) =	o Gravity Wall =
o Drill Shaft wall (w tie backs) =	o Wire mesh wall =
o Tie Back wall =	o MSE Wall =
o Nailed wall =	o Gabion wall =
Which 3 wall types would you recommend for remote areas with limited specialized workforce?	
YOUR PARTICIPATION AND RESPONSES ARE GREATLY APPRECIATED	

The different factors considered by the experts were considered as input for the Field Observation campaign performed and described in Section 3.4. The data collected from these field observations was used in combination with the literature references and survey results to determine “typical” unit costs and production rates for the different wall types.

The completed survey forms for the eight experts that participated in them are included in Appendix B. The results of these data collection surveys were summarized in comparison charts in order to identify these parameters to be used as input in the decision model and also as a database for engineers in need of determining a wall type for a future locations and projects. The summary charts, as well as the result of the comprehensive analysis performed from the surveys are included in Section 3.5.

3.3.2 Interview to Five Expert Engineers.

As identified and discussed in Section 3.3, the literature and published information regarding a comprehensive database for wall selection is scarce. Five interviews were designed to be performed to expert engineers with more than 10 years of design and construction in heavy civil projects in several different countries such as Spain, Canada, Chile, Portugal, UK, Ireland and United States.

The selection of those expert individuals to participate in the interview processes was carefully analyzed based on the needs identified from the literature review as well as their background in regards to the most relevant types of walls. The lack of data affects greatly to some walls than others, for example to tie backs, drill shaft or nailed walls.

The different engineers interviewed are included below, Engineers participating in the interviews chose to remain undisclosed for the purpose of this Thesis but authorized the use of the interview results.

Table 3.4. List of Interviewed Experts

Interview #	Position	Experience in wall design and/or construction
1	Construction Design Manager	29 years
2	Geotechnical Design Manager	13 years
3	Technical Office Manager	11 years
4	Geotechnical Specialty Company Area Manager	17 years
5	Geotechnical Design Firm Principal	21 years

The questions and interviewed personnel were carefully tailored for the specific needs identified once the literature review and analysis of previous models were completed. A sample interview form is included in the following Table 3.5.

Table 3.5. Sample Retaining Wall Selection Interview Form

Name:	Years of experience:
Position:	Date:
Area of expertise:	Location:
What are the main 5 factors do you consider when determining the most appropriate types of walls for a certain location?	
Which are the areas where information is lacking to perform an appropriate design?	
Where would you set the bar for the height of the following upward type walls?	
o MSE =	o Gabion wall =
o CIP =	o Wire mesh wall =
o Gravity wall =	
Where would you set the bar for the height of the following downward type walls?	
o Nailed wall =	o Drill Shaft wall (w/ anchors) =
o Tie Back wall =	o Sheet pile wall =
o Drill Shaft wall (w/o anchors) =	o Diaphragm wall =
Which wall requires a higher supervision and designer expertise in your opinion?	
For which types of walls is the groundwater a critical factor that makes them less appropriate?	
What would be the three most common issues regarding the construction of the following wall types?	
o Cast in place =	o Sheet pile wall =
o Drill Shaft wall =	o Diaphragm wall =
o MSE Wall =	o Wire mesh wall =
o Tie Back wall =	o Gravity wall =
o Nailed wall =	o Gabion wall =
Could you please rank the following walls in order of construction difficulty?	
o Cast in place =	o Sheet pile wall =
o Drill Shaft wall =	o Diaphragm wall =
o MSE Wall =	o Wire mesh wall =
o Tie Back wall =	o Gravity wall =
o Nailed wall =	o Gabion wall =

Table 3.5 Continuation

Which wall type do you believe to be more appropriate for fast-track needs for upward and downward construction?	
Which wall types do you believe to be result in increased maintenance needs?	
What would you consider a "no-go" condition for the following types of walls (i.e. those factors that automatically discard the wall type as non-adequate for them)?	
o Cast in place =	o Sheet pile wall =
o Drill Shaft wall =	o Diaphragm wall =
o MSE Wall =	o Wire mesh wall =
o Tie Back wall =	o Gravity wall =
o Nailed wall =	o Gabion wall =
Which of the previously discussed wall types have, in your experience, been discarded or re-designed due to the lack of specialized equipment and/or materials?	
Would you please rank the following upward type walls in terms of unit cost of construction?	
o MSE =	o Gabion wall =
o CIP =	o Wire mesh wall =
o Gravity wall =	
Would you please rank the following downward type walls in terms of unit cost of construction?	
o Nailed wall =	o Drill Shaft wall (w/ anchors) =
o Tie Back wall =	o Sheet pile wall =
o Drill Shaft wall (w/o anchors) =	o Diaphragm wall =
Would you please rank the following upward type walls in terms of duration of construction?	
o MSE =	o Gabion wall =
o CIP =	o Wire mesh wall =
o Gravity wall =	
Would you please rank the following downward type walls in terms of duration of construction?	
o Nailed wall =	o Drill Shaft wall (w/ anchors) =
o Tie Back wall =	o Sheet pile wall =
o Drill Shaft wall (w/o anchors) =	o Diaphragm wall =
What would be a standard design life for the following wall types?	
o Cast in place =	o Sheet pile wall =
o Drill Shaft wall =	o Diaphragm wall =
o MSE Wall =	o Wire mesh wall =
o Tie Back wall =	o Gravity wall =
o Nailed wall =	o Gabion wall =
Is there any additional point that you believe needed to be included in this analysis?	
YOUR PARTICIPATION AND RESPONSES ARE GREATLY APPRECIATED	

This interview form was provided a week in advance of the established interview date in order to allow the experts to prepare the responses and to obtain a more accurate representation of the goals and needs set. During the interview, the form included in Table 3.5 was followed in all of them, keeping the responses restricted to the different items and requesting additional information at the end of the interview. This fixed process was intended to yield comparable results.

The completed interview forms for the five experts that participated in them are included in Appendix C. The results of these interviews were summarized in comparison charts in order to identify these parameters to be used as input in the decision model and also as a database for engineers in need of determining a wall type for a future locations and projects. The summary charts, as well as the result of the comprehensive analysis performed from the interviews are included in Section 3.5.2.

3.4 Field Observations

Retaining wall construction operations are complicated tasks that involve several phases where different equipment and personnel interact repeatedly. Therefore, a thorough analysis is required to proper design the field observation campaign performed. Both the literature review and the information from surveys and interviews were used to identify those critical factors that needed to constitute the core of these observations.

The variability and potential for change of unit costs and production rates is acknowledged. However, due to the lack of literature or published information, direct observation is deemed as the most appropriate approach to determine these values for use in the selection model (Mubarak, 2010; Murawski, 2001).

Not all retaining wall types entrain the same degree of complexity. Therefore, a preliminary selection was performed in order to determine the five most appropriate to constitute the field observations. The availability of costs and production data was also considered when selecting these five wall types, focusing in those where the interviews and literature review showed an increased lack of available data. These field observations allowed the development of real unit costs and production rates for use in the selection model and wall database.

Table 3.6. Retaining Wall Types selected for the field observations

OBSERVATION #	WALL TYPE	OBSERVATION PERIOD (One crew)
1	Cast in place Cantilever	7 working days
2	MSE Wall (metallic straps)	5 working days
3	Drill shaft Wall	20 working days
4	Rock Nail Wall	5+7 working days
5	Tie Back Wall	7+7 working days

The field observations were designed accounting for the specific characteristics of each type of wall. For example, drill shaft walls cannot be analyzed in a short time span as the drilling operations extend over a long period while the excavation later performed is executed rapidly. Only the comprehensive analysis over the entire construction duration can result in reliable production rates (Mubarak, 2010). On the other hand, wall types such as MSE walls or cast in place cantilever are executed as repetitive cycles where an observation period of five working days can be assumed to provide sufficient information to develop production unit rates.

Also, for tie back walls, it is required to complete the stressing and testing before excavating downwards for execution of the next rows, therefore, the period of observations needs to be increased for this type of wall as well.

The costs incurred during the different periods of time are analyzed as well as the square footage/wall volume constructed. This allow the development of unit rates for each type of wall observed. An extensive research and interview process was performed along with the observations. By interviewing the personnel and researching the documentation associated with the construction, the unit costs and the details associated with the construction of the different walls were obtained. Due to proprietary nature of the information and the requirements for disclosing this type of information, details of the companies involved will be reserved and the unit costs will be slightly adjusted by rounding.

It is relevant to mention the importance of the specific project factors for each wall and its influence for the unit costs and production rates. Each constraint has an influence on actual costs and durations. Therefore, an effort was made to select walls in absence of those factors such as great heights, reduce work space or limited work shifts. This would allow the development of standard rates that could be adjusted to more stringent project constraints.

Additionally, the wall height can result in differing unit rates and costs. A more detailed analysis would yield results that can be applicable for a certain range. For example, based on the records from previous construction project where the author had access to, an MSE wall of height from 20 to 30 feet resulted in costs a 20% lower than one between 10 and 20 feet. This occurs due to the lower impact of the costs of coping, leveling pad, subgrade preparation, or auxiliary equipment. However, if height exceeded 30 feet, the unit cost increased due to the higher consumption of backfill and strap length as well as increased requirements in subgrade preparation and backfill quality.

For the purpose of this thesis, nominal unit rates are calculated and the constraints of the walls used for it are detailed. This would allow using this factors as a starting point that should be adjusted to project specific factors to yield reliable results.

Determining the cost of certain operations and/or materials is a highly complicated task that involves observation periods that span over several different project and that needs to account for a variety of factors such as operator experience, market conditions, financial health of purchaser, type of soil, etc. Therefore, obtaining the unit costs for items such as the drilling would constitute a major challenge in itself. For those unit costs that involve machinery ownership, depreciation and idle times have a critical influence in the calculated unit costs. Benefiting from the privileged position that the author finds himself, real unit costs of two projects been constructed in the DFW area are used for the purpose of calculating typical unit costs for the five wall types been analyzed. These costs have been slightly adjusted to preserve the Companies rights, maintaining the final unit cost per square foot of wall.

By using these values, one can benefit from years of accumulated experience over several different projects in different conditions and requirements. This is consisted with the industries common practice as future bid´s unit costs are based on the actual values obtained in previous experiences as recorded in the companies' databases.

The results of the observations are organized in phases with durations and work completed for each of them. Once the total production is known for the observation period, it can be compared with the total cost to calculate the direct cost per unit of wall constructed. A summary of the unit costs calculated as well as a comparison with the ones obtained in the surveys is included in Section 3.5. These direct costs are calculated for Dallas (TX) in 2014.

3.4.1 Observation 1: Cast in Place Cantilever Wall

The first observation consisted in a 10 ft. high cantilever wall to be constructed for retention of a highway connector ramp. This wall was analyzed from the commencement of the excavation works until forms were removed and backfill was placed. The construction is performed in a sequential process where operations are repeated on a cycle basis. The cycle of activities observed is listed below:

- <u>Day 1</u>: Excavation and subgrade preparation for first 3 modulus of 50 feet long.
- <u>Day 2</u>: Placement of formwork for footing and rebar placement for first 2*50 ft.
- <u>Day 3</u>: Placement of concrete for first two 50 ft. modulus footing and delivery of formwork and rebar for wall stem.
- <u>Day 4</u>: Placement of formwork back face and reinforcing steel for stems (note: high early strength concrete used to allow expedited construction of the stem).
- <u>Day 5</u>: Closing of formwork and concrete placement for stem and removal of footing formwork in the first two modulus.
- <u>Day 6</u>: Curing of concrete stem, placement of footing formwork in modulus 3 and 4.
- <u>Day 7</u>: Removal of formwork in modulus 1 and 2 stem and placement of rebar and concrete is modulus 3 and 4 footings. Backfill of modulus 1 and 2.

Figure 3-2 Observed Wall #1

The analysis of the production cycle as shown above is conservative in terms of unit costs as some activities can be performed during the curing times. Additionally, the team executing the formwork for footing continued forming in days 6 and 7. This advanced work is not considered in the analysis to yield conservative unit costs and production rates, as project specific factors can results in increased costs.

The costs for the production performed during the observation cycle as well as the calculation of the unit cost per cubic yard and square foot of wall are summarized below:

Table 3.7. Development of Unit cost for observed Cast In Place Cantilever Wall

Equipment/Labor	**Details**	**Quantity (hrs.)**	**Unit Cost**	**Total Cost**
Labor	Move rebar and support	40	25	$1,000
Foreman	Move rebar from Stockpile and supervision	80	30	$2,400
Roller (14 tons)	Subgrade and backfill	20	95	$950
Loader (950)	Subgrade and backfill	20	110	$2,200
			TOTAL	*6550*
Subcontract	**Details**	**Quantity (CY)**	**Unit Cost**	**Total Cost**
Supply and tie steel	Supplied and placed	5440	0.67	$3,645
Rebar&Formwork (include materials, labor and equip.)	Rebar, Form, Pour and Strip (average price footing&stem)	64	445	$25,920
			TOTAL	*$29,564.80*
Materials	**Details**	**Quantity (CY)**	**Unit Cost**	**Total Cost**
Concrete supply	Class H concrete	70.4	75.5	$5,315.2
		10% losses	*TOTAL*	$*5,508.8*
TOTAL COST	$**41,623.6**	**Production (CY):**	**64**	

The availability of subcontract costs facilitated the analysis as the rebar placement, formwork and concreting operations were accounted for in the subcontract unit rate. This reduced the need to estimate for auxiliary methods or equipment. The native material excavated to allow the wall construction was used for backfill and therefore only the machinery constituted a cost to account for.

The data collection and calculations performed during Observation #1 resulted in a unit cost of 650.6 $/cy or 72.2 $/SF, with a production rate of 64 CY/day or 576 SF/day (one face).

3.4.2 Observation 2: Mechanically Stabilized Earth Wall (MSE) with metallic strips

The second observation was performed in a Mechanically Reinforced Earth (MSE) wall of heights between 15 and 20 feet. This wall had a total length of 1680 linear feet and was constructed with precast concrete panel facing and galvanized metallic straps. The wall was constructed to retain the edge and abutment of a highway bridge supported with drill shafts.

Figure 3-3 Observed Wall #2

The subgrade preparation required the removal of the unsuitable soil and the replacement with one layer of 10” of engineered fill.

Differently than the case analyzed for the cast in place wall, this wall is constructed in a repeated cycle on a daily basis. Every day during the observation period, panels and straps were placed, backfill was compacted and new rows were added. Thus, in order to calculate the unit costs and production rates, the total costs and production for the 5 day observations were calculated.

The costs for the production performed during the observation cycle as well as the calculation of the unit cost per square foot of wall are summarized in Table 3.8:

Table 3.8. Development of Unit cost for observed MSE Wall

Labor/Subcontractor	**Unit**	**Quantity**	**Unit Cost**	**Total Cost**
Install MSE panels and straps	SF	6250	10	$62,500.00
Excavation and subgrade preparation	CY	2143	8	$17,144.59
Install backfill Type B	CY	4080	11	$44,875.86
Construct MSE leveling pad	LF	402	65	$26,115.75
Install underdrain pipe, filter fabric and gravel	LF	402	2	$803.56
Install coping	LF	68	25	$1,701.92
Install 1/2 connector coping	LF	334	25	$8,342.60
Place concrete flume	LF	13	70	$940.53
Construct Mow strip	LF	402	20	$8,035.62
Construct Moment slab	CY	67	70	$4,702.67
Place and Tie rebar	LB	5710	0.35	$1,998.51
			TOTAL	*$177,161.61*
Equipment	**Details**	**Quantity**	**Unit Cost**	**Total Cost**
trucking (backfill type B) load and haul backfill	CY	4080	9	$36,716.61
			TOTAL	$36,716.61
Materials	**Details**	**Quantity**	**Unit Cost**	**Total Cost**
Furnish MSE panels	SF	6250	11.3	$70,790.69
Supply Backfill type B	ton	6935	12.2	$84,611.39
Concrete footing, flume, mow strip and moment slab	CY	106	78.5	$8,297.30
Furnish underdrain pipe, filter fabric and gravel	LF	402	3.2	$1,285.70
Supply Coping	LF	68	33	$2,243.13
Supply 1/2 connector coping	LF	334	45.8	$15,266.96
Furnish steel	LB	5710	0.33	$1,855.76
			TOTAL.	*$184,350.92*

TOTAL COST PERIOD	**$398,229.14**	**Production Period (SF):**	**6250**

The data collection and calculations performed during Observation #2 resulted in a unit cost of 63.72 $/SF, with a production rate of 1250 SF/day.

3.4.3 Observation 3: Drill Shaft Wall

The third of the observations performed consisted in the extended monitoring of a drill shaft wall with a maximum exposed height of 25 feet, with 48” diameter shaft of 45 feet total length. The concrete used for this shafts was Class C 3600 psi, having a reinforcement of 16 #10 longitudinal bars with a #4 spiral at 6” pitch. The drill shafts were spaced at 6-1/2 feet center to center, being the space between them reinforced with a layer of wire mesh covered with 6” thick shotcrete. The particular aesthetic constraints of the observed wall determined the need for the high-quality precast facing.

The definition of the appropriate timeframe of observation for this third case was the most complicated. During the preliminary studies, it was observed that there were three separate main stages of construction. First, the drilling of the shafts needed to be completed. Only then the capping beam could be reinforced, formed and the concrete placed. Lastly, when the concrete had attained sufficient compressive strength, the excavation of the wall face was executed.

Figure 3-4 Observed Wall #3

Based on these different stages, a long observation period of 20 days was selected in order to properly account for all costs involved in the wall construction.

In terms of square footage of wall "constructed", there is no actual wall that can be observed for the duration of the shafts and capping beam operations. Only when the excavation is performed, the wall quickly "appears" behind the material being hauled out. It is only by the observation of all phases, duration and costs how the unit costs and rates can be calculated.

Table 3.9. Development of Unit cost for observed Drill Shaft Wall

DRILLED SHAFTS 48' 10 DAYS OF EXECUTION 3 PER DAY					
Equipment/Labor	**Unit**	**Quantity**	**Unit Cost**	**Total Cost**	
Labor move rebar and support	HR	80	25	$2,000.00	
Foreman move rebar and supervision	HR	80	30	$2,400.00	
Backhoe remove spoils	HR	80	95	$7,600.00	
Dump Truck remove spoils	HR	160	85	$13,600.00	
			TOTAL. -	*$25,600.00*	
Subcontract		**Quantity**	**Unit Cost**	**Total Cost**	
Mobilization proportioned to total LF	LF	1.35	5000	$6,750.00	
Drilling, rebar and concrete placement	LF	1350	82.5	$111,375.00	
			TOTAL. -	*$118,125.00*	
Materials		**Quantity (CY)**	**Unit Cost**	**Total Cost**	
Concrete supply C Class concrete	CY	691.15	80.5	$55,637.61	
		10% losses	*TOTAL. -*	*$55,637.61*	
TOTAL COST DRILL SHAFT	**$199,362.61**	**Production 10 Days (LFT):**	**1350**	**Unit Cost ($/LFT)**	**147.7**
CAST IN PLACE CONCRETE CAPPING BEAM 4 DAYS OF EXECUTION					
Equipment/Labor	**Unit**	**Quantity**	**Unit Cost**	**Total Cost**	
Labor move rebar and support	HR	20	25	$500.00	
Foreman move rebar and support	HR	20	30	$600.00	
			TOTAL. -	*$1,100.00*	

Table 3.9 Continued

Subcontract		Quantity	Unit Cost	Total Cost	
Supply and tie steel	LB	10667	0.67	$7,146.67	
Form, Pour and Strip (average price footing and stem)	CY	133	485	$64,666.67	
			TOTAL. -	*$71,813.33*	
Table 3.9 Continuation					
Materials		**Quantity (CY)**	**Unit Cost**	**Total Cost**	
Supply C Class concrete	CY	146.67	80.5	$11,806.67	
		10% losses	*TOTAL. -*	*$11,806.67*	
TOTAL COST CAPPING BEAM	**$84,720.00**	**Production (CY):**	**133**	**Unit Cost ($/CY)**	**635.4**

SHOTCRETE BETWEEN DRILLL SHAFTS AND FINAL FACING 6 DAYS EXECUTION					
Concept	**Unit**	**Quantity**	**Unit Cost**	**Total Cost**	
Final 2 feet excavation	SF	3000	0.5	$1,500.00	
Geocomposite drainage blanket	SF	750	1.25	$937.50	
6´´ Shotcrete w/WWM, (Smooth)	SF	1800	9.25	$16,650.00	
8" concrete Class C 3600 psi	SF	1800	7	$12,600.00	
# 4 bars @ 12" OCEW	SF	1800	1.5	$2,700.00	
Fascia cast + delivery	SF	1800	6.8	$12,240.00	
Installation hardware	SF	1800	1.3	$2,340.00	
Shear studs 6-1/2" long, welded onsite	EA	300	15.5	$4,650.00	
Fascia panel installation	SF	4500	11.5	$51,750.00	
			TOTAL	*$105,367.50*	
TOTAL COST FACING	**$105,367.50**	**Production 6 Days (SF):**	**4500**	**Unit Cost ($/SF)**	**23.4**
TOTAL COST WALL	**$389,450.11**	**Production Total Period (SF):**	**4500**	**Unit Cost ($/LFT)**	**86.5**

The data collection and calculations performed during Observation #3 resulted in a wall unit cost of 86.54 $/SF, with an overall production rate of 225 SF of wall/day. In order to allow separate analysis such as the one of a potential drill shaft wall with tie backs, the cost of the three identified components have been obtained as well. These are 147.68 $/ft of drill shaft, 635.40 $/cy of capping beam and 23.42 $/SF of facing.

3.4.4 Observation 4: Rock Nail Wall

The fourth observation was selected to be performed in a rock nail wall with variable height from 15 to 35 feet. This wall retained unweathered limestone rock to allow a direct connector to be executed from a service road under a highway bridge. This rock nail was designed to be executed with 25 feet long nails, constructed with Grade 75 steel size 9 bars. The facing consisted in a 6” shotcrete layer covered by precast concrete panels and a 8” thick concrete closure pour. Groundwater was determined not to be a factor for this wall.

Figure 3-5 Observed Wall #4

Only by observing the complete sequence of activities for the selected wall area, it is possible to calculate unit costs and production rates. The same wall area where the nails and shotcrete were installed during the initial 5-day period was observed during the second 7-day period for the final facing. The lower production rate of the second phase determined the need of extending it two extra days to allow the facing to cover for the entire wall constructed in the initial observation period.

The sequence of installation was repetitive in nature during each observation period. Every day, drilling operations, steel placement, grouting, shotcrete and plate placement were executed. The total wall footage completed in the initial 5-day period was accounted to determine the unit cost once the total expenses were calculated.

Rock Nail wall construction is a highly specialized task and therefore the development of the costs associated is complicated in nature. The availability of subcontract prices is the more adequate approach for it as the knowledge of these specialized companies can be benefited from.

It is important to emphasize the repercussion of the cost of the precast fascia panels. In most circumstances, the final shotcrete layer can serve a permanent layer for the design life of the wall. The particular aesthetic constraints of the observed wall determined the need for the high-quality precast facing. Without considering the cost of the precast facing and associated tasks, the unit cost of the wall is reduced to approximately 50 $/SF.

Table 3.10. Development of Unit cost for observed Rock Nail Wall

Concept	**Unit**	**Quantity**	**Unit Cost**	**Total Cost**
OBSERVATION PERIOD 1				
Final 2 feet excavation	SF	2500	$0.50	$1,250.00
Geocomposite drainage blanket	SF	875	$1.25	$1,093.75
6´´ Shotcrete w/WWM, (Smooth finish)	SF	2500	$9.25	$23,125.0
25' long Nail 6" Diameter. #9 GR. 75	LF	5000	$17.50	$87,500.0
9"x 9"x 1" w/ 4 x 5/8" Plate (galvanized)	EA	200	$55.80	$11,160.00
Proof test rock nails	EA	25	$70.00	$1,750.00
Verification test rock nails	EA	5	$250.00	$1,250.00
OBSERVATION PERIOD 2				
8" concrete Class C 3600 psi	SF	2500	$7.00	$17,500.0
# 4 bars @ 12" OCEW	SF	2500	$1.50	$3,750.00
Fascia panel casting + delivery	SF	2500	$6.80	$17,000.00
Installation hardware	SF	2500	$1.30	$3,250.00
Shear studs 6-1/2" long, welded onsite	EA	200	$6.75	$1,350.00
Fascia panel installation	SF	2500	$11.50	$28,750.0
			TOTAL	$198,729

TOTAL COST PERIOD	**$198,729**	**Production Period (SF):**	**2500**	**Unit Cost ($/SF)**	**79.5**

The data collection and calculations performed during Observation #4 resulted in a unit cost of 79.49 $/SF, with a production rate of 500 SF/day without considering the facing and 210 SF/day when accounting for it.

3.4.5 Observation 5: Tie Back Wall

The fifth and last observation performed selected a Tie Back wall, executed for the retention of a highway section, half supported by a bridge and half by conventional embankment topped with a reinforced concrete pavement. The wall height varied between 25 feet and 45 feet, retaining clayey soils in the first two rows and limestone at different weathering degrees for the lower ones. Groundwater was determined not to be a factor for this wall.

As in the previous observation #4, the particular aesthetic constraints of the observed wall determined the need for the high-quality precast facing consisting in precast concrete panels with a 8” thick concrete closure pour.

The processes involved in the construction of the tie back walls are similar than the ones for the rock nail walls. However, certain specific considerations apply such as longer drilling, need for stressing and testing before excavating to lower rows, increased plates, higher quality steel reinforcement and more complicated corrosion protection systems.

Figure 3-6 Observed Wall #5

Although slower and more complicated, due to the longer spacing between tie backs, the overall production rates do not differ excessively from the ones for nails, under normal circumstances. The unit costs for tie back walls result higher than the ones for nailed walls in all cases.

Tie backs require stressing before considering the constructed wall footage as finished. It was observed that day 7 of the cycle was dedicated to the stressing operations required as a previous stage before excavating to the lower level.

As indicated in Observation #4 tie back wall construction is also a highly specialized task and therefore the development of the costs associated is complicated in nature. The availability of subcontract prices is also the optimum approach for it as the knowledge of these specialized companies can be relied on.

The reasoning described in Section 3.4.4 was also applied to this tie back wall in order to determine reliable unit costs and rates accounting for the two separate phases. The first phase included from excavation until the shotcrete is placed and the second the precast fascia placement and associated works.

Table 3.11. Development of Unit cost for observed Tie Back Wall

Concept	Unit	Quantity	Unit Cost	Total Cost	
Final 2 feet excavation	SF	3308	$0.50	$1,653.75	
Geocomposite drainage blanket	SF	827	$1.25	$1,033.59	
10´´ Shotcrete w/WWM,	SF	3308	$13.20	$43,659.0	
tie-backs 6´´ hole GR150. 75 feet long average	LF	5250	$30.00	$157,500.0	
Proof test tie-backs	EA	56	$70.00	$3,920.00	
Performance test tie-backs	EA	7	$250.00	$1,750.00	
Sacrificial test tie backs	EA	7	$250.00	$1,750.00	
Plate 15´´x 15´´x 1' with studs for tie-backs	EA	70	$180.00	$12,600.00	
8" concrete Class C 3600 psi	SF	3308	$7.00	$23,152.50	
# 4 rebar @ 12" OCEW	SF	3308	$1.50	$4,961.25	
Fascia panel cast + delivery	SF	3308	$6.80	$22,491.00	
Installation hardware	SF	3308	$1.30	$4,299.75	
Shear studs 6-1/2" long, welded	EA	70	$7.50	$525.00	
Fascia panel installation	SF	3308	$11.50	$38,036.25	
			TOTAL COST	$317,332.	
TOTAL COST PERIOD	**$317,332**	**Production Period (SF):**	**3307.5**	**Unit Cost ($/SF)**	**95.9**

The data collection and calculations performed during Observation #5 resulted in a unit cost of 95.94 $/SF, with a production rate of 470 SF/day without considering the facing and 236

SF/day when accounting for it. Without considering the cost of the precast facing and associated tasks, the unit cost of the wall is reduced to approximately 68 $/SF.

The data obtained in Observations 3, 4 and 5 could be used to obtain the unit costs of walls consisting in combinations of drill shafts, nails and tie backs. For example, considering a drill shaft wall where the type of soil would determine the need of incorporating tie backs. Using the values obtained in Observation 3 and 5, a unit cost 159.06$/SF could be calculated by adding the unit cost of the drill shafts and tie back walls and deducting the duplicated cost of the facing. These could serve as preliminary unit costs for initial comparative studies, but would require a project specific analysis for a more detail need such as budget control.

Production rates on the other hand cannot be arithmetically combined to determine the construction pace of hybrid walls. Only an specific analysis can provide actual values, for example of the impact of adding tie backs to a known drill shaft wall production rate.

3.5 Data organization, analysis and conclusions for use in selection model and database

Once the information from the literature review, previous experiences, surveys and interviews to expert engineers was collected, it was necessary to organize it to allow an analysis that could lead to conclusions for use in the selection model and the creation of a database for future reference.

The conclusions obtained from the analysis of the information obtained from the different aforementioned sources are included in the next sections.

3.5.1 Summary of the Survey to Eight Expert professionals.

The information obtained during the data collection phase in the surveys completed by the eight collaborating professionals was organized and compiled in order to allow proper analysis and use. These surveys were targeted to obtain unit costs and production rates, therefore, average values and variability of the responses were calculated.

The summary of the information collected is included in Table 3.13. This summary chart is used to identify those trends of response that can lead to driving factors for each wall type. Additionally, average values of limiting height, unit cost and production rates are calculated based on the responses given by the experts.

3.5.1.1 Identified trends and observations from expert responses

Once the responses were tabulated and compared, some responses were observed to coincide for two or more experts. This showed trends that could be assumed as "expert-facts" and therefore, could be incorporated as driving factors for the selection model. These recurrent responses and identified trends are summarized below:

- Gabion walls are rarely used in heavy civil construction. 6 of the experts had either not worked with this type or were not familiar with it.
- Sheet pile walls are not considered by the consulted experts as a permanent retaining wall in highway construction. Only one expert considered its use for a temporary retention but none of them considered it for a permanent structure.
- There is a general agreement in the wall types that result more appropriate for remote locations where the work force is limited. These walls are ranked by the number of experts that agreed in its adequacy for these constraints:
    - MSE: 8 experts
    - Cast in place: 8 experts
    - Wire mesh: 3 experts
    - Drill shaft: 1 expert
    - Gabion: 1 expert*
    - Sheet pile: 1 expert*

A considerable variability is identified in the responses obtained from the different surveys in terms of production and unit costs as well as for the limiting height that makes a specific wall type economically inadequate.

- Differences up to 25$/SF. are observed between responses for typical unit costs (19% maximum variability).
- Differences up to 450 SF./day are observed between responses for typical production rates (64% maximum variability).
- Differences up to 20 ft. are observed between responses for limiting wall heights (22 % maximum variability).

The background and experience of each one of the experts is included in the Survey forms included in Appendix B. A correlation is observed between the experience of the expert and the values responded. The increased confidence of the more experienced experts resulted in less conservative values for costs (cheaper), production rates (slower) and heights (higher).

Additionally, during most of the interviews, the experts referenced previous experiences as the basis for their determinations regarding unit costs and production rates for each type of wall. This finding is consistent with the ones identified during the literature review included in Section 2.2.3.2 as shown in Figure 2.25 developed based on the work of Hancher et al. (1992). Moreover, six of the experts stated that unit costs being used for certain types of walls were increased due to previous experiences where the economic output was not adequate. This would act as an economic safety factor for those project specific and unforeseen occurrences unknown at the stage of determining the most suitable wall for a certain need.

The information regarding the main factors to develop unit costs and production rates as well as the rest of the information collected in the surveys is summarized in the Table 3.13.

An analysis is performed with the experts' values for wall unit costs, production rates and limiting factors in order to determine a nominal value for each type of wall that can serve as criteria for the selection model and to be incorporated into the database.

Table 3.12. Analysis of expert's rates and calculation of nominal values for selection model

TYPICAL VALUES FOR EACH WALL		**MAX**	**MIN**	**AVERAGE**	**STD. DEV**
LIMIT OF ECONOMICALLY FEASIBLE WALL HEIGHT	*CAST IN PLACE*	35	20	**26**	5.0
	DRILL SHAFT W/O TIE BACK	70	50	**59**	6.9
	DRILL SHAFT W/ TIE BACK	90	70	**83**	7.5
	TIE BACK	75	55	**64**	6.3
	NAILED	50	30	**40**	8.7
	DIAPHRAGM	55	35	**44**	6.4
	WIRE MESH	30	15	**24**	6.4
	MSE	60	40	**47**	6.6
TYPICAL UNIT COST	*CAST IN PLACE*	75	55	**64**	6.9
	DRILL SHAFT W/O TIE BACK	95	80	**88**	6.5
	DRILL SHAFT W/ TIE BACK	130	105	**117**	9.5
	TIE BACK	95	80	**86**	4.5
	NAILED	75	60	**68**	5.2
	DIAPHRAGM	80	55	**71**	8.4
	WIRE MESH	55	35	**44**	7.4
	MSE	65	50	**57**	4.6

Table 3.12 Continued					
TYPICAL PRODUCTION RATE	*CAST IN PLACE*	750	500	**606**	86.3
	DRILL SHAFT W/O TIE BACK	550	350	**406**	72.9
	DRILL SHAFT W/ TIE BACK	450	250	**321**	69.9
	TIE BACK	500	400	**436**	47.6
	NAILED	700	450	**618**	94.3
	DIAPHRAGM	550	100	**319**	148.7
	WIRE MESH	1,000	700	**850**	92.6
	MSE	1,500	1,000	**1,225**	175.3

The average values for unit costs and production rates shown in Table 3.12 above are selected for comparison with the ones obtained by the Observations detailed in Section 3.4 and to select the final values to be used as typical for each wall type in the selection model.

The limiting values for each type of wall are selected from Table 3.12 for comparison with the ones obtained in the interviews included in Section 3.5.2. This comparison and analysis is included in Section 3.5.4 for determination of the values for the selection model. The consideration of the economic height limitation responds to the industry trend of restricting the use of a certain wall to the economic limitation rather than the technical boundary of structural behavior or stability.

The summary of the information collected in the surveys performed to the eight expert engineers is included in Table 3.13.

Table 3.13. Summary of information obtained during the Surveys to the eight experts engineers

SURVEY QUESTIONS		1	2	3	4	5	6	7	8
3 Main factors to develop wall unit cost in general		Cost of materials involved in wall construction	Auxiliary equipment required	Anticipated delays due to weather and external affection	Previous experience with wall	Wall location and access routes	Access and storage conditions	Wall location and traffic control needs	Availability of materials
		Design and monitoring costs	Potential use of existing crews and equipment	Accessibility and space for storage	Testing and instrumentation requirements	Potential for "just in time" purchasing policy	New crews or continuing work (learning curve)	Degree of specialization required by subcontractors	Miscellaneous requirements as aesthetics, painting, etc.
		Subcontractor availability	Cost of materials required	Cost of subcontractors and suppliers	Cost of materials, labor and equipment at wall location	Traffic control requirements	Availability of raw materials (concrete aggregates, backfill, etc.)	Owner requirements for noise and nuisances	Local requirements for Unions and/or sub trades
3 Main factors to develop wall production rates in general		Accessibility and readily available supply materials	Possibility of continuous production and extended shifts	Anticipated delays due to weather and external affection	Previous experience with wall	Logic between prior and after activities	Anticipated weather affection	Wall location and traffic control needs	Supply strategy for subcontractors and materials
		Need to waiting times (such as concrete/grout curing)	Degree of specialization required by subcontractors	Accessibility and space for storage	Accessibility and space for storage	Quality and experience of subcontractors	Number of weekdays and production cycles	Degree of specialization required by subcontractors	Potential for continuous production
		Site specific constraints (schedule, conflicts, noise reduction, etc.).	Potential of conflict between different activities	Potential for weekend work and double shifts	Need for movement monitoring and control	Previous experience with wall	Materials involved and degree of specialty of local subcontractor	Owner requirements for noise and nuisances	Availability of workspace
MAIN FACTORS TO DEVELOP UNIT COSTS FOR THESE TYPES OF WALLS	*CIP*	Presence of nearby batch plants, cost of reinforcing steel and formwork based on their complexity	Availability of concrete, height and one/two face formwork required	Space available and need for shoring or traffic control	Use of on-hand formwork, need for reinforcement placement at the stem, wall panel length	Potential use of local labor and existing formwork, difficulty of reinforcement	Cost of concrete, potential for longer panels and formwork reuse	Availability of formwork already in use, potential for rebar cage at ground level, need for shoring	Cost of concrete, rebar and formwork
	DRILL SHAFT W/O TIE BACK	Cranes and rigging, cost of spoil disposal, availability of drilling subcontractors	Type of soil, depth and clearance for cage introduction with normal methods	Cost of rebar cages, cost of drilling and type of soil to be drilled	Need for casing, need for underwater concrete placement, shaft spacing	Current cost of rebar, concrete and subcontractors	Length of shafts, spacing between shafts, type of soil	Soil hardness, presence of groundwater, casing requirements	Type of soil, drill shaft spacing and reinforcement. Need for underwater concrete placement

MAIN FACTORS TO DEVELOP UNIT COSTS FOR THESE TYPES OF WALLS	*DRILL SHAFT W/ TIE BACK*	Combine above and below	Cost of materials, specialized subcontractors and phasing	I do not have experience with this type of wall	Add the availability of local specialized tie back companies to the costs included for the case w/o anchors	Current cost of rebar, current cost of concrete, cost of subcontractors	Same as above plus cost of subcontractors for anchor operations	Combine upper and lower responses	Type of soil, drill shaft spacing and reinforcement. Need for underwater concrete placement
	TIE BACK	Material cost, requirements for testing and stressing, availability of subcontractors	Need for monitoring, spacing of tie backs, availability of subcontractors	I do not have experience with this type of wall	Total tie back lengths and spacing, requirements for plates and studs, fascia panel requirements?	Subcontractor availability, spacing and length of tie backs	Tie back length, spacing and requirements for materials	Complication of system, presence of groundwater, testing/loading requirements	Total length, spacing and bonded/unbonded requirements
	NAILED	Material cost, grout supply or site mixing, availability of subcontractors	Spacing of nails, length and corrosion protection requirements	Height for the drilling equipment to work at, maximum step between rows, cost of material at wall location	Face requirements, length and spacing of tie backs, type of corrosion protection	Size of bars, length of bars, water/cement relation for grout	Type of soil, potential for use of more than one rig, lateral space for material preparation and storage	Availability of lateral space, potential for machinery quick movement, length	Spacing and maximum step, length of nails
	SHEET PILE	I would not consider this wall	I would not consider this wall	I have not encountered this for permanent construction in transportation projects	Only used for temporary shoring with sheet reuse, cannot compare with other	I do not have experience with this type of wall	I have never worked with this type	I have never worked with this type	Unknown
	DIAPHRAG	Cost of reinforcement steel, subcontractor fees, cranes and rigging.	Depth, width of panels and type of joint/waterproofing required	I do not have experience with this type of wall	Depth, need for slurry and cage reinforcement	I do not have experience with this type of wall	Slurry needs, storage areas and distance to reinforcement preparation area	Wall spacing, potential for cage preparation nearby, dump site distance	Need for slurry, thickness and maximum depth
	WIRE MESH	Cost of backfill, proprietary systems cost, compaction equipment	Maximum basket height, width and requirements for backfill	Cost of fill and materials needed for wire and filter baskets	Availability of on-site material for backfill, basket size and lateral space for machinery movement	Need for shoring, requirements for fill, cost of proprietary systems for baskets	Basket length and vertical spacing, requirements for backfill	Need for shoring, type of backfill, fill storage potential	Maximum basket height, availability of access and storage of backfill

MAIN FACTORS TO DEVELOP UNIT COSTS FOR THESE TYPES OF WALLS	*MSE*	Precast panels cost, availability of selected backfill, accesses and supply complications	Requirements for selected fill and availability onsite, maximum backfill lift., length of straps	Space available and need for shoring or traffic control	Panel size, length of straps and backfill lift. thickness	MSE Wall =Need for shoring, requirements for selected fill, cost of proprietary systems for panels and straps	Straps length and vertical spacing, requirements for backfill	Need for shoring, aesthetic requirements for panels, panel size and number of straps	Height, panel aesthetic requirement
	GABION	I would not consider this wall	I would not consider this wall	Availability of aggregates for basket, availability of local experience in gabion fabrication and gabion size	I would not consider this wall	Unknown	Availability of aggregates for basket filling	I have never worked with this type	Unknown
LIMIT OF ECONOMIC FEASIBLE WALL TYPE	*CIP*	25 ft..	30 ft.	20 ft.	25 ft.	25 ft.	20 ft.	35 ft.	25 ft.
	DRILL SHAFT W/O T.B	60 ft.	65 ft.	60 ft.	50 ft.	55 ft.	50 ft.	70 ft.	60 ft.
	DRILL SHAFT W/ T.B.	85 ft.	90 ft.	I do not have experience with this type of wall	80 ft.	I do not have experience with this type of wall	70 ft.	90 ft.	85 ft.
	TIE BACK	65 ft.	60 ft.	I do not have experience	60 ft.	55 ft.	65 ft.	75 ft.	65 ft.
	NAILED	35 ft.	40 ft.	45 ft.	50 ft.	30 ft.	30 ft.	50 ft.	I would not consider this
	SHEET PILE	I would not consider this wall	I would not consider this wall	I have not encountered this for permanent construction in transportation projects	Only used for temporary shoring with sheet reuse, cannot compare with other	I do not have experience with this type of wall	I have never worked with this type	I have never worked with this type	Unknown
	DIAPHRAG	40 ft.	45 ft.	50 ft.	45 ft.	40 ft.	35 ft.	40 ft.	55 ft.
	WIRE MESH	15 ft.	25 ft.	30 ft.	25 ft.	30 ft.	30 ft.	20 ft.	15 ft.
	MSE	40 ft.	50 ft.	50 ft.	60 ft.	44 ft.	50 ft.	45 ft.	40 ft.
	GABION	I would not consider this wall	I would not consider this wall	8 ft.	I would not consider this wall	I do not have experience with this type of wall	20 ft.	I would not consider this wall	I would not consider this wall

TYPICAL UNIT COST	*CIP*	55$/SF.	60$/SF.	70$/SF.	75$/SF.	65$/SF.	65$/SF.	65$/SF.	55$/SF.
	DRILL SHAFT. W/O TIE BACK	80$/SF.	90$/SF.	85 $/SF.	95 $/SF.	85$/SF.	95$/SF.	95$/SF.	80$/SF.
	DRILL SHAFT. W/ TIE BACK	105 $/SF.	115 $/SF.	I do not have experience with this type of wall	130$/SF.	125 $/SF.	120 $/SF.	120 $/SF.	105 $/SF.
	TIE BACK	85$/SF.	80$/SF.	I do not have experience with this type of wall	85 $/SF.	95$/SF.	85$/SF.	85$/SF.	85$/SF.
	NAILED	70$/SF.	65$/SF.	I do not have experience with this type of wall	75 $/SF.	I would not consider this wall	65 $/SF.	60$/SF.	70$/SF.
	SHEET PILE	I would not consider this wall	I would not consider this wall	I have not encountered this for permanent construction in transportation projects	Only for temporary shoring with sheet reuse, cannot compare with other	I do not have experience with this type of wall	I would not consider this wall	I have never worked with this type	Unknown
	DIAPHRAG	65$/SF.	80$/SF.	75$/SF.	70$/SF.	60$/SF.	55$/SF.	65$/SF.	75$/SF.
	WIRE MESH	40$/SF.	40$/SF.	45 $/SF.	55 $/SF.	55$/SF.	35$/SF.	40$/SF.	40$/SF.
	MSE	55$/SF.	50$/SF.	55 $/SF.	60 $/SF.	65$/SF.	60$/SF.	55$/SF.	55$/SF.
	GABION	I would not consider this wall	I would not consider this wall	350 SF./day	I would not consider this wall	I would not consider this wall	65$/SF.	I have never worked with this type	I would not consider this wall
TYPICAL RATE	*CIP*	600 SF./day	650 SF./day	550 SF./day	500 SF./day	650 SF./day	750 SF./day	650 SF./day	500 SF./day
	DRILL SHAFT. W/O TIE BACK	350 SF./day	450 SF./day	350 SF./day	350 SF./day	400 SF./day	550 SF./day	450 SF./day	350 SF./day
	DRILL SHAFT. W/ TIE BACK	250 SF./day	350 SF./day	I do not have experience with this type of wall	250 SF./day	300 SF./day	450 SF./day	350 SF./day	300 SF./day
	TIE BACK	450 $/SF.	500 $/SF.	I do not have experience with this type of wall	400 $/SF.	400 $/SF.	400 $/SF.	500 $/SF.	400 $/SF.
	NAILED	625 SF./day	700 SF./day	I do not have experience with this type	450 SF./day	700 SF./day	600 SF./day	700 SF./day	550 SF./day

TYPICAL RATE	*SHEET PILE*	I would not consider this wall	I would not consider this wall	I have not encountered this for permanent construction in transportation projects	Only used for temporary shoring with sheet reuse, cannot compare with other	I do not have experience with this type of wall	I have never worked with this type	I have never worked with this type	Unknown
	DIAPHRAG	450 SF./day	150 SF./day	250 SF./day	100 SF./day	550 SF./day	350 SF./day	350 SF./day	350 SF./day
	WIRE MESH	800 SF./day	850 SF./day	850 SF./day	1000 SF./day	950 SF./day	700 SF./day	850 SF./day	800 SF./day
	MSE	1150 SF./day	1250 SF./day	1000 SF./day	1500 SF./day	1400 SF./day	1250 SF./day	1250 SF./day	1000 SF./day
	GABION	I would not consider this wall	I would not consider this wall	50 $/SF.	I would not consider this wall	I would not consider this wall	450 SF./day	I have never worked with this type	Unknown
Appropriate wall for remote areas where specialized workforce is limited		MSE Walls	Concrete cast in place	Concrete cast in place	Sheet pile Wall	Soil/Rock nail	Concrete cast in place	Soil/Rock Nails	Cast in place wall
		Soil/Rock Nails	MSE Wall	MSE Wall	Concrete wall	MSE Wall	MSE Wall	MSE/Wire mesh walls	Mechanically Stabilized
		Concrete cast in place walls	Wire mesh wall	Gabion Wall	MSE Wall	Gravity Wall	Wire mesh wall	Concrete cast in place walls	Drill Shaft.

3.5.2 Summary of the Interviews to Five Expert professionals.

As performed in Section 3.5.1 for the surveys, the information obtained during the data collection phase in the interviews to the five collaborating professionals was organized and compiled for analysis. These interviews were tailored in order to supplement those areas where the references and the surveys could not provide a consistent basis for the development of the selection model. For example, an specific question regarding standard design life for each type of wall was included to supplement the lack of information in the literature review included in Section 2.2.

In many engineering circumstances, a preliminary analysis is performed in terms of rankings, without the need of developing actual values to compare. In order to allow this comparison to be performed, the five experts were asked to rank the different types of walls being evaluated in terms of difficulty of construction, cost and duration of construction.

Due to the variability of the responses in the surveys regarding limiting wall height, the limiting wall height was also included as a question in the interview forms used. This information was compared and analyzed in Section 3.5.4 for use in the selection model and incorporation into the database.

3.5.2.1 Identified trends and observations from expert responses

Once the responses were tabulated and compared, some responses were observed to coincide for two or more experts. As in the previous survey comparison, the data showed trends that could be assumed as “expert-facts” and therefore, could be incorporated as driving factors for the selection model. These recurrent responses and identified trends are summarized below:

- As shown in the survey, gabion walls are rarely used in heavy civil construction. 2 of the interviewed experts would not use this type for civil construction.
- As shown by the survey responses, sheet pile walls are rarely used in heavy civil construction. 4 of the interviewed experts would not use this type for permanent construction.
    - Gabion and Sheet pile will not be considered in the selection model. This is based on the fact that 95% of the experts consulted in the surveys and interviews would not use them for permanent civil construction.

- When inquired regarding areas where information is insufficient, the experts responded referencing the actual parameters of the walls in 7 out of 15 instances. This related to actual wall construction phasing, loading, geometry and construction systems to be utilized.

Table 3.14. Areas where information is insufficient for the experts interviewed

INTERVIEW #	**1**	**2**	**3**	**4**	**5**
Areas where information lacks <u>during preliminary studies</u>	Actual construction sequence	Actual project specific constraints	Geotechnical report specific for wall type	Specific site conditions	Procurement constraints
	Loading during construction	Final geometry	Unit costs with project specific assumptions	Owner final requirements	Actual cost of materials
	Construction system	Final loading configuration	Groundwater and soil chemical analyses	Schedule and conflicts between activities	Geotechnical investigation

- A general agreement exists among the experts' responses in regards to the most common construction issues for each type of wall. The most repeated responses relate to concrete consolidation issues, improper drainage measures, construction errors, low-quality materials and incorrect reinforcement execution. These identified factors, included in Table 3.18, could be used to develop a quality control/assurance plan for any retaining wall construction.

3.5.2.2 Driving factors for wall determination

The selection model needs to account for those factors that the experts determine as critical when defining a certain wall type for a particular need and location. These factors were built into the model and are summarized in the Table 3.15:

Table 3.15. Driving factors for wall determination

INTERVIEW #	**1**	**2**	**3**	**4**	**5**
Driving factors for wall determination	Geotechnical information	Direction of construction	Type of soil	Height	Soil type
	Allowable cost and duration	Height and type of soil	Loading direction	Maximum unit cost	Maximum height
	Phasing and construction sequence	Maximum unit cost	Available specialized personnel and equipment	Actual design life	Unit cost and production rate required

Economic and schedule factors are repeated in 4 of the 12 received responses. This evidences the importance of accounting for them when determining the most suitable wall for a certain location as discussed in Sections 1.2, 2.2, 2.6 as well as supports the need for the present Thesis' objectives.

3.5.2.3 Retaining Wall types ranking in terms of difficulty, cost and duration of construction

Once the responses were tabulated and analyzed, a ranking of the different types of retaining walls was developed for use in the selection model and future needs of wall comparison. The data used and the resulting ranking is shown in Table 3.16 and Figure 3.2.

Table 3.16. Ranking of walls based in terms of difficulty, cost and duration of construction

CONCEPT	WALL TYPE	RANKING IN INTERVIEW					MOST REPEATED (MODE)
RANKING IN ORDER OF DIFFICULTY OF CONSTRUCTION (1 most difficult)	*CIP*	9	8	6	7	8	***9***
	DRILL SHAFT	2	3	4	2	4	***3***
	MSE	8	6	8	8	6	***8***
	TIE BACK	3	1	2	1	2	***2***
	NAILED	4	5	3	4	3	***4***
	SHEET PILE	5	4	5	5	5	***5***
	DIAPHRAGM	1	2	1	3	1	***1***
	WIRE MESH	7	7	9	9	7	***7***
	GRAVITY	10	9	10	10	10	***10***
	GABION	6	10	7	6	9	***6***
RANKING IN ORDER OF CONSTRUCTION UNIT COST (1 most expensive)	*MSE*	3	3	3	4	4	***3***
	CIP	1	1	1	3	2	***1***
	GRAVITY	2	2	2	1	3	***2***
	GABION	5	4	4	2	1	***4***
	WIRE MESH	4	5	5	5	5	***5***
	NAILED	6	5	5	6	6	***5***
	TIE BACK	4	4	4	4	5	***4***
	D.S. W/O ANCHOR	3	3	3	3	3	***3***
	D.S. W/ANCHOR	2	1	2	1	2	***1***
	SHEET PILE	5	6	6	5	4	***6***
	DIAPHRAGM	1	2	1	2	1	***2***
CONCEPT	**WALL TYPE**	**RANKING IN INTERVIEW**					**MOST REPEATED (MODE)**
RANKING IN ORDER OF DURATION OF CONSTRUCTION (1 slowest)	*MSE*	5	4	3	3	2	***5***
	CIP	3	1	2	1	1	***2***
	GRAVITY	2	2	1	2	3	***3***
	GABION	4	1	2	1	1	***1***
	WIRE MESH	1	4	3	3	2	***4***
	NAILED	6	5	5	6	5	***5***
	TIE BACK	5	4	4	4	6	***4***
	D.S. W/O ANCHOR	3	2	3	3	3	***3***
	D.S. W/ANCHOR	1	1	2	2	1	***1***
	SHEET PILE	4	6	6	5	4	***6***
	DIAPHRAGM	2	3	1	1	2	***2***

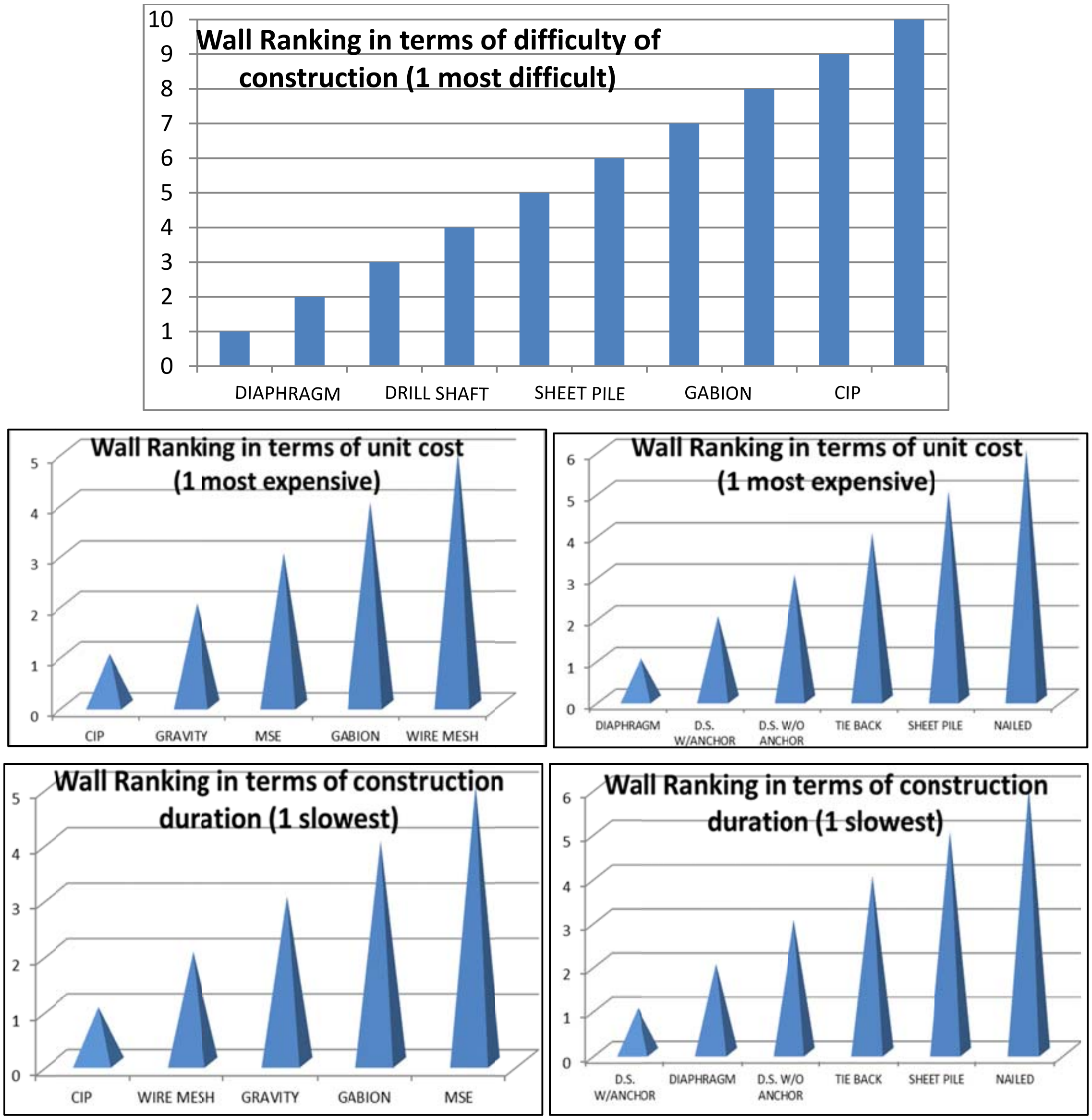


Figure 3-7 Graphical representation of the rankings shown in Table 3.16

3.5.2.4 Identification of the “no-go” conditions based on the interviews results

The experts responses were analyzed in order to determine those conditions that if exist, automatically causes a certain wall to be unsuitable. These conditions are built into the selection model and are presented in Table 3.17 for future needs of preliminary wall comparison.

Table 3.17. "No-go" conditions for each retaining wall type based on the interview's results

		INTERVIEW #				
		1	**2**	**3**	**4**	**5**
NO GO CONDITION FOR EACH TYPE OF WALL	*CIP*	Excessive height	If MSE can be used and height is more than 15 feet is more economical	Lack of space for proper footing	Excessive height of lack of space for footing	Height over 20 feet
	DRILL SHAFT	Limited cost	Costly option, suitable for high loads and soft soils	Potential for use of simpler walls or rock nail	Reduced height and availability of space	Boulders exceeding shaft diameter
	MSE	Reduced lateral space	Heights over 40 feet	Lack of cost-efficient backfill	Corrosive soil, heights less than 15 feet	Flowing water and corrosive soil/water
	TIE BACK	Schedule or limitations in subsurface ROW	GW and fractured soils	Lack of specific needs, GW that requires control	Remote areas with lack of specialized companies	Creeping soils
	NAILED	Limitations in subsurface ROW	Groundwater (GW) and fractured soils	Groundwater that requires control	Corrosive soils and remote areas	Corrosive soils
	SHEET PILE	Permanent configuration. Hard soils or boulders	Would only use if rest are non-feasible or for temporary shoring in high GW and/or with movements limitation in deep excavations	Would not use for permanent	Would not use for permanent	Permanent construction
	DIAPH.	Hard rock	Absence of very strict requirements for lateral movements	Out of urban areas where lateral movement and GW control is not a requirement (i.e. tunnels)	Absence of specific GW and movement control such as in urban areas	H<20 feet height except in high load cases or water control needs
	WIRE MESH	Aesthetic requirement	Normally only to be used in temporary configurations, very flexible for that can lead to issues for roadway construction	Permanent situation where aesthetic requirements exist	Would not recommend it in most circumstances unless temporary situations	Potential water flow and need for lateral loading
	GRAVITY	Height over 8 feet	Difficult or expensive concrete supply	Most cases would recommend cantilever instead.	Height over 5 feet, as cantilever results more economic	Height over 10 feet, soft subgrade and difficult concrete supply
NO GO CONDITION FOR EACH TYPE OF WALL	*GABION*	Dynamic loading	Only for projects where aesthetics is a requirement or slope stabilization.	I would not use a gabion wall for civil construction	I would not use a gabion wall for civil construction	Height over 15 feet, reduced lateral ROW and lateral loads

These identified factors will be used in the selection model when evaluating the adequacy of each type of wall for the different input parameters for a certain location or need. The factors included in Table 3.17 can be used for future reference.

Although current technology advancements in terms of design, equipment and materials can make possible the construction of most of the potential combinations, only those that are normally selected to be constructed by common methods are used. It is possible that some “no-go” conditions could be resolved by highly complicated and/or costly solutions but for the purpose of the development of the selection model, only common practices are selected.

The summary of the information collected in the interviews performed to the five expert engineers is included in Table 3.18.

Table 3.18. Summary of information obtained during the Interviews to the five experts engineers

INTERVIEW QUESTION		**INTERVIEW #**				
		1	**2**	**3**	**4**	**5**
Factors for wall determination		Geotechnical information	Direction of construction	Type of soil	Height	Soil type
		Allowable cost and duration	Height and type of soil	Loading direction	Maximum unit cost	Maximum height
		Phasing and construction sequence	Maximum unit cost	Available specialized personnel and equipment	Actual design life	Unit cost and production rate required
Areas where information lacks		Actual construction sequence	Actual project specific constraints	Geotechnical report specific for wall type	Specific site conditions	Procurement constraints
		Loading during construction	Final geometry	Unit costs with project specific assumptions	Owner final requirements	Actual cost of materials
		Construction system	Final loading configuration	Groundwater and soil chemical analyses	Schedule requirements and conflicts with other activities	Geotechnical investigation
MAXIMUM WALL HEIGHT (ft)	*MSE*	60 feet	40 feet	50 feet	50 feet	45 feet
	CIP	20 feet	30 feet, higher MSE	25 feet	30 feet	25 feet due to uneconomical formwork required
	GRAVITY	8 feet	8 feet, if higher I would use cantilever	8 feet	10 feet	5 feet, if higher I would use cantilever
	GABION	30 feet	Only in residential construction up to 10 feet. Requires a considerable lateral space (ROW)	I would not use a gabion wall for civil construction	I would not use a gabion wall for civil construction	Can go up to 40 feet with high lateral space consumption
	WIRE MESH	50 feet	15 feet, would not normally use for permanent. Ok for temporary	25 feet	20 feet	25 feet with delicate construction and backfill control
MAXIMUM WALL HEIGHT (ft)	*NAILED*	80 feet	35 feet	35 feet, highly dependent on soil	40 feet	35 feet
	TIE BACK	100 feet	50 feet	55 feet	65 feet	55 feet
	D.S. W/O ANCHOR	25 feet	35 feet	45 feet, more with very competent stratums	50 feet for rock bearing	40 feet in good bearing stratum such as unweathered rock
	D.S. W/ANCHOR	100 feet	50 feet with anchors	65 feet with anchors	80 feet with anchors	65 feet with anchors
	SHEET PILE	30 feet with anchors	25 feet bulkhead	I would not use a sheet wall in most circumstances	25 feet	45 feet with the incorporation of anchors
	DIAPHRAGM	30 feet	70 feet with anchors or tie beams	100 feet with anchors or tie beams	100 feet with anchors or tie beams	90 feet with anchors or tie beams

Walls where design and supervision expertise is most critical		Any wall that includes anchors Any downward wall	Any downward wall	Anchored walls Drill shafts	Drill shafts Diaphragm	Anchored walls
Walls where groundwater results critical		Diaphragm walls as there is no possibility of drainage unless with highly complicated details	Tie backs Rock nails	Tie backs Rock nails	Tie backs and nails MSE Walls	Tie backs and nails MSE Walls
Walls with increased maintenance needs		Anchored walls, wire mesh and MSE	Depending in the quality of construction, specifically in drainage measures for upward. For downward walls without permanent facing	MSE, wire mesh or Cast in place as improper drainage can lead to backfill being washed out and subsidence on the retained structure	Anchored walls (tie backs, drill shafts and diaphragm with anchors) in high load situations also require load/movement monitoring	Wire mesh, mechanically stabilized earth and gabion
NO GO CONDITIONS FOR EACH TYPE OF WALL	*CIP*	Excessive height	If MSE can be used and height is more than 15 feet is normally quicker and more economical	Lack of space for proper footing	Excessive height of lack of space for footing	Height over 20 feet
	DRILL SHAFT	Limited cost	Costly option, suitable for high loads and soft soils	Potential for use of simpler walls or rock soil	Reduced height and availability of space	Boulders exceeding shaft diameter
	MSE	Reduced lateral space	Heights over 40 feet	Lack of cost-efficient backfill	Corrosive soil, heights less than 15 feet	Flowing water and corrosive soil/water
	TIE BACK	Schedule or limitations in subsurface ROW	Groundwater and fractured soils	Lack of specific needs, groundwater that requires control	Remote areas with lack of specialized companies	Creeping soils
	NAILED	Limitations in subsurface ROW	Groundwater and fractured soils	Groundwater that requires control	Corrosive soils and remote areas with lack of specialized companies	Corrosive soils
	SHEET PILE	Permanent configuration. Hard soils or boulders	Would only use if rest are non-feasible or for temporary shoring in high groundwater and/or where movements are to be controlled in deep excavations	Would not use for permanent	Would not use for permanent	Permanent construction
	DIAPHRAGM	Hard rock	Absence of very strict requirements for lateral movements	Out of urban areas where lateral movement and groundwater control is not required	Absence of groundwater and movement control such as in urban areas	Less than 20 feet height except in high load cases or water control needs

NO GO CONDITIONS FOR EACH TYPE OF WALL	*WIRE MESH*	Aesthetic requirements	Normally only to be used in temporary, very flexible for that can lead to issues for roadway construction	Permanent situation where aesthetic requirements exist	Would not recommend it in most circumstances unless temporary situations	Potential water flow and need for lateral loading
	GRAVITY	Height over 8 feet	Difficult or expensive concrete supply	Most cases would recommend cantilever instead.	Height over 5 feet, as cantilever results more economic	Height over 10 feet, soft subgrade and difficult concrete supply
	GABION	Dynamic loading	Only where aesthetics is a requirement or slope stabilization. Other types more economic in most circumstances	I would not use a gabion wall for civil construction	I would not use a gabion wall for civil construction	Height over 15 feet, reduced lateral ROW and lateral loads
3 MOST COMMON CONSTRUCTION ISSUES	*CIP*	Formwork blowouts, incorrect rebar placement, construction joints	Unforeseen boulders, out of plumbness, excessively reused sheets	I would not use a sheet wall in most circumstances	I do not have experience with the construction of this type of walls	Water infiltration, unforeseen boulders that difficult the driving processes and failing bulk heads/anchors
	DRILL SHAFT	Differing soil, water intrusions, honeycombing	Incorrect joint execution and water intrusions, insufficient slurry filtering and rebar cage collapses	Similar to drill shafts, with the specific concerns of oversized cages being lifted and moved before introduction in excavated panels	As for drill shafts Cage lifting and introduction, plumbness, soil intrusions and no use of tremie tubes	Failing cages during lifting and introduction, excessive sand in slurry and soil intrusions in concrete/honeycombing
	MSE	Backfill washing, strap corrosion, damage to facing	Plumbness, backfill washing and damage to fabric	Llack of the filter fabric between rock and selected fill and damaged wires.	Backfill, damage to wires and ripped fabric (washing)	Plumbness, backfill washing and damage to fabric. Lack of proper drainage
	TIE BACK	Incorrect geometry of tie back, low-quality grout and improper corrosion protection	Deviation from angle of inclination and length, lack of proper proof/performance testing, lack of sacrificial testing to verify design assumptions	Damages to the corrosion protection measures, incorrect centralizers placement, deviations from design inclination/length.	As for nailed walls damage to corrosion protective measures, inclination, insufficient bonded length. Recurrent issues during stressing and locking operations	Deviation from angle of inclination, improper sleeve connection and incorrect testing practices
	NAILED	Incorrect geometry of tie back, low-quality grout and improper corrosion protection	Insufficient testing, lack of control of actual soil and insufficient nail length	Damages to the corrosion protection measures, incorrect centralizers, deviations from design inclination/length.	Damage to corrosion protective measures, inclination, insufficient bonded length	Damaged corrosion protection, improper locking processes and deviation from the required angle/length

3 MOST COMMON CONSTRUCTION ISSUES	*SHEET PILE*	Water infiltration, unforeseen boulders that difficult the driving processes and sheet corrosion	Unforeseen boulders, out of plumbness, excessively reused sheets	I would not use a sheet wall in most circumstances	I do not have experience with the construction of this type of walls	Water infiltration, unforeseen boulders that difficult the driving processes and failing bulk heads/anchors
	DIAPHRAGM	Collapse of cages, incorrect joints and water level unintended modifications (subsidences)	Incorrect joint execution and water intrusions, insufficient slurry filtering and rebar cage collapses	Similar to drill shafts, with the specific concerns of oversized cages being lifted and moved before introduction in excavated panels	As for drill shafts Cage lifting and introduction, plumbness, soil intrusions and no use of tremie tubes	Failing cages during lifting and introduction, excessive sand in slurry and soil intrusions in concrete/honeycombing
	WIRE MESH	Ripped fabric, incorrect aggregate distribution and excessive lift thickness	Plumbness, backfill washing and damage to fabric	Lack of proper drainage, lack of the required filter fabric between rock and selected fill (then material washout occurs) and damaged wires.	Backfill, damage to wires and ripped fabric that leads to washing	Plumbness, backfill washing and damage to fabric
	GRAVITY	Improper vibration, construction joints and formwork blowouts	Improper concrete vibration, excessive concrete free fall and segregation	Improper concrete practices with excessive free fall, out of plumb or improperly supported lateral formwork	Lack of concrete vibration, joints between placements, subgrade preparation	Cleanness of the area prior to concrete, support of formwork, excessive concreting speed which leads to unconsolidations and formwork blowouts
	GABION	Low quality aggregate, incorrect placement, plumbness	Improperly prepared subgrade, incorrect connection in basket, damaged wires	I would not use a gabion wall for civil construction	I do not have experience with the construction of this type of walls	Damage to wire baskets, out of plumbness and use of rock subject to weathering
RANKING IN ORDER OF DIFFICULTY OF CONSTRUCTION (1 most difficult)	*CIP*	9	8	6	7	8
	DRILL SHAFT	2	3	4	2	4
	MSE	8	6	8	8	6
	TIE BACK	3	1	2	1	2
	NAILED	4	5	3	4	3
	SHEET PILE	5	4	5	5	5
	DIAPHRAGM	1	2	1	3	1
	WIRE MESH	7	7	9	9	7
	GRAVITY	10	9	10	10	10
	GABION	6	10	7	6	9

RANKING IN ORDER OF CONSTRUCTION UNIT COST (1 most expensive)	*MSE*	3	3 (standard facing, can be 1 if aesthetics are complicated)	3	4	4
	CIP	1	1	1	3	2
	GRAVITY	2	2	2	1	3
	GABION	5	4 (low heights, if >7-10 ft. uneconomical)	4	2	1
	WIRE MESH	4	5	5	5	5
	NAILED	6	5	5	6	6
	TIE BACK	4	4	4	4	5
	D.S. W/O ANCHOR	3	3	3	3	3
	D.S. W/ANCHOR	2	1	2	1	2
	SHEET PILE	5	6	6	5	4 (higher if sheet stay)
	DIAPHRAGM	1	2	1	2	1
RANKING IN ORDER OF DURATION OF CONSTRUCTION (1 slowest)	*MSE*	5	4	3	3	2
	CIP	3	1	2	1	1
	GRAVITY	2	2	1	2	3
	GABION	4	1	3	3	2
	WIRE MESH	1	4	3	3	2
	NAILED	6	5	5	6	5
	TIE BACK	5	4	4	4	6
	D.S. W/O ANCHOR	4	2	3	3	3
	D.S. W/ANCHOR	1	1	2	2	1
	SHEET PILE	4	6	6	5	4
	DIAPHRAGM	2	3	1	1	2
STANDARD DESIGN LIFE (years)	*CIP*	50	50	50	50	50
	DRILL SHAFT	75	50	50	50	75
	MSE	50	50	50	50	50
	TIE BACK	50	50	50	50	50
	NAILED	50	15	25 unless in rock	25/50 (soil/rock)	25/50 (soil/rock)
	SHEET PILE	1	5	I would not use a sheet wall in most circumstances	Would not use for permanent, I would say 5	10
	DIAPHRAGM	75	50	50	50	75
	WIRE MESH	50	5, temporary retention	25 feet	15	25
	GRAVITY	100	50	50	50	50
	GABION	50	15	I would not use a gabion wall for civil construction	Would not use for permanent, would say 10	25

3.5.3 Summary of the Field Observations and comparison with the survey results.

As described in Section 3.4, specific Field Observations were designed for the five types of retaining walls. The obtained values resulted within the ranges established by the consulted engineers during the surveys. As expected, a high variability was observed among the different values obtained. This responds to the great impact of the actual project factors in the determination of the construction unit costs and production rates.

Although several values have been obtained for each wall, only one typical costs or production rate can be assumed for use in the selection model. Therefore, an analysis of all different sources of information was required. The summary of information obtained during the literature review, field observations and surveys regarding cost and production rates is included in Table 3.19 below:

Table 3.19. Summary of Unit Costs and Production Rates

TYPICAL VALUES FOR EACH WALL		**SURVEY (2014)**	**FIELD OBS. (2014)**	**TDOT (2012)**	**TXDOT (2007)**	**SPANISH HIGH SPEED TRAIN (2007-2009)**	**KNOWN WALLS (2014) (Section 2.5)**
TYPICAL UNIT COST	*CAST IN PLACE*	**64**	**72**	55	85	75	**57**
	DRILL SHAFT W/O TIE BACK	**88**	**87**	78	70	108	**N/A**
	DRILL SHAFT W/ TIE BACK	**117**	**N/A**	135	N/A	135	**152**
	TIE BACK	**86**	**96**	75	95	N/A	**N/A**
	NAILED	**68**	**80**	51	65	95	**73**
	DIAPHRAGM	**71**	**N/A**	86	N/A	N/A	**N/A**
	WIRE MESH	**44**	**N/A**	30	N/A	N/A	**N/A**
	MSE	**57**	**64**	35	35	58	**53**
TYPICAL PRODUCTION RATE	*CAST IN PLACE*	**606**	**576**	N/A	N/A	N/A	**750**
	DRILL SHAFT W/O TIE BACK	**406**	**225**	N/A	N/A	N/A	**N/A**
	DRILL SHAFT W/ TIE BACK	**321**	**N/A**	N/A	N/A	N/A	**450**
	TIE BACK	**436**	**470**	N/A	N/A	N/A	**N/A**
	NAILED	**618**	**500**	N/A	N/A	N/A	**625**
	DIAPHRAGM	**319**	**N/A**	N/A	N/A	N/A	**N/A**
	WIRE MESH	**850**	**N/A**	N/A	N/A	N/A	**N/A**
	MSE	**1,225**	**1250**	N/A	N/A	N/A	**1150**

It is noted that the values included from the surveys for each wall type are the averages of the eight different responses obtained as previously included in Table 3.12.

The year of analysis has a considerable affection in the actual costs for each type of wall. Therefore, a higher relevance is given to the values obtained from the surveys, field observations and the known walls analyses as they were performed in the current year and therefore represent better the current market condition.

The values of the previous projects and literature references are used as an external check to verify the values collected. These values obtained from both the surveys and observations are generally neither the maximum or minimum of all the ones available as shown in Table 3.19 (with the exception of the drill shaft with tie backs in Section 2.5. This wall was located in a highly complicated geotechnical area and thus its cost was greatly higher). This provides increased assurance in the adequacy of these values for use in the selection model and to incorporate them into the database as an starting point for preliminary analyses that can be later adjusted for project specific factors.

A lower variability in terms of unit costs and production rates is identified for wall types of cast in place concrete and mechanically stabilized earth. This responds to the less complicated design and construction processes for these wall types. Therefore, the reliability of the cost and production records is greater than in the case of more complicated types such as tied back drill shaft walls.

The values from the surveys are consistently less conservative than the field observation and previous projects records. This is deemed to be caused by the extensive experience and background of the experts consulted, as discussed in Section 3.5.1.1.

Downward construction for underground transportation infrastructure is uncommon in the southern states such as Texas or Tennessee, therefore the references available for these walls is limited as evidenced by the literature review of the TxDOT and TDOT manuals included in Section 2.2.

3.5.4 Selection of limiting height, typical unit cost and production rates for the selection model.

Once all the information from the different phases was collected, summarized and analyzed, it could be compared in order to select those parameters to be used in the selection model. These values of unit cost, production rates and limiting height will be utilized for the determination of the most suitable wall for a certain set of input constraints.

The unit costs and production values are selected from the analysis and comparison included in Table 3.20:

Table 3.20. Unit Costs and Production Rates to be used in the selection model

TYPICAL VALUES FOR EACH WALL		VALUE ASSUMED
TYPICAL UNIT COST FOR USE IN SELECTION MODEL ($/SF)	*CAST IN PLACE*	**70**
	DRILL SHAFT W/O TIE BACK	**85**
	DRILL SHAFT W/ TIE BACK	**120**
	TIE BACK	**90**
	NAILED	**77**
	DIAPHRAGM	**75**
	WIRE MESH	**40**
	MSE	**55**
TYPICAL PRODUCTION RATE FOR USE IN SELECTION MODEL (SF/day)	*CAST IN PLACE*	**600**
	DRILL SHAFT W/O TIE BACK	**350**
	DRILL SHAFT W/ TIE BACK	**320**
	TIE BACK	**425**
	NAILED	**550**
	DIAPHRAGM	**320**
	WIRE MESH	**850**
	MSE	**1,200**

In relation to the limiting height for each one of the different walls being considered, not only the technical boundaries of each wall have been considered. As discussed in Sections 3.5.1 and 3.5.2, economic limitations are commonly used instead of the actual structural limits of the wall behavior. Therefore, the information obtained from the surveys and interviews to the experts are given a higher relevance, as these are mainly driven by economic factors. Assuming the technical limitations to the wall heights would result in the need of specific economic and production analysis, which would yield increased costs and lower productions than the ones shown in Table 3.20 which specific complications in design and construction.

A summary of the different height limitations obtained from the survey and interview processes is included in Table 3.21 as well as the actual limit value to be used during the wall evaluations in the selection model included in Section 4.

Table 3.21. Limiting height for the different wall types

MAXIMUM WALL HEIGHT (ft.)	INTERVIEW #					SURVEY #							
	1	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
MSE	60	40	50	50	45	40	50	50	60	44	50	45	40
CIP	20	30	25	30	25	25	30	20	25	25	20	35	25
GRAVITY	8	8	8	10	5	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
*GABION***	30	10	N/A	N/A	40	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
WIRE MESH	50	15	25	20	25	15	25	30	25	30	30	20	15
NAILED	80	35	35	40	35	35	40	45	50	30	30	50	N/A
TIE BACK	100	50	55	65	55	65	60	N/A	60	55	65	75	65
D.S. W/O ANCHOR	25	35	45	50	40	60	65	60	50	55	50	70	60
D.S. W/ANCHOR	100	50	65	80	65	85	90	N/A	80	N/A	70	90	85
*SHEET PILE***	30	25	N/A	25	45	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
DIAPHRAGM	30	70	100	100	90	40	45	50	45	40	35	40	55

Table 3.21 Continued

MAXIMUM WALL HEIGHT (ft.)	CALCULATION OF NOMINAL VALUES				
	MAX	**MIN**	**AVERAGE**	**STD. DEV**	**DEVIATION (%)**
MSE	60	40	**48**	6.7	14%
CIP	35	20	**25**	4.5	17%
GRAVITY	10	5	**8**	1.8	23%
*GABION***	40	10	**25**	15.3	57%**
WIRE MESH	50	15	**30**	9.4	37%
NAILED	80	30	**42**	13.7	33%
TIE BACK	100	50	**64**	13.1	20%
D.S. W/O ANCHOR	70	25	**51**	12.6	25%
D.S. W/ANCHOR	100	50	**78**	14.4	18%
*SHEET PILE***	45	25	**31**	9.5	30%**
DIAPHRAGM	100	30	**57**	24.8	44%

*(**not to be considered in the selection model)*

As identified for the unit costs and production rates, a substantial variability is observed among the different values obtained from the interviews and surveys. Previous experiences and specific project factors have a great effect in the limitation of the economic feasibility of a certain wall type. The values shown in the average column are selected for use in the selection model presented in Section 4.

Chapter 4

Results

Based on all the information collected and analyzed in Chapters 2 and 3, the Retaining Wall Selection Model (RWSM) is developed and presented in Section 4.2 and Appendix C. Additionally, as defined in Section 1.3, one of the main objectives of this Thesis is to develop a database of information regarding retaining walls.

In order to provide a better organized set of information, the different sections of Chapter 3 served as the most appropriate location to present the findings for the development of the retaining wall database.

Section 1.3 defined the objectives of the present Thesis. The results for some of these were already included in previous sections as indicated below:

- Analyze the currently available retaining wall types in civil construction, identifying their applicability, advantages and disadvantages →Results included in Section 2.2
- Identify the main types of walls for heavy civil construction and transportation projects based on the previous analysis → Results included in Section 2.2
- Collect accurate information regarding cost and production rates by performing observations, research, interviews and surveys that can serve as a starting point for retaining wall selection and preliminary studies, therefore developing a database of retaining wall information → Results included in Section 3.1, 3.2, 3.3 and 3.4.
- Develop a comprehensive database that provides adequate information for use in preliminary studies and for the determination of the most suitable wall type for a certain project needs, including limiting heights, unit costs and production rates → Results included in Section 3.1 to 3.5 and 4.1.
- Develop a set of guidelines for retaining wall selection based on a given set of constraints, by constructing a sequential decision model based on a flowchart structure → Results included in Section 4.2.

4.1 Retaining Wall Database

The retaining wall database has been included and analyzed in previous sections 2.2, 3.5.1, 3.5.2 and 3.5.3, particularly as shown Tables 3.12, 3.12, 3.16, 3.18, 3.20 and 3.21, which summarize the information collected by the field observations, literature review, interviews and surveys to the selected expert subjects. This database can be used as a comprehensive guideline to determine those typical values to assume for preliminary studies and comparisons. Its main parameters are included below for convenience in future references.

Table 4.1. Table of typical values of height, unit cost and production rates for the wall types used in the RWSM

	TYPICAL UNIT COST ($/SF.)	TYPICAL PRODUCTION RATE (SF./day)	MAXIMUM WALL HEIGHT (ft.)
CAST IN PLACE	**70**	**600**	**25**
DRILL SHAFT W/O TIE BACK	**85**	**350**	**51**
DRILL SHAFT W/ TIE BACK	**120**	**320**	**78**
TIE BACK	**90**	**425**	**64**
NAILED	**77**	**550**	**42**
DIAPHRAGM	**75**	**320**	**57**
WIRE MESH	**40**	**850**	**30**
MSE	**55**	**1,200**	**48**

The data collection phase presented in Section 3 concluded with the development of a database of retaining wall information. This included advantages, disadvantages, equipment and materials required, construction phases, unit costs, production rates, limiting heights, frequent construction issues and special features of each of the most used wall types.

These identified common construction problems can serve as a reference when developing the Quality Control/Quality Assurance Programs required before the commencement of the wall construction operations. Only by the implementation of a comprehensive target-oriented QC/QA plan, a successful long-term performance of the retaining wall can be achieved. A summary of the most frequent issues encountered during the construction of the different walls analyzed is included in Table 4.2.

Table 4.2. Table of typical construction issues for the different types of retaining wall for implementation in QC/QA plans

CIP	Formwork blowouts, incorrect rebar placement, construction joints	Unforeseen boulders, out of plumbness, excessively reused sheets	Water infiltration, boulders that difficult the driving processes and failing bulk heads
DRILL SHAFT	Differing soil, soil/water intrusions, honeycombing due to no use of tremie tubes	Incorrect joint execution and water intrusions, insufficient slurry filtering and rebar cage collapses	Oversized cages being lifted and moved before introduction in excavated panels. Plumbness
MSE	Backfill wash, strap corrosion, damage to facing	Plumbness, backfill washing and damage to fabric that leads to washing	Lack of proper drainage, filter between rock and select fill (washout) and damaged wires.
TIE BACK	Damage to corrosion measures, inclination, insufficient bond length. Incorrect stressing and locking operations	Deviation from angle of inclination and length, lack of proper proof/performance testing, lack of sacrificial testing to verify design	Damages to the corrosion protection, incorrect centralizers placement, deviations from inclination/length.
NAILED	Incorrect geometry of tie back, low-quality grout and improper corrosion protection	Insufficient testing, lack of control of actual soil and insufficient nail bonded length. Improper locking processes	Damages to the corrosion protection, incorrect centralizers placement, deviations from inclination/angle/length.
SHEET PILE	Water infiltration, unforeseen boulders that difficult the driving processes and failing bulk heads/anchors	Unforeseen boulders, out of plumbness.	Excessively reused sheets
DIAPHRAGM	Collapse of cage, incorrect joints and water level modification (subsidence). Plumbness	Incorrect joint execution and water intrusions, insufficient slurry filtering and rebar cage collapses, soil intrusions due to no use of tremie tubes and excess of sand in slurry	Similar to drill shafts, with the specific concerns of oversized cages being lifted and moved before introduction in excavated panels
WIRE MESH	Ripped fabric, incorrect aggregate distribution and excessive lift thickness	Plumbness, backfill washing and damage to fabric	Lack of proper drainage, lack of the required filter fabric between rock and selected fill (then material washout occurs) and damaged wires.
GRAVITY	Improper vibration, construction joints and formwork blowouts. Improper subgrade preparation	Improper concrete vibration, excessive concrete free fall and segregation. Excessive concreting speed and incorrect subgrade preparation	Improper concrete practices with excessive free fall, out of plumb or improperly supported lateral formwork
GABION	Low quality aggregate, incorrect placement, plumbness	Improperly prepared subgrade, incorrect connection between baskets, damage to wires	Damage to wire baskets, out of plumbness and use of rock subject to weathering

4.2 Retaining Wall Selection Model (RWSM)

The most adequate approach to determine an optimum retaining wall type for a given set of constraints is not equal in every case. The particular features of each case need to be accounted for and therefore, specific approaches are built into the model for the different scenarios that can occur. For these circumstances, those parameters that can help discarding non-adequate walls are used first.

4.2.1 Structure of the RWSM

The RWSM model developed in the present Thesis was based on two premises, ease of use and concise results. Although the RWSM does not intend to provide detailed parameters of the selected wall, the associated database included in Chapter 3 can provide additional information regarding typical unit costs, production rates or construction issues. Although quick and simple, the developed model can return the most suitable wall for a given set of constraints with 4 parameters, which reduces the cost and time required to obtaining detailed data during the preliminary studies phase of any given project.

It is necessary to emphasize the relevance of the wall direction of construction and height. These two parameters resulted as driving factors in every potential scenario developed during the model validation. Therefore, the RWSM incorporated these two parameters as the initial steps in order to discard those walls not adequate for the given data. Moreover, in some cases, additional information such as the maximum unit cost or the required production rate are not required by the model in order to return the most adequate (or “last one standing”) retaining wall type. It is in these scenarios where additional project control measures are required to achieve the required results, such as increasing the number of crews to obtain a certain production rate in excess of the wall typical value.

As discussed in Section 3.2.5.1, the interviews and surveys performed with expert subjects showed an almost general agreement in regards to the gabion and sheet walls. 95% of the consulted engineers responded that these two types of walls would not be considered as a potential solution for a permanent retaining wall to be constructed in a transportation project and therefore these two types will not be considered as potential options for use in the model.

The decision parameters to be used in each type of wall are not necessarily the same and therefore a specific analysis is performed in order to determine the ones that drive the selection in each case. The wall types used in the RWSM are cantilever, gravity, MSE, wire mesh, drill shafts with and without anchors, diaphragm, tie backs and nails.

4.2.2 Determination of the selection drivers and decision parameters

Not all scenarios require of the same number of input parameters and type of known information in order to select the most appropriate type of retaining wall. Most potential sets of input information can be resolved by the model with three or four steps. The additional information collected followed the aforementioned objective of developing a retaining wall database.

Through the analysis of the required direction of construction, wall height, type of soil, available lateral space, presence of groundwater, availability of certain materials and/or equipment, production rate and aesthetic requirements, all potential scenarios can be resolved.

For those cases where all given parameters have been evaluated but more than one type of wall remain unit cost and production requirements needed to be considered.

In order to develop the model with the most critical driving factors, an analysis of the information collected from the literature, surveys and interviews was performed to identify them. These main drivers for each type of wall are included in Table 4.3 below:

Table 4.3. Selection Drivers for each direction of construction

UPWARD CONSTRUCTION	**DOWNWARD CONSTRUCTION**
WALL HEIGHT	HEIGHT
LATERAL SPACE	GROUNDWATER PRESENCE
AVAILABILITY OF FORMS	NEED TO PERMIT GROUNDWATER FLOW
CONCRETE SUPPLY	LATERAL LOAD
AESTHETIC REQUIREMENTS	ROCK OR SOIL IN WALL FACE
POTENTIAL FOR FLOODING	POTENTIAL FOR ANCHOR BOND
PRODUCTION RATE	PRODUCTION RATE
UNIT COST	UNIT COST

The process followed in the RWSM is equal for all scenarios until the third decision parameter. Direction of construction and wall height serve as the first two filters that select only the feasible options for the required wall configuration and geometry. The longest of the model's "branches" was able to converge with just four separate iterations, equaling to four different decision parameters being required.

Although certain walls are technically feasible under some conditions, the information obtained from the different data collection phases has been used in order to select the most appropriate options.

For example, tie back walls can be constructed in areas with presence of groundwater, but the complications for the design, construction and long term performance make them a less appropriate solution than a drill shaft wall.

4.2.3 RWSM Development and Implementation into Flowchart Model

Based on the literature review and the findings of the preliminary survey performed to construction professionals, it was determined that the model needed to be concise and easy to use. Thus, it was decided that a flowchart structure would be the most appropriate approach to develop the RWSM.

The conditions and typical parameters presented in previous sections 4.1 and 4.2.2 are built into the model following a cascade approach where by successive comparisons, only the most adequate wall type for the given set of conditions remain.

The Imperialistic Chaotic Algorithm (ICA) developed by Poubarba (2012) is used as a baseline for the development of the RWSM. All the potential combinations for each set of constraints are applied to the different types of retaining walls that can fit the requirements until only one remains (i.e. Imperium).

As previously described in Section 4.2.2, direction of construction and wall height are in every case used as the first two decision parameters considered by the RWSM. Although the number of options that are discarded by the use of these two parameters varies in each scenario, they result highly appropriate to set the base and simplify next model steps.

The developed model is a combination of a sequence of comparisons between the different applicable walls types along with a knowledge-based sequence of decision parameters to discard those options that do not fit the required filter for each model step.

The model follows the reasoning process from general to detail, using first the decision parameters that discard a higher number of alternatives but maintaining the different options open until a “no-go” condition appears for a certain type of wall. Each step of the model causes the elimination of at least one potentially used retaining wall type.

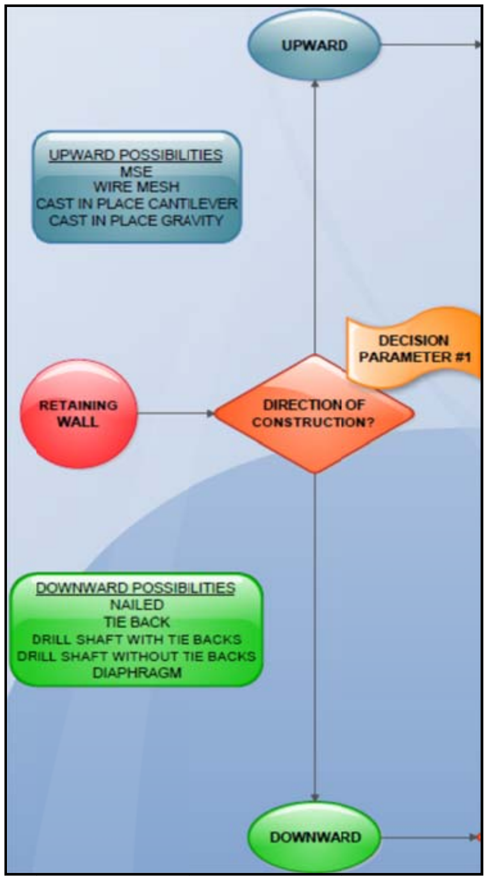


Figure 4-1 Detail of the two initial steps of the RWSM

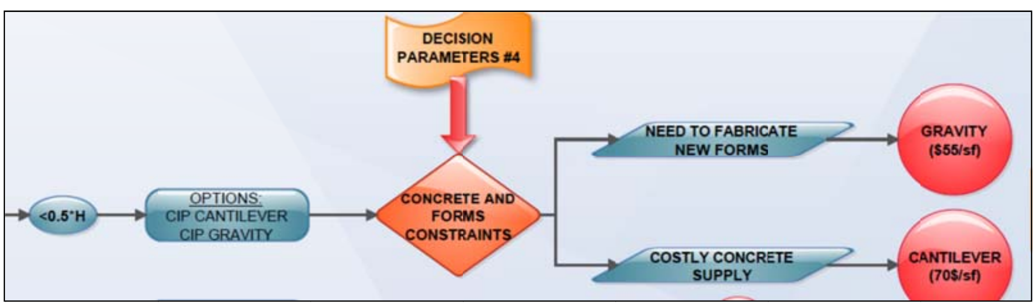


Figure 4-2 Detail of one section of the selection model for determination of upward wall <10 ft

A specific color coding was selected to facilitate the understanding and use of the RWSM different steps. All upward construction walls were included in the upper section in color blue, being the downward ones in the lower one and in green labels for the entire RWSM process. Additionally, the final solutions when the model converges into a single wall type are marked as circular red labels. The different decision parameters are marked as triangular orange labels. This criteria is constant throughout the different model combinations.

An important finding was identified once the model was complete and all scenarios were evaluated. This was the lack of actual influence of the unit cost during the selection process. Most of the different scenarios built into the model for the comparison of the potentially selected walls did not require using unit costs. Just by considering geometrical, geotechnical and logistic constraints, the model is able to converge to one single solution in most cases. The unit cost for each solution is displayed in the model to support the decision returned.

The model incorporates certain assumptions in order to select the most adequate wall type for each scenario. However, certain situations might require different approaches or solutions. Additional information is provided at the end of each "model branch" as Notes where important facts are presented for the different cases of decision making. For example, for upward walls at low heights, cantilever and gravity walls result more appropriate in terms of unit cost and ease of construction. Although MSE and Wire mesh walls can also be used, the model does not consider them as a potential solution. These additional details are included as notes at the end of the decision process that converges to cantilever and gravity walls as shown in Figure 4.3.

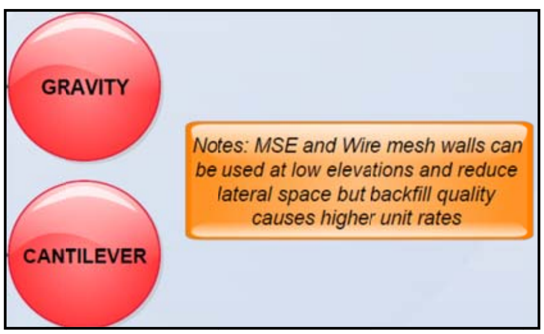


Figure 4-3 Detail of additional notes in the selection model for upward wall <10 ft

The model is capped in the upper end of the retaining walls height both for the upward and downward directions of construction. The values used to draw the separation point between walls and bridge/tunnel were obtained during the interview process presented in Section 3.3.2. Although certain walls are technically possible for upward heights over 50 ft. and downward over 100 ft., the design and construction complications make them less adequate solutions.

The completed Retaining Wall Selection Model (RWSM) is included in Appendix C. The model was verified and validated by means of comparison with the Known Walls presented in Section 2.2.5 and the decisions of two selected experts when asked about two potential wall needs.

Chapter 5

Discussion of Results

The two main outcomes of the present Thesis were the development of a retaining wall database and a selection model. Any engineering development needs to be verified against known solutions, potential problems and/or the judgment of expert matter subjects.

The database was evaluated for completeness and adequacy for use in future retaining wall projects, including the results in Section 5.1. An analysis was required to determine the potential weaknesses of it, as well as those considerations that are required to be taken into account when selecting the values presented in it.

Additionally, once the Retaining Wall Selection Model (RWSM) was complete, verification and validation was required to ensure its proper performance when real cases were to be resolved. Thus, two separate approaches were developed as defined in Sections 5.2 and 5.3.

5.1 Analysis of the Retaining Wall Database

Different specific considerations apply to the database presented in previous Chapters 3 and 4. This was developed by obtaining information from experts subjects and heavy civil projects in the DFW area. Although the multinational background of the recipients of the surveys and interviews provided a wider scope, the field observations and unit costs were restricted to different projects in the DFW area and the first half of year 2014.

Additionally, the observations were performed during variable times spanning from five working days in the case of the MSE wall up to a month for the drill shaft wall. This observation periods do not completely take into account the variation of the different production drivers such as weather, worker morale, learning curves, material supply, market conditions, etc. However, the presented values can serve as a reliable starting points, as evidenced by the responses retrieved during the interview and survey processes. The experts provided typical unit costs similar to the ones calculated during the Observation process. This comparison is included in Section 3.5.3 and specifically in Table 3.19.

Unit costs vary greatly depending on the geographical area, and the current market conditions. Hence, the use of the presented values in a different state or time would require an adjustment by the appropriate factors. The adjustment values included in the RS Means construction books are the most commonly used approach in the US.

DIVISION		TEXAS											
		BRYAN			CHILDRESS			CORPUS CHRISTI			DALLAS		
		MAT.	INST.	TOTAL	MAT.	INST.	TOTAL	MAT.	INST.	TOTAL	MAT.	INST.	TOTAL
015433	CONTRACTOR EQUIPMENT		90.1	90.1		89.4	89.4		96.1	96.1		99.0	99.0
0241, 31 - 34	SITE & INFRASTRUCTURE, DEMOLITION	78.4	88.6	85.6	104.1	86.5	91.7	142.0	82.7	100.4	105.3	88.3	93.4
0310	Concrete Forming & Accessories	82.5	41.0	46.6	94.9	60.5	65.1	98.6	37.5	45.7	96.8	64.4	68.8
0320	Concrete Reinforcing	89.5	48.3	68.9	90.3	48.7	69.6	83.8	46.7	65.3	96.2	51.7	74.0
0330	Cast-in-Place Concrete	67.2	65.2	66.4	99.7	49.5	79.1	109.2	45.6	83.0	96.5	55.7	79.7
03	CONCRETE	79.0	51.9	65.7	105.6	55.1	80.7	99.6	43.9	72.1	99.2	60.4	80.0
04	MASONRY	140.6	56.5	89.2	107.9	50.7	73.0	90.9	48.5	65.0	102.3	57.8	75.1
05	METALS	96.5	67.4	87.4	97.0	63.8	86.6	94.4	75.1	88.3	102.0	79.6	94.9
06	WOOD, PLASTICS & COMPOSITES	80.4	34.3	54.1	101.1	65.4	80.7	118.8	36.7	71.9	100.1	67.7	81.6
07	THERMAL & MOISTURE PROTECTION	95.0	56.0	79.3	99.0	49.4	79.0	98.9	45.3	77.3	94.1	63.2	81.7
08	OPENINGS	101.2	42.4	86.9	89.8	55.0	81.3	104.5	38.0	88.3	100.3	58.3	90.1
0920	Plaster & Gypsum Board	81.2	32.8	47.4	82.1	64.9	70.1	86.0	35.1	50.4	93.2	67.0	74.9
0950, 0980	Ceilings & Acoustic Treatment	88.2	32.8	51.3	88.2	64.9	72.7	92.9	35.1	54.4	95.3	67.0	76.5
0960	Flooring	79.9	54.6	72.4	107.1	42.4	87.8	107.6	65.4	95.0	98.3	49.5	83.8
0970, 0990	Wall Finishes & Painting/Coating	88.8	61.9	72.7	99.1	39.5	63.4	115.5	59.0	81.6	105.5	52.7	73.9
09	FINISHES	78.5	43.9	59.1	94.9	56.0	73.1	100.4	44.3	69.0	97.6	60.9	77.0
COVERS	DIVS. 10 - 14, 25, 28, 41, 43, 44, 46	100.0	79.0	95.7	100.0	70.7	94.0	100.0	77.3	95.4	100.0	82.4	96.4
21, 22, 23	FIRE SUPPRESSION, PLUMBING & HVAC	94.1	66.2	82.7	94.3	51.8	76.9	100.1	39.4	75.3	99.9	63.3	84.9
26, 27, 3370	ELECTRICAL, COMMUNICATIONS & UTIL.	92.0	68.6	79.7	96.5	44.2	69.0	92.6	53.7	72.1	93.5	66.3	79.2
MF2010	WEIGHTED AVERAGE	94.5	61.6	80.0	97.5	56.5	79.4	99.7	51.7	78.6	99.5	66.5	85.0

Figure 5-1 RS Means City Cost Index Year 2013 (R.S. Means Company, Inc. (2013)

A project specific analysis is required to adequate the values presented to the constraints of each location and need. There are several factors to be accounted for. The list presented in Section 2.2 based on the work of Murawski (2001) and Chong (2005) can be used for that purpose:

- Uniqueness of Projects
- Labor
- Varied Locations.
- Dependence on the Economy
- Weather and Seasonality
- Risk of Worker Accidents
- Disruptions and material supply
- Traffic and accessibility
- Advancement in technology
- Effect of learning curves

The potential variation in the Ownership and Operating costs is also required to be considered for the use of the presented unit costs. To reduce this variability, subcontractor rates were used to develop the unit costs during the Observations included in Section 3.5. The development of unit costs is highly impacted for the particular constraints of each company in terms of depreciation, age of equipment and material contracts. Only an extended analysis based on detailed and accurate record-keeping can provide reliable results for each company set of constraints.

The companies used for the development of these unit costs and production rates are expert specialized corporations that bring years of experience in several projects and therefore, the potential variability for unforeseen conditions is built into the presented rates. Actual unit costs in the heavy civil projects where subcontractors are used are dependent in the unit rates included in their bids rather than the general contractor ownership and operating costs.

The database developed does not just include cost and production values. Additional information is included for use when evaluating different potential solutions for an specific retaining wall need. Advantages and disadvantages for each type of wall are included to allow a comparative analysis to be performed. Additionally, the equipment, materials and construction phases required for the construction of each type are detailed, including general Specification references for the standards that are generally required by the industry.

Height limitation is commonly the driving factor when determining the retaining wall to be used in an specific location. Typical values are included in Sections 3.5 and 4.1 based on the information obtained from the limited references identified for this topic and the interviews and surveys performed.

The database created incorporates a variety of useful information to determine the most adequate retaining wall for a certain project as well as provides additional considerations for the development of preliminary budget and schedule.

Retaining wall are complicated structures that commonly show defects and unsatisfactory performance in a short term period when construction is not performed properly. Therefore, a comprehensive preventatively-targeted Quality Control and Quality Assurance (QA/QC) is required to be implemented prior to the commencement of the construction activities. The most frequent construction issues identified during the expert interviews presented in Table 3.18 could be used to establish the required inspection and testing measures to avoid their occurrence. These recurrent construction issues are also included in Table 4.2, under Section 4.1 for convenient reference.

None of the more than 80 references consulted during the literature review included information in reference to unit costs and production rates for the construction of retaining walls. Additionally, the information in regards to the equipment, materials and construction issues is commonly restricted to private companies records and is rarely disclosed for public use. The presented database includes a detailed compilation of data to help fill the void identified among the literature references.

5.2 Validation of the Retaining Wall Selection Model (RWSM)

Retaining wall selection cannot be analytically verified. However, only by comparison with known solutions and expert judgment, the developed model can be checked and validated. Thus, a two-phase approach is designed for the validation of the RWSM detailed in Section 4.2.

First, the four known walls analyzed in Section 2.2.5 are used here as potential needs to be evaluated by using the RWSM. Thus, the input parameters for each known wall will be used as the starting point for the model, comparing the solutions obtained from it against the actual wall types that were constructed in the field to evaluate and validate the model's performance.

Secondly, the experts consulted in Interview #1 and Survey #1 were asked to determine the most adequate retaining wall for a determined set of constraints. The wall types deemed most appropriate by the experts were verified against the solutions obtained from the model to evaluate and validate its performance.

5.2.1 Model Validation by use of 4 Known Walls

The constraints that were identified during the data collection campaign for each one of the known walls are used as input in the RWSM. The results of the validation performed are included in the next sections.

5.2.1.1 Known Wall #1 Verification

The constraints identified for Wall #1 are listed below:

- Upward
- Maximum Height 15 feet
- Lateral Space available <0.7*H
- <u>DESIGNED CONFIGURATION: Cast-in-place Cantilever Wall</u>

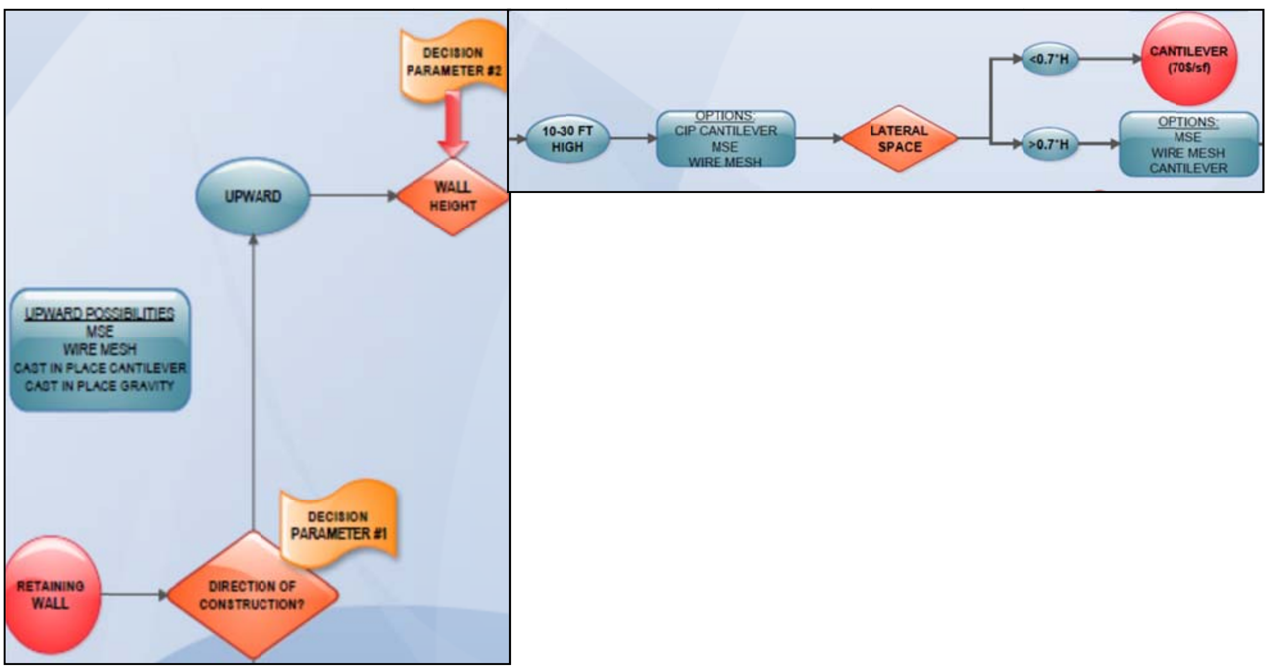


Figure 5-2 Model Validation for Known Wall #1

As can be observed in Figure 4.5 above, just by the use of the height, lateral space restriction and direction of construction, the RWSM is able to return the solution of the actual wall that was constructed in the field as deemed most appropriate by the wall designers.

5.2.1.2 Known Wall #2 Verification:

The constraints identified for Wall #2 are listed below:

- Downward
- Maximum Height 32 feet
- Tan and Grey Limestone in Wall face
- No groundwater identified in geotechnical report
- No lateral load, roadway retention
- <u>DESIGNED CONFIGURATION: Rock Nail Wall</u>

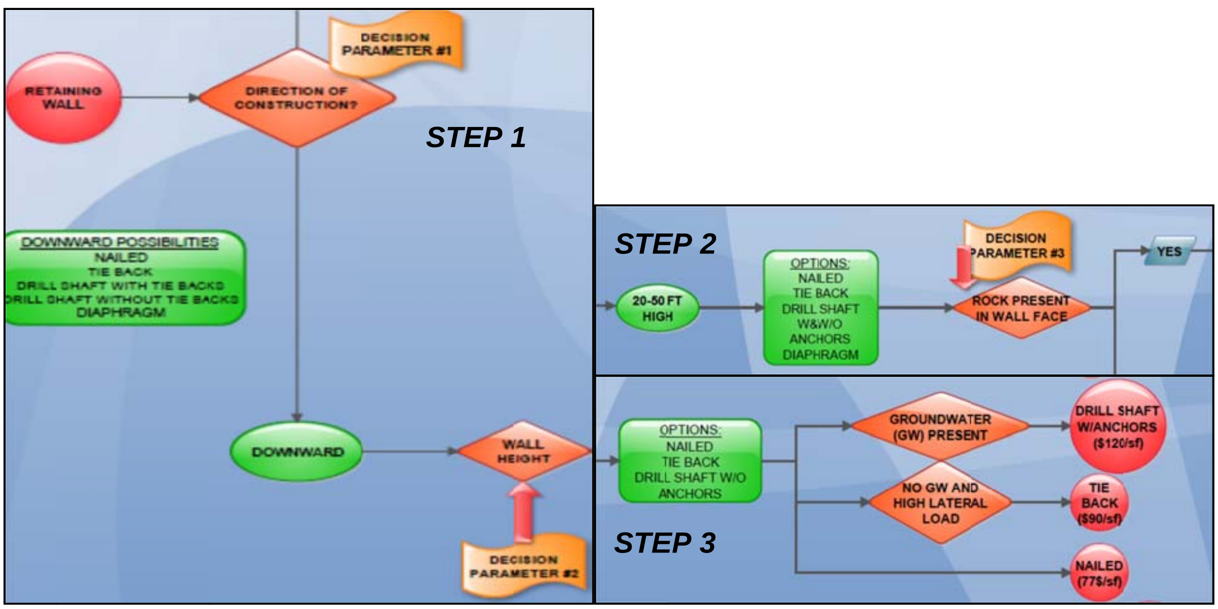


Figure 5-3 Model Validation for Known Wall #2

As can be observed in Figure 4.6 above, just by the use of the height, direction of construction, geotechnical and loading parameters the RWSM is able to return the solution of the actual wall that was constructed in the field as deemed most appropriate by the original designers.

5.2.1.3 Known Wall #3 Verification:

The constraints identified for Wall #3 are listed below:

- Downward
- Maximum Height 32 feet
- Shaley Clay and Weathered Shale in Wall face.
- Groundwater identified in geotechnical report
- Nearby structures, need to avoid phreatic modifications
- No lateral load, roadway retention
- DESIGNED CONFIGURATION: Drill Shaft with Anchors Wall

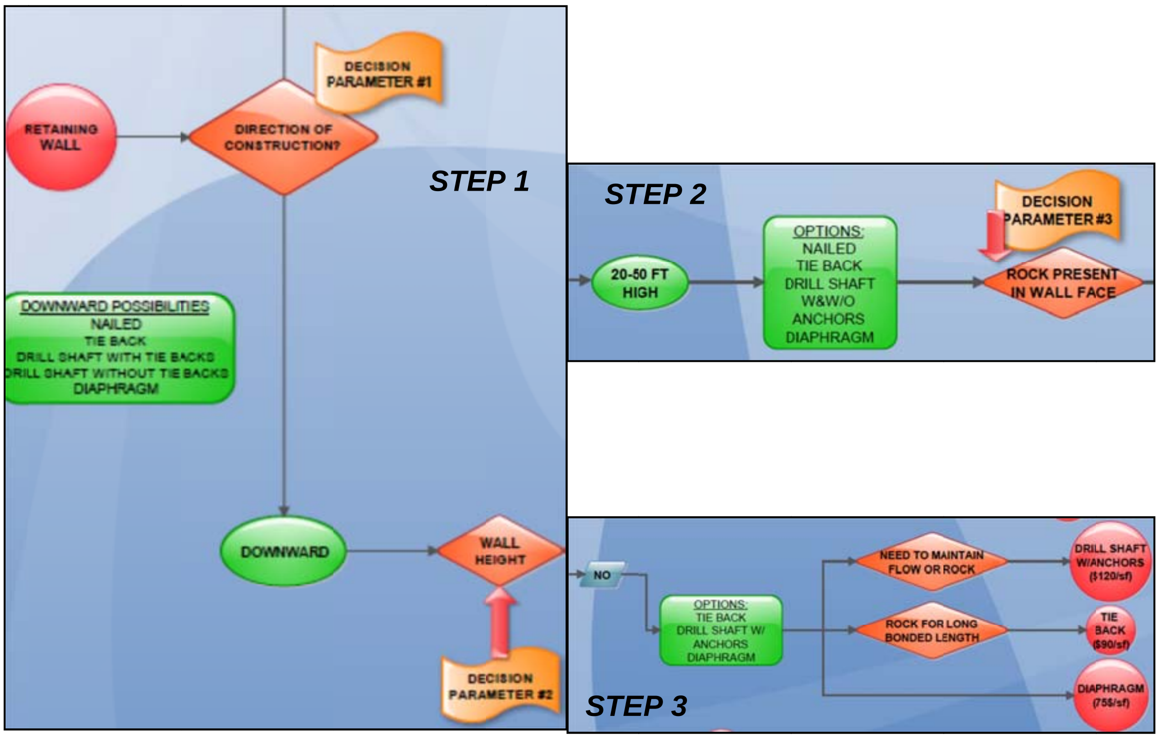


Figure 5-4 Model Validation for Known Wall #3

As can be observed in Figure 4.7 above, just by the use of the height, direction of construction, wall location, geotechnical and loading parameters the RWSM is able to return the solution of the actual wall that was constructed in the field as deemed most appropriate by the original designers.

5.2.1.4 Known Wall #4 Verification:

The constraints identified for Wall #4 are listed below:

- Upward
- Maximum Height 12 feet

- Lateral Space available >0.7*H
- Inside 100-yr Flooding area
- Aesthetics required
- DESIGNED CONFIGURATION: Mechanically Stabilized Earth

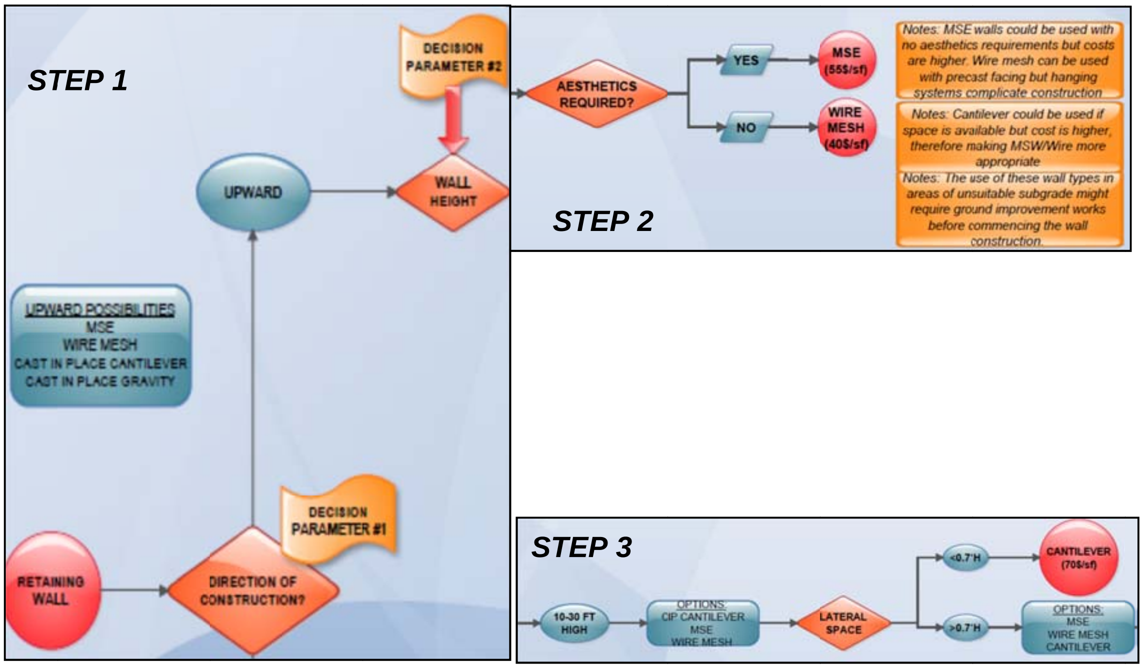


Figure 5-5 Model Validation for Known Wall #4

As can be observed in Figure 4.8 above, just by the use of the height, lateral space restriction and direction of construction, the RWSM is able to return the solution of the actual wall that was constructed in the field as deemed most appropriate by the designers.

5.2.2 Model Validation by use of expert's judgment

Retaining wall selection is an experience-based decision process that can only be approached by comparison with previous successful detailed designs. In order to perform a second validation of the RWSM, the experts that participated in Interview #1 and Survey #1 were again consulted. Each one of the experts was asked to determine the most adequate type of retaining wall when faced with a given set of constraints.

Since the RWSM is based on information collected from literature, surveys, interviews and field observations, it is the intention of this second validation to prove that the model can recreate the reasoning performed by subjects with years of experience in wall design and construction.

Expert from Interview #1 was requested to determine the most adequate retaining wall for the following set of constraints:

- Upward construction
- Maximum height 25 ft

The expert requested additional information by means of two additional questions:

- Speed of construction required? 1150 SF/day.
- Is it permanent construction? Yes.

The expert concluded that the most adequate retaining wall would be an MSE Wall because in his experience, wire mesh walls present a slightly higher rate of long-term issues, mostly related to drainage measures.

The expert selection is compared with the results of the RWSM when the same criteria are used as input. The results are shown in Figure 4.8 as the example returns the same wall than the validation performed for Known Wall #4. As shown in Figure 4.8, the RWSM is able to converge to the same solution than the expert that participated in Interview #1.

Expert from Survey #1 was requested to determine the most adequate retaining wall for the following set of constraints:

- Downward construction
- Maximum height 40 ft

The expert requested additional information by means of three additional questions:

- What type of material is present at the wall face? Unweathered rock
- Is it permanent construction? Yes
- Is there groundwater behind the wall face? No

The expert concluded that the most adequate retaining wall would be a Rock Nail Wall because of their lower unit cost and increased production rates. The expert mentioned that if groundwater was present or the lateral loading was of critical importance, a drill shaft or diaphragm retaining wall would have been selected.

The expert selection is compared with the results of the RWSM when the same criteria are used as input. The results are shown below:

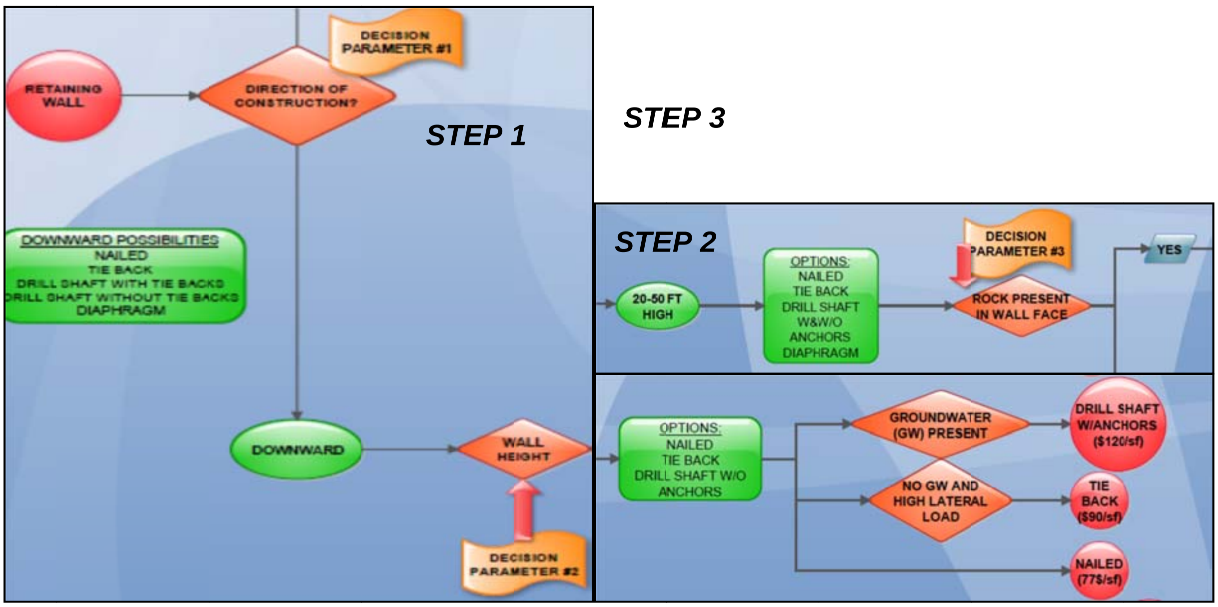


Figure 5-6 Model Validation for Expert from Survey #1

As shown above, the RWSM is able to converge to the same solution than the expert that participated in Survey #1.

5.2.3 Summary of the RWSM Validation process

As evidenced by the two different methods included in previous sections 5.2.1 and 5.2.2, the RWSM is validated against real-world solutions for four existing walls and the judgment of two experienced professionals.

These two validations provide the required confidence level in the RWSM for its use in preliminary studies and wall selection. As evidenced by these validation processes, the information required by the model to converge is small, and commonly occurs within 3 or 4 steps.

5.3 Analysis and Evaluation of the Retaining Wall Selection Model (RWSM)

Once the model was validated by the aforementioned two phase approach as detailed in Sections 5.2.1 and 5.2.2, a final analysis and evaluation is performed.

Although limiting for some of the options and the multivariable analysis required, the graphical approach implemented in the RWSM constitutes a quick tool that enables easy analysis and decision processes for engineers of all levels of experience.

The model is based on general parameters and constraints, project specific restrictions are not considered and therefore an individual analysis is required to account for them. For example, one of the “no-go” factors identified during the interview process for anchored/nailed walls was the restrictions regarding subsurface ROW. If a downward wall higher than 50 feet is required in existing soil where ROW prevents the use of anchors, highly specialized solutions would be required, and these would be outside the scope of the RWSM.

It was identified that the influence of the unit cost during the selection process is very limited. Just by considering geometrical, geotechnical and logistic constraints, the model is able to converge to one single solution in the majority of the cases. The only exception is the *“Cantilever Vs. MSE Vs. Wire for less than 10 ft. with availability of lateral space”* where the lower unit cost for the wire mesh wall determined its selection. Similarly, the production rates developed during the data collection phase have a limited affection in the selection process.

The model successfully converged to equal solutions in the six validation cases presented in Sections 5.2.1 and 5.2.2. Therefore, it is concluded that the model can be useful for real-world wall determination. The validation performed to the two subject experts showed that the model was able to replicate the reasoning process performed by them to determine the most suitable type of retaining wall.

The model is particularly based in three parameters. These are direction of construction, height and soil type. The determination of these project constraints enable the reduction of the potential wall types to just one or two solutions.

Chapter 6

Conclusions and Recommendations for Future Research

6.1 Summary and Conclusions

In the present research, retaining wall selection processes have been investigated. Retaining Walls constitute one of the most important elements in most construction projects, therefore a proper decision process is key for the overall project outcome. Wall Selection has been traditionally performed by experience as reported by Hancher et al. (1992).

Chong (2005) showed that rather than relying on pure experience or improperly appraised historical records, a comprehensive research would lead to more accurate data and decision-making processes. Yang (2004) showed that some construction problems cannot be represented nor resolved with the use of conventional scientific algorithms, thus the need of different systems and approaches. Although experience-oriented problems represent a suitable alternative where solutions are obtained by previous experience solutions, Hess and Adams (1995) indicated that the majority of the engineers tend to restrict themselves to select retaining wall types that they have experience with.

These studies established the need of developing knowledge-based systems in order to better determine the most adequate solutions for the different project needs. Although previous research have attempted to develop knowledge-based models, no single reference has been identified to include factors as critical as direction of construction, unit costs and production rates as driving parameters for the selection process.

Existing literature in regards to retaining wall advantages and disadvantages, as well as the particular drivers for each wall type is limited, and in order to fill these gaps, the present research gathered additional information for use in the selection model.

The data collection campaign performed in the present Thesis consisted in a series of five field observations, five interviews and eight surveys to expert subjects undertaken to collect data in regards to retaining wall such as limiting factors, common construction issues, unit costs or production rates. This data was gathered with the literature references, author's previous experiences and known walls in order to develop a retaining wall database for use in both the selection model and future needs during preliminary studies.

Retaining Wall Database

A specific data collection campaign was developed to obtain the lacking data identified during the literature review. Five field observations in DFW transportation construction projects were performed to develop typical unit costs and productions for the most commonly used retaining wall types. Additionally, specially designed survey and interview forms were used with 13 expert subjects to obtain additional data for use in both the database and selection model.

In addition to unit costs and production rates, additional important data was collected in regards to factors for wall determination, areas where information lacks, limiting heights, groundwater affection, maintenance needs, selection drivers, common construction issues and rankings (in order of construction difficulty, unit costs and duration of construction). The common construction issues can be particularly useful for development of QA/QC programs to be implemented in construction as wall failure represent a recurrent issue in civil construction.

Retaining Wall Selection Model (RWSM)

Using the information collected in both the literature review, field observations, surveys and interviews, a Retaining Wall Selection Model (RWSM was developed. The critical driving factors for each type of wall, as well as those "no-go" parameters that determine the non-adequacy under certain conditions were identified.

An Imperialistic Chaotic model following the research of Poubarba (2012) was developed. For a certain condition, the different potential solutions are compared to determine the most adequate solution. The remaining "empire" (wall) after the sequence of comparisons is selected as the optimum solution for the set of constraints used as model input.

The interviews and surveys performed with expert subjects showed a general agreement in regards to the gabion and sheet walls. 95% of the consulted engineers responded that these two types of walls would not be considered as a potential solution for a permanent retaining wall to be constructed in a transportation project and therefore these two types were not be considered as potential options for use in the model.

The RWSM is implemented in a graphical flowchart framework that return quick solutions in cases where limited information is available. The model is validated in a two-phase approach. First, four known walls were used as real-world model evaluations where these wall's constraints were used as input for the model, where all solutions returned matching the wall types constructed in the four cases. Additionally, two experts from the interview and survey data collection phases were selected to determine the most adequate wall type for a given set of conditions. The model was able to replicate the reasoning process and yield same wall types than the ones concluded by the experts.

It was identified that the influence of the unit cost during the selection process was very limited. Just by considering geometrical, geotechnical and logistic constraints, the model is able to converge to one single solution in the majority of the cases.

The final results of this research were the development of a retaining wall database and the Retaining Wall Selection Model (RWSM). These can be used as a starting point to determine the most suitable permanent retaining wall for a given set of conditions.

The model can also result highly useful as a selection tool during preliminary and feasibility studies where the information is limited. Only by the identification of few driving factors, the model is able to return one single optimum retaining wall type.

The presented database fills the gaps of data in regards to those considerations that are not commonly available in the existing references due to lack of research or commercial implications. This database is intended to allow engineers to perform preliminary cost estimations, duration calculations and wall comparisons in initial phases of construction projects.

6.2 Recommendations for Future Research

The following recommendations are presented for future studies in regards to the retaining wall types, costs, production rates, applicability and development of selection models.

1. Analyze each one of the retaining walls by different height ranges, determining their typical costs and production rates for each. Incorporate the influence of the wall height in the unit costs and production rates to develop a database that can accurately represent a wider spectrum of projects.
2. Analyze the influence of different geotechnical parameters in the unit costs of each type of wall. For example by determining the unit cost of MSE Vs. internal friction angle of the backfill for several different combinations to determine a correlation.
3. Perform extended observations for several walls of the same type to better address the project specific variability in unit costs and production rates. Include geosynthetic reinforcement for the MSE Walls in addition to metallic straps.
4. Develop a more detailed unit cost database, incorporating actual Ownership & Operating costs for the different equipment involved, to reduce the dependence in companies' costs presented.
5. Extend the interviews and surveys campaign to personnel in smaller size projects, as well as State Engineers, to develop a wider scope and more representative data pool to develop both the database and the selection model. Analyze the impact of the respondent's role in the responses obtained.
6. Implement the selection model into an easy-to-use programming language platform such as Visual Basic® or Macro®, for web-based applications. A series of drop-down menus in a cascade selection process appears to be a promising solution.
7. Incorporate studies in unit costs and production rates from different geographical areas to address the variability in costs, construction processes, weather, availability of materials, equipment and labor, etc.

Appendix A

Abreviations used in this Thesis

ANOVA - Analysis Of Variance
ASCE – American Society of Civil Engineers
ASD – Allowable Strength Design
ASTM – American Society for Testing and Materials
CASTLES - Case-Based Retaining Wall Selection System
CIP – Cast in Place
D.S. – Drill Shaft
DFW – Dallas-Fort Worth
DMS – Departamental Material Specifications
EMS – Environmental Management System
ES – Expert System
FHWA – Federal Highway Administration
ICA – Imperialistic Chaotic Algorithm
KBES - Knowledge Based Expert System
LBJ – Lyndon Baines Johnson
LRFD – Load and Resistance Factor Design
MSE – Mechanically Stabilized Earth
OBS - Observation
OCEW – On Center Each Way
PTI – Post-Tensioning Institute
QC/QA – Quality Control and Quality Assurance
RBKS - Rule-Based Knowledge System
RI – Rule Induction
ROW – Right Of Way
RWSM – Retaining Wall Selection Model
RWSS - Retaining Wall Selection System
STD. DEV – Standard Deviation
TDOT – Tennessee Department of Transportation
TXDOT – Texas Department of Transportation
W/ - With
W/O - Without
WWM – Welded Wire Mesh

Appendix B

Completed Forms of Surveys performed to Expert Subjects during the data collection campaign

Survey Recipient: #1	Years of experience:
Position: Construction Manager	Date: 03/10/2014
Area of expertise: Heavy civil PPP Construction Management	Country where highest experience: Ireland/Chile
Please list the 3 main factors you consider when developing unit costs for retaining walls in general terms:	
Cost of materials involved in wall construction	
Design and monitoring costs	
Subcontractor availability	
Please list the 3 main factors you consider when developing production rates for retaining walls in general terms:	
Accessibility and readily available supply materials	
Need to waiting times (such as concrete/grout curing)	
Site specific constraints (schedule, conflicts, noise reduction, etc.).	
Please list the 3 main factors to consider when developing unit costs for retaining walls for the following types:	
o Cast in place = Presence of nearby batch plants, cost of reinforcing steel and formwork based on their complexity	o Sheet pile wall = I would not consider this wall
o Drill Shaft wall (w/o tie backs) =Cranes and rigging, cost of spoil disposal, availability of drilling subcontractors	o Diaphragm wall = Cost of reinforcement steel, subcontractor fees, cranes and rigging.
o Drill Shaft wall (w/ tie backs) = Combine above and below	o Wire mesh wall = Cost of backfill, proprietary systems cost, compaction
o Tie Back wall = Material cost, requirements for testing and stressing, availability of subcontractors	o MSE Wall = Precast panels cost, availability of selected backfill, accesses and supply complications
o Nailed wall =Material cost, grout supply or site mixing, availability of subcontractors	o Gabion wall = I would not consider this wall
What wall height would be the limit of economically feasible construction for these walls in your opinion?	
o Cast in place = 25 ft	o Sheet pile wall = I would not consider this wall
o Drill Shaft wall (w/o tie backs) = 60 ft	o Gravity Wall = 10 ft
o Drill Shaft wall (w/ tie backs) = 85 ft	o Wire mesh wall = 15 ft
o Tie Back wall = 65 ft	o MSE Wall = 40 ft
o Nailed wall = 35 ft	o Gabion wall = I would not consider this wall
Which typical unit cost do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 55$/SF.	o Sheet pile wall = I would not consider this
o Drill Shaft wall (w/o tie backs) = 80$/SF.	o Gravity Wall = 45$/SF.
o Drill Shaft wall (w/ tie backs) = 105 $/SF.	o Wire mesh wall = 40$/SF.
o Tie Back wall = 85$/SF.	o MSE Wall = 55$/SF.
o Nailed wall = 70$/SF.	o Gabion wall = I would not consider this

Which typical production rates do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 600 SF/day	o Sheet pile wall = I would not consider this wall
o Drill Shaft wall (w/o tie backs) = 350 SF/day	o Gravity Wall = 450 SF/day
o Drill Shaft wall (w/ tie backs) = 250 SF/day	o Wire mesh wall = 800 SF/day
o Tie Back wall = 450 $/SF.	o MSE Wall = 1150 SF/day
o Nailed wall = 625 SF/day	o Gabion wall = I would not consider this wall

Which 3 wall types would you recommend for remote areas where specialized workforce is limited?
MSE Walls
Soil/Rock Nails
Concrete cast in place walls

Survey Recipient: #2	Years of experience:
Position: Segment Construction Manager	Date: 03/11/2014
Area of expertise: Heavy civil PPP Construction	Country where highest experience: Ireland
Please list the 3 main factors you consider when developing unit costs for retaining walls in general terms:	
Auxiliary equipment required	
Potential use of existing crews and equipment	
Cost of materials required	
Please list the 3 main factors you consider when developing production rates for retaining walls in general terms:	
Possibility of continuous production and extended shifts	
Degree of specialization required by subcontractors	
Potential of conflict between different activities	
Please list the 3 main factors to consider when developing unit costs for retaining walls for the following types:	
o Cast in place = Availability of concrete, height and one/two face formwork required	o Sheet pile wall = I would not consider this wall
o Drill Shaft wall (w/o tie backs) = Type of soil, depth and clearance for cage introduction with normal methods	o Diaphragm wall = Depth, width of panels and type of joint/waterproofing required
o Drill Shaft wall (w/ tie backs) = Cost of materials, specialized subcontractors and phasing	o Wire mesh wall = Maximum basket height, width and requirements for backfill
o Tie Back wall = Need for monitoring, spacing of tie backs, availability of subcontractors	o MSE Wall = Requirements for selected fill and availability onsite, maximum backfill lift, length of straps
o Nailed wall = Spacing of nails, length and corrosion protection requirements	o Gabion wall = I would not consider this wall
What wall height would be the limit of economically feasible construction for these walls in your opinion?	
o Cast in place = 30 ft.	o Sheet pile wall = I would not consider this wall
o Drill Shaft wall (w/o tie backs) = 65 ft.	o Gravity Wall = 8 ft.
o Drill Shaft wall (w/ tie backs) = 90 ft.	o Wire mesh wall = 25 ft.
o Tie Back wall = 60 ft.	o MSE Wall = 50 ft.
o Nailed wall = 40 ft.	o Gabion wall = I would not consider this wall
Which typical unit cost do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 60$/SF.	o Sheet pile wall = I would not consider this wall
o Drill Shaft wall (w/o tie backs) = 90$/SF.	o Gravity Wall = 40$/SF.
o Drill Shaft wall (w/ tie backs) = 115 $/SF.	o Wire mesh wall = 40$/SF.
o Tie Back wall = 80$/SF.	o MSE Wall = 50$/SF.
o Nailed wall = 65$/SF.	o Gabion wall = I would not consider this wall

<table>
<tr><th colspan="2">Which typical production rates do you consider when performing preliminary analysis of these retaining wall types?</th></tr>
<tr><td>o Cast in place = 650 SF/day</td><td>o Sheet pile wall = I would not consider this wall</td></tr>
<tr><td>o Drill Shaft wall (w/o tie backs) = 450 SF/day</td><td>o Gravity Wall = 150 SF/day</td></tr>
<tr><td>o Drill Shaft wall (w/ tie backs) = 350 SF/day</td><td>o Wire mesh wall = 850 SF/day</td></tr>
<tr><td>o Tie Back wall = 500 $/SF.</td><td>o MSE Wall = 1250 SF/day</td></tr>
<tr><td>o Nailed wall = 700 SF/day</td><td>o Gabion wall = I would not consider this wall</td></tr>
<tr><th colspan="2">Which 3 wall types would you recommend for remote areas where specialized workforce is limited?</th></tr>
<tr><td colspan="2">Concrete cast in place</td></tr>
<tr><td colspan="2">MSE Wall</td></tr>
<tr><td colspan="2">Wire mesh wall</td></tr>
</table>

Survey Recipient: #3	Years of experience:
Position: Sub-Segment Construction Manager	Date: 03/10/2014
Area of expertise: Construction Management	Country where highest experience: Spain
Please list the 3 main factors you consider when developing unit costs for retaining walls in general terms:	
Anticipated delays due to weather and external affection	
Accessibility and space for storage	
Cost of subcontractors and suppliers	
Please list the 3 main factors you consider when developing production rates for retaining walls in general terms:	
Anticipated delays due to weather and external affection	
Accessibility and space for storage	
Potential for weekend work and double shifts	
Please list the 3 main factors to consider when developing unit costs for retaining walls for the following types:	
o Cast in place = Space available and need for shoring or traffic control	o Sheet pile wall = I have not encountered this for permanent construction in transportation projects
o Drill Shaft wall (w/o tie backs) = Cost of rebar cages, cost of drilling and type of soil to be drilled	o Diaphragm wall = I do not have experience with this type of wall
o Drill Shaft wall (w/ tie backs) = I do not have experience with this type of wall	o Wire mesh wall = Cost of fill and materials needed for wire and filter baskets
o Tie Back wall = I do not have experience with this type of wall	o MSE Wall = Space available and need for shoring or traffic control
o Nailed wall = Height for the drilling equipment to work at, maximum step between rows, cost of material at wall location	o Gabion wall = Availability of aggregates for basket filling, availability of local experience in gabion fabrication and gabion size
What wall height would be the limit of economically feasible construction for these walls in your opinion?	
o Cast in place = 20 ft.	o Sheet pile wall = I have not encountered this for permanent construction in transportation projects
o Drill Shaft wall (w/o tie backs) = 60 ft.	o Gravity Wall = 12 ft.
o Drill Shaft wall (w/ tie backs) = I do not have experience with this type of wall	o Wire mesh wall = 30 ft.
o Tie Back wall = I do not have experience with this type of wall	o MSE Wall = 50 ft.
o Nailed wall = 45 ft.	o Gabion wall = 8 ft.

Which typical unit cost do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 70 $/SF.	o Sheet pile wall = I have not encountered this for permanent construction in transportation projects
o Drill Shaft wall (w/o tie backs) = 85 $/SF.	o Gravity Wall = 50 $/SF.
o Drill Shaft wall (w/ tie backs) = I do not have experience with this type of wall	o Wire mesh wall = 45 $/SF.
o Tie Back wall = I do not have experience with this type of wall	o MSE Wall = 55 $/SF.
o Nailed wall = I do not have experience with this type of wall	o Gabion wall = 350 SF/day
Which typical production rates do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 550 SF/day	o Sheet pile wall = I have not encountered this for permanent construction in transportation projects
o Drill Shaft wall (w/o tie backs) = 350 SF/day	o Gravity Wall = 250 SF./day
o Drill Shaft wall (w/ tie backs) = I do not have experience with this type of wall	o Wire mesh wall = 850 SF/day
o Tie Back wall = I do not have experience with this type of wall	o MSE Wall = 1000 SF/day
o Nailed wall = I do not have experience with this type of wall	o Gabion wall = 50 $/SF.
Which 3 wall types would you recommend for remote areas where specialized workforce is limited?	
Concrete cast in place	
MSE Wall	
Gabion Wall	

Survey Recipient: #4	Years of experience:
Position: Project Manager	Date: 03/06/2014
Area of expertise: Project Management	Country where highest experience: USA
Please list the 3 main factors you consider when developing unit costs for retaining walls in general terms:	
Previous experience with wall	
Testing and instrumentation requirements	
Cost of materials, labor and equipment at wall location	
Please list the 3 main factors you consider when developing production rates for retaining walls in general terms:	
Previous experience with wall	
Accessibility and space for storage	
Need for movement monitoring and control	
Please list the 3 main factors to consider when developing unit costs for retaining walls for the following types:	
o Cast in place = Use of on-hand formwork, need for rebar at the stem, wall panel length	o Sheet pile wall = Only used for temporary shoring with sheet reuse, cannot compare with other types
o Drill Shaft wall (w/o tie backs) = Need for casing, underwater concrete, shaft spacing	o Diaphragm wall = Depth, need for slurry and cage reinforcement
o Drill Shaft wall (w/ tie backs) = Add the availability of local specialized tie back companies to the costs included for the case w/o anchors	o Wire mesh wall = Availability of on-site material for backfill, basket size and lateral space for machinery movement
o Tie Back wall = Total tie back lengths and spacing, plates and studs, fascia panel?	o MSE Wall = Panel size, length of straps and backfill lift thickness
o Nailed wall = Face requirements, length and spacing of tie backs, corrosion protection	o Gabion wall = I would not consider this wall
What wall height would be the limit of economically feasible construction for these walls in your opinion?	
o Cast in place = 25 ft.	o Sheet pile wall = Only used for temporary shoring with sheet reuse, cannot compare with other types
o Drill Shaft wall (w/o tie backs) = 50 ft.	o Gravity Wall = 10 ft.
o Drill Shaft wall (w/ tie backs) = 80 ft.	o Wire mesh wall = 25 ft.
o Tie Back wall = 60 ft.	o MSE Wall = 60 ft.
o Nailed wall = 50 ft.	o Gabion wall = I would not consider it
Which typical unit cost do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 75$/SF.	o Sheet pile wall = Only used for temporary shoring with sheet reuse, cannot compare with other types
o Drill Shaft wall (w/o tie backs) = 95 $/SF.	o Gravity Wall = 70 $/SF.
o Drill Shaft wall (w/ tie backs) = 130$/SF.	o Wire mesh wall = 55 $/SF.
o Tie Back wall = 85 $/SF.	o MSE Wall = 60 $/SF.
o Nailed wall = 75 $/SF.	o Gabion wall = I would not consider it

Which typical production rates do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place =	o Sheet pile wall = Only used for temporary shoring with sheet reuse, cannot compare with other types
o Drill Shaft wall (w/o tie backs) =	o Gravity Wall = 100 SF/day
o Drill Shaft wall (w/ tie backs) =	o Wire mesh wall = 1000 SF/day
o Tie Back wall =	o MSE Wall = 1500 SF/day
o Nailed wall =	o Gabion wall = I would not consider this wall

Which 3 wall types would you recommend for remote areas where specialized workforce is limited?
Sheet pile Wall
Concrete wall
MSE Wall

Survey Recipient: #5	Years of experience:
Position: Project Manager	Date: 03/04/2014
Area of expertise: Project Management	Country where highest experience: USA
Please list the 3 main factors you consider when developing unit costs for retaining walls in general terms:	
Wall location and access routes	
Potential for "just in time" purchasing policy	
Traffic control requirements	
Please list the 3 main factors you consider when developing production rates for retaining walls in general terms:	
Logic between prior and after activities	
Quality and experience of subcontractors	
Previous experience with wall	
Please list the 3 main factors to consider when developing unit costs for retaining walls for the following types:	
o Cast in place = Potential use of local labor and existing formwork, reinforcement	o Sheet pile wall = I do not have experience with this type of wall
o Drill Shaft wall (w/o tie backs) = Current cost of rebar, current cost of concrete, cost of subcontractors	o Diaphragm wall = I do not have experience with this type of wall
o Drill Shaft wall (w/ tie backs) =Current cost of rebar, current cost of concrete, cost of subcontractors	o Wire mesh wall = Need for shoring, requirements for selected fill, cost of proprietary systems for baskets
o Tie Back wall = Subcontractor availability, spacing and length of tie backs	o MSE Wall =Need for shoring, requirements for selected fill, cost of proprietary systems for panels/straps
o Nailed wall = Size of bars, length of bars, water/cement relation for grout	o Gabion wall = Unknown
What wall height would be the limit of economically feasible construction for these walls in your opinion?	
o Cast in place = 25 ft.	o Sheet pile wall = I do not have experience with this type of wall
o Drill Shaft wall (w/o tie backs) = 55 ft.	o Gravity Wall = 15 ft.
o Drill Shaft wall (w/ tie backs) = I do not have experience with this type of wall	o Wire mesh wall = 30 ft.
o Tie Back wall = 55 ft.	o MSE Wall = 44 ft.
o Nailed wall = 30 ft.	o Gabion wall = I do not have experience with this type of wall
Which typical unit cost do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 65$/SF.	o Sheet pile wall = I do not have experience with this type of wall
o Drill Shaft wall (w/o tie backs) = 85$/SF.	o Gravity Wall = 60$/SF.
o Drill Shaft wall (w/ tie backs) = 125 $/SF.	o Wire mesh wall = 55$/SF.
o Tie Back wall = 95$/SF.	o MSE Wall = 65$/SF.
o Nailed wall = 65$/SF.	o Gabion wall = I would not consider I

Which typical production rates do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 650 SF/day	o Sheet pile wall = I do not have experience with this type of wall
o Drill Shaft wall (w/o tie backs) = 400 SF/day	o Gravity Wall = 550 SF/day
o Drill Shaft wall (w/ tie backs) = 300 SF/day	o Wire mesh wall = 950 SF/day
o Tie Back wall = 400 $/SF.	o MSE Wall = 1400 SF/day
o Nailed wall = 700 SF/day	o Gabion wall = I would not consider this wall

Which 3 wall types would you recommend for remote areas where specialized workforce is limited?
Soil/Rock nail
MSE Wall
Gravity Wall

Survey Recipient: #6	Years of experience:
Position: Chief Executive Officer	Date: 03/12/2014
Area of expertise: Heavy civil PPP Construction Management	Country where highest experience: Ireland
Please list the 3 main factors you consider when developing unit costs for retaining walls in general terms:	
Access and storage conditions	
New crews or continuing work (learning curve)	
Availability of raw materials (concrete aggregates, backfill, etc.)	
Please list the 3 main factors you consider when developing production rates for retaining walls in general terms:	
Anticipated weather affection	
Number of weekdays and production cycles	
Materials involved and degree of specialty of local subcontractor	
Please list the 3 main factors to consider when developing unit costs for retaining walls for the following types:	
o Cast in place = Cost of concrete, potential for longer panels and formwork reuse	o Sheet pile wall = I have never worked with this type
o Drill Shaft wall (w/o tie backs) = Length of shafts, spacing between shafts, type of soil	o Diaphragm wall = Slurry needs, storage areas and distance to reinforcement preparation area
o Drill Shaft wall (w/ tie backs) = Same as above plus cost of subcontractors for anchor operations	o Wire mesh wall = Basket length and vertical spacing, requirements for backfill
o Tie Back wall = Tie back length, spacing and requirements for materials	o MSE Wall = Straps length and vertical spacing, requirements for backfill
o Nailed wall = Type of soil, potential for use of more than one rig, lateral space for material preparation and storage	o Gabion wall = Availability of aggregates for basket filling
What wall height would be the limit of economically feasible construction for these walls in your opinion?	
o Cast in place =	o Sheet pile wall = I have never worked with this type
o Drill Shaft wall (w/o tie backs) = 50 ft.	o Gravity Wall = 10 ft.
o Drill Shaft wall (w/ tie backs) = 70 ft.	o Wire mesh wall = 30 ft.
o Tie Back wall = 65 ft.	o MSE Wall = 50 ft.
o Nailed wall = 30 ft.	o Gabion wall = 20 ft.
Which typical unit cost do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 65$/SF.	o Sheet pile wall = I would not consider this wall
o Drill Shaft wall (w/o tie backs) = 95$/SF.	o Gravity Wall = 55$/SF.
o Drill Shaft wall (w/ tie backs) = 120 $/SF.	o Wire mesh wall = 35$/SF.
o Tie Back wall = 85$/SF.	o MSE Wall = 60$/SF.
o Nailed wall =	o Gabion wall = 65$/SF.

Which typical production rates do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 750 SF/day	o Sheet pile wall = I have never worked with this type
o Drill Shaft wall (w/o tie backs) = 550 SF/day	o Gravity Wall = 350 SF/day
o Drill Shaft wall (w/ tie backs) = 450 SF/day	o Wire mesh wall = 700 SF/day
o Tie Back wall = 400 $/SF.	o MSE Wall = 1250 SF/day
o Nailed wall = 600 SF/day	o Gabion wall = 450 SF/day

Which 3 wall types would you recommend for remote areas where specialized workforce is limited?
Concrete cast in place
MSE Wall
Wire mesh wall

Survey Recipient: #7	Years of experience:
Position: Sub-Segment Construction Manager	Date: 03/12/2014
Area of expertise: Construction Management	Country where highest experience: USA
Please list the 3 main factors you consider when developing unit costs for retaining walls in general terms:	
Wall location and traffic control needs	
Degree of specialization required by subcontractors	
Owner requirements for noise and nuisances	
Please list the 3 main factors you consider when developing production rates for retaining walls in general terms:	
Wall location and traffic control needs	
Degree of specialization required by subcontractors	
Owner requirements for noise and nuisances	
Please list the 3 main factors to consider when developing unit costs for retaining walls for the following types:	
o Cast in place = Availability of formwork already in use, potential for rebar cage preparation at ground level, need for shoring	o Sheet pile wall = I have never worked with this type
o Drill Shaft wall (w/o tie backs) = Soil hardness, presence of groundwater, casing requirements	o Diaphragm wall = Wall spacing, potential for cage preparation nearby, dump site distance
o Drill Shaft wall (w/ tie backs) = Combine upper and lower responses	o Wire mesh wall = Need for shoring, type of backfill, fill storage potential
o Tie Back wall = Complication of system, presence of groundwater, testing/loading requirements	o MSE Wall = Need for shoring, aesthetic requirements for panels, panel size and number of straps
o Nailed wall = Availability of lateral space, potential for machinery quick movement, length of nails	o Gabion wall = I have never worked with this type
What wall height would be the limit of economically feasible construction for these walls in your opinion?	
o Cast in place = 35 ft.	o Sheet pile wall = I have never worked with this type
o Drill Shaft wall (w/o tie backs) = 70 ft.	o Gravity Wall = 10 ft.
o Drill Shaft wall (w/ tie backs) = 90 ft.	o Wire mesh wall = 20 ft.
o Tie Back wall = 75 ft.	o MSE Wall = 45 ft.
o Nailed wall = 50 ft.	o Gabion wall = I would not consider this wall
Which typical unit cost do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 65$/SF.	o Sheet pile wall = I have never worked with this type
o Drill Shaft wall (w/o tie backs) = 95$/SF.	o Gravity Wall = 45$/SF.
o Drill Shaft wall (w/ tie backs) = 120 $/SF.	o Wire mesh wall = 40$/SF.
o Tie Back wall = 85$/SF.	o MSE Wall = 55$/SF.
o Nailed wall = 60$/SF.	o Gabion wall = I have never worked with this type

Which typical production rates do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 650 SF/day	o Sheet pile wall = I have never worked with this type
o Drill Shaft wall (w/o tie backs) = 450 SF/day	o Gravity Wall = 350 SF/day
o Drill Shaft wall (w/ tie backs) = 350 SF/day	o Wire mesh wall = 850 SF/day
o Tie Back wall = 500 $/SF.	o MSE Wall = 1250 SF/day
o Nailed wall = 700 SF/day	o Gabion wall = I have never worked with this type
Which 3 wall types would you recommend for remote areas where specialized workforce is limited?	
Soil/Rock Nails	
MSE/Wire mesh walls	
Concrete cast in place walls	

Survey Recipient: #8	Years of experience:
Position: Segment Construction Manager	Date: 03/06/2014
Area of expertise: Construction Management	Country where highest experience: Spain/Poland

Please list the 3 main factors you consider when developing unit costs for retaining walls in general terms:
Availability of materials
Miscellaneous requirements such as aesthetics, painting, finishing, etc.
Local requirements for Unions and/or sub trades
Please list the 3 main factors you consider when developing production rates for retaining walls in general terms:
Supply strategy for subcontractors and materials
Potential for continuous production
Availability of workspace

Please list the 3 main factors to consider when developing unit costs for retaining walls for the following types:

o Cast in place = Cost of concrete, rebar and formwork	o Sheet pile wall = Unknown
o Drill Shaft wall (w/o tie backs) = Type of soil, drill shaft spacing and reinforcement. Need for underwater concrete placement	o Diaphragm wall = Need for slurry, thickness and maximum depth
o Drill Shaft wall (w/ tie backs) = Type of soil, drill shaft spacing and reinforcement. Need for underwater concrete placement	o Wire mesh wall = Maximum basket height, availability of access and storage of backfill
o Tie Back wall = Total length, spacing and bonded/unbonded requirements	o MSE Wall = Height, panel aesthetic requirement
o Nailed wall = Spacing and maximum step, length of nails	o Gabion wall = Unknown

What wall height would be the limit of economically feasible construction for these walls in your opinion?

o Cast in place = 25 ft.	o Sheet pile wall = Unknown
o Drill Shaft wall (w/o tie backs) = 60 ft.	o Gravity Wall = 10 ft.
o Drill Shaft wall (w/ tie backs) = 85 ft.	o Wire mesh wall = 15 ft.
o Tie Back wall = 65 ft.	o MSE Wall = 40 ft.
o Nailed wall = 35 ft.	o Gabion wall = I would not consider this wall

Which typical unit cost do you consider when performing preliminary analysis of these retaining wall types?

o Cast in place = 55$/SF.	o Sheet pile wall =Unknown
o Drill Shaft wall (w/o tie backs) = 80$/SF.	o Gravity Wall = 45$/SF.
o Drill Shaft wall (w/ tie backs) = 105 $/SF.	o Wire mesh wall = 40$/SF.
o Tie Back wall = 85$/SF.	o MSE Wall = 55$/SF.

o Nailed wall = 70$/SF.	o Gabion wall = I would not consider this wall
Which typical production rates do you consider when performing preliminary analysis of these retaining wall types?	
o Cast in place = 500 SF/day	o Sheet pile wall = Unknown
o Drill Shaft wall (w/o tie backs) = 350 SF/day	o Gravity Wall = 350 SF/day
o Drill Shaft wall (w/ tie backs) = 300 SF/day	o Wire mesh wall = 800 SF/day
o Tie Back wall = 400 $/SF.	o MSE Wall = 1000 SF/day
o Nailed wall = 550 SF/day	o Gabion wall = Unknown
Which 3 wall types would you recommend for remote areas where specialized workforce is limited?	
Cast in place wall	
Mechanically Stabilized	
Drill Shaft	

Appendix C

Completed Forms of Interviews performed to Expert Subjects during the data collection campaign

<table>
<tr><th colspan="2"><u>RETAINING WALL SELECTION INTERVIEW TO EXPERT PERSONNEL</u></th></tr>
<tr><td>Name: Interview #1 P.E.</td><td>Years of experience: 29</td></tr>
<tr><td>Position: Construction Design Manager</td><td>Date: 03/12/2014</td></tr>
<tr><td>Area of expertise: Construction Technical Support and General Engineering</td><td>Location: Dallas TX</td></tr>
<tr><td colspan="2">· What are the main 4 factors do you consider when determining the most appropriate types of walls for a certain location?</td></tr>
<tr><td colspan="2">The geotechnical information available for the specific location, the allowable construction duration, the maximum unit cost per area of wall and the construction system/phasing of activities.</td></tr>
<tr><td colspan="2">· Which are the areas where information is lacking for you to perform a proper design?</td></tr>
<tr><td colspan="2">Phasing sequence and actual configuration of the wall at the different construction stages of the general project concept</td></tr>
<tr><td colspan="2">· Where would you set the bar for the height of the following upward type walls?</td></tr>
<tr><td>o MSE = 60 feet</td><td>o Gabion wall = 30 feet</td></tr>
<tr><td>o CIP = 20 feet</td><td>o Wire mesh wall = 50 feet</td></tr>
<tr><td>o Gravity wall = 8 feet</td><td></td></tr>
<tr><td colspan="2">· Where would you set the bar for the height of the following downward type walls?</td></tr>
<tr><td>o Nailed wall = 80 feet</td><td>o Drill Shaft wall (w/ anchors) = 100 feet</td></tr>
<tr><td>o Tie Back wall = 100 feet</td><td>o Sheet pile wall = 30 feet with anchors</td></tr>
<tr><td>o Drill Shaft wall (w/o anchors) = 25 feet</td><td>o Diaphragm wall = 30 feet</td></tr>
<tr><td colspan="2">· Which wall requires a higher supervision and designer expertise in your opinion?</td></tr>
<tr><td colspan="2">Any wall that includes anchors and all walls of downward construction direction.</td></tr>
<tr><td colspan="2">· For which types of walls is the groundwater a critical factor that makes them less appropriate?</td></tr>
<tr><td colspan="2">Diaphragm walls as there is no possibility of drainage unless highly specialized details are designed and executed</td></tr>
<tr><td colspan="2">· What would be the three most common issues regarding the construction of the following wall types?</td></tr>
<tr><td>o Cast in place = Formwork blowouts, incorrect rebar placement, construction joints</td><td>o Sheet pile wall = Water infiltration, unforeseen boulders that difficult the driving processes and sheet corrosion</td></tr>
<tr><td>o Drill Shaft wall = Differing soil, water intrusions, honeycombing</td><td>o Diaphragm wall = Collapse of cages, incorrect joints and water level unintended modifications (subsidences)</td></tr>
<tr><td>o MSE Wall = Backfill washing, strap corrosion, damage to facing</td><td>o Wire mesh wall = Ripped fabric, incorrect aggregate distribution and excessive lift thickness</td></tr>
<tr><td>o Tie Back wall = Incorrect geometry of tie back, low-quality grout and corrosion</td><td>o Gravity wall = Improper vibration, construction joints and form blowouts</td></tr>
<tr><td>o Nailed wall = Incorrect geometry of tie back, low-quality grout and corrosion</td><td>o Gabion wall = Low quality aggregate, incorrect placement, plumbness</td></tr>
</table>

Could you please rank the following walls in order of construction difficulty? (1 most dif)	
o Cast in place = 9	o Sheet pile wall = 5
o Drill Shaft wall = 2	o Diaphragm wall = 1
o MSE Wall = 8	o Wire mesh wall = 7
o Tie Back wall = 3	o Gravity wall = 10
o Nailed wall = 4	o Gabion wall = 6
· **Which wall type do you believe to be more appropriate for fast-track needs?**	
MSE walls for upward and nailed walls for downward construction	
· **Which wall types do you believe to be result in increased maintenance needs?**	
Anchored walls, wire mesh and MSE	
· **What would you consider a "no-go" condition for the following types of walls (i.e. those factors that automatically discard the wall type as non-adequate?**	
o Cast in place = Excessive height	o Sheet pile wall = Permanent configuration. Hard soils or boulders
o Drill Shaft wall = Limited cost	o Diaphragm wall = Hard rock
o MSE Wall = Reduced lateral space	o Wire mesh wall = Aesthetic requirements
o Tie Back wall = Schedule or limitations in subsurface ROW for the nails to be drilled	o Gravity wall = Height over 8 feet
o Nailed wall = Limitations in subsurface ROW for the nails to be drilled	o Gabion wall = Dynamic loading
· **Which of the previously discussed wall types have, in your experience, been discarded or re-designed due to the lack of specialized equipment and/or materials?**	
Diaphragm walls and anchored walls	
· **Would you please rank the following upward type walls in terms of unit cost of construction? (1 most expensive)**	
o MSE = 3	o Gabion wall = 5
o CIP = 1	o Wire mesh wall = 4
o Gravity wall = 2	
· **Would you please rank the following downward type walls in terms of unit cost of construction? (1 most expensive)**	
o Nailed wall = 6	o Drill Shaft wall (w/ anchors) = 4
o Tie Back wall = 4	o Sheet pile wall = 5
o Drill Shaft wall (w/o anchors) = 3	o Diaphragm wall = 1
· **Would you please rank the following upward type walls in terms of duration of construction? (1 slowest)**	
o MSE = 5	o Gabion wall = 4
o CIP = 3	o Wire mesh wall = 1
o Gravity wall = 2	
· **Would you please rank the following downward type walls in terms of duration of construction? (1 slowest)**	
o Nailed wall = 6	o Drill Shaft wall (w/ anchors) = 1
o Tie Back wall = 5	o Sheet pile wall = 3
o Drill Shaft wall (w/o anchors) = 3	o Diaphragm wall = 2

What would be a standard design life for the following wall types?	
o Cast in place = 50	o Sheet pile wall = 1
o Drill Shaft wall = 75	o Diaphragm wall = 75
o MSE Wall = 50	o Wire mesh wall = 50
o Tie Back wall = 50	o Gravity wall = 100
o Nailed wall = 50	o Gabion wall = 50
Is there any additional point that you believe needed to be included in this analysis?	
"When performing wall analysis, I tend to develop relationships between geotechnical parameters and wall unit costs. For example, the influence of the backfill internal friction angle on the MSE wall cost per square foot of wall".	
YOUR PARTICIPATION AND RESPONSES ARE GREATLY APPRECIATED	

RETAINING WALL SELECTION INTERVIEW TO EXPERT PERSONNEL	
Name: Interview #2 P.E.	Years of experience: 11
Position: Technical Office Manager	Date: 03/11/2014
Area of expertise: Construction Technical Support and General Engineering. Tunnels	Location: Dallas TX
· What are the main 4 factors do you consider when determining the most appropriate types of walls for a certain location?	
First and foremost the direction of construction, then the height, type of soil and maximum unit cost allowed for the specific wall	
· Which are the areas where information is lacking for you to perform an appropriate design?	
In most cases, the actual constraints are not known at the time of the original design, later modifications, adjustments, geometry and loading determine successive changes that altogether could have potentially made more adequate a different type.	
· Where would you set the bar for the height of the following upward type walls?	
o MSE = 40 feet	o Gabion wall = Only used in residential construction up to 10 feet. Requires a considerable amount of lateral space (ROW?)
o CIP = 30 feet, higher MSE	o Wire mesh wall = 15 feet, would not normally use for permanent structures. Ok for temporary retention
o Gravity wall = 8 feet, if higher I would use cantilever	
· Where would you set the bar for the height of the following downward type walls?	
o Nailed wall = 35 feet	o Drill Shaft wall (w/ anchors) = 50 feet with anchors
o Tie Back wall = 50 feet	o Sheet pile wall = 25 feet bulkhead
o Drill Shaft wall (w/o anchors) = 35 feet	o Diaphragm wall = 70 feet with anchors or tie beams
· Which wall requires a higher supervision and designer expertise in your opinion?	
Downward construction is in most cases more delicate than upward construction. Any wall of that direction of construction would result more sensitive in terms of design and construction supervision	
· For which types of walls is the groundwater a critical factor that makes them less appropriate?	
Groundwater is a key factor for most of the walls. Although with proper measures it can be resolved for all of them, anchor capacity in saturated soils is greatly reduced therefore being more suitable a drill shaft or diaphragm wall. For upward construction, most walls can sort groundwater with appropriate drainage measures.	
· What would be the three most common issues regarding the construction of the following wall types?	
o Cast in place = Excessive free fall, concrete segregation/honeycombing, incorrect reinforcement or insufficient splice length from footing	o Sheet pile wall = Unforeseen boulders, out of plumbness, excessively reused sheets

o Drill Shaft wall = Differing bearing conditions, water intrusions and collapsing holes in granular soils	o Diaphragm wall = Incorrect joint execution and water intrusions, insufficient slurry filtering and rebar cage collapses
o MSE Wall = Clogged drainage measures, incorrect backfill and excessive gaps between panels	o Wire mesh wall = Plumbness, backfill washing and damage to fabric
o Tie Back wall = Deviation from angle of inclination and length, lack of proper proof/performance testing, lack of sacrificial testing to verify design assumptions	o Gravity wall = Improper concrete vibration, excessive concrete free fall and segregation
o Nailed wall = Insufficient testing, lack of control of actual soil and insufficient nail length	o Gabion wall = Improperly prepared subgrade, incorrect connection between baskets, damage to wires
Could you please rank the following walls in order of construction difficulty? (1 most dif)	
o Cast in place = 8	o Sheet pile wall = 4
o Drill Shaft wall = 3	o Diaphragm wall = 2
o MSE Wall = 6	o Wire mesh wall = 7
o Tie Back wall = 1	o Gravity wall = 9
o Nailed wall = 5	o Gabion wall = 10
· **Which wall type do you believe to be more appropriate for fast-track needs?**	
MSE Walls and rock/soil nails	
· **Which wall types do you believe to be result in increased maintenance needs?**	
Maintenance needs are highly dependent in the quality of construction, specifically in drainage measures for upward construction. Regarding downward construction, walls without permanent facing do require repairs and preventative maintenance that for anchors can include re-stressing.	
· **What would you consider a "no-go" condition for the following types of walls (i.e. those factors that automatically discard the wall type as non-adequate for them)?**	
o Cast in place = If MSE can be used and height is more than 15 feet is normally quicker and more economical	o Sheet pile wall = Would only use if rest are non-feasible or for temporary shoring in high groundwater levels and/or where movements are to be controlled in deep excavations
o Drill Shaft wall = Costly option, suitable for high loads and soft soils	o Diaphragm wall = Absence of very strict requirements for lateral moves
o MSE Wall = Heights over 40 feet	o Wire mesh wall = Normally only to be used in temporary configurations, very flexible for that can lead to issues for roadway construction
o Tie Back wall = Groundwater and fractured soils	o Gravity wall = Difficult or expensive concrete supply
o Nailed wall = Groundwater and fractured soils	o Gabion wall = Only for projects where aesthetics is a requirement or slope stabilization. Other types result more economical in most circumstances

▪ Which of the previously discussed wall types have, in your experience, been discarded or re-designed due to the lack of specialized equipment and/or materials?	
In my experience those that require specialized machinery that is either not available in remote areas or that the mobilization is not economically feasible. This would apply to anchored walls as well as diaphragm walls. Drill rigs are more common than clamshells	
▪ Would you please rank the following upward type walls in terms of unit cost of construction? (1 most expensive)	
o MSE = 3 (for a standard facing, can be 1 if aesthetics are complicated)	o Gabion wall = 4 (for low heights, if more than 7-10 ft. results uneconomical)
o CIP = 1	o Wire mesh wall = 5
o Gravity wall = 2	
▪ Would you please rank the following upward type walls in terms of unit cost of construction? (1 most expensive)	
o Nailed wall = 5	o Drill Shaft wall (w/ anchors) = 1
o Tie Back wall = 4	o Sheet pile wall = 6
o Drill Shaft wall (w/o anchors) = 3	o Diaphragm wall = 2
▪ Would you please rank the following upward type walls in terms of duration of construction? (1 slowest)	
o MSE = 4	o Gabion wall = 3
o CIP = 1	o Wire mesh wall = 5
o Gravity wall = 2	
▪ Would you please rank the following downward type walls in terms of duration of construction? (1 slowest)	
o Nailed wall = 5	o Drill Shaft wall (w/ anchors) = 1
o Tie Back wall = 4	o Sheet pile wall = 6
o Drill Shaft wall (w/o anchors) = 2	o Diaphragm wall = 3
▪ What would be a standard design life for the following wall types? (years)	
o Cast in place = 50	o Sheet pile wall = 5
o Drill Shaft wall = 50	o Diaphragm wall = 50
o MSE Wall = 50	o Wire mesh wall = 5, temporary retention
o Tie Back wall = 50	o Gravity wall = 50
o Nailed wall = 15	o Gabion wall = 15
• Is there any additional point that you believe needed to be included in this analysis?	
"For those engineers performing technical support for construction companies, being aware of the potential capabilities of each type of wall results essential to develop alternative solutions for optimized cost and schedule. Only by the understanding of the actual needs and constraints, the optimum solution can be achieved"	
YOUR PARTICIPATION AND RESPONSES ARE GREATLY APPRECIATED	

RETAINING WALL SELECTION INTERVIEW TO EXPERT PERSONNEL	
Name: Interview #3 P.E.	Years of experience: 13
Position: Geotechnical Design Manager	Date: 03/14/2014
Area of expertise: Soil retention structures in general and underground construction	Location: Dallas TX
· What are the main 4 factors do you consider when determining the most appropriate types of walls for a certain location?	
Type of soil, loading requirements in terms of directions and capacity required. Availability of specialized construction personnel and equipment.	
· Which are the areas where information is lacking for you to perform an appropriate design?	
Normally geotechnical reports are performed in a standard manner that does not focus in the particular needs of the wall to be constructed. Also, for those projects where a cost comparison is necessary at the design level, accurate unit costs are not always readily available. Soil type is an essential factor as well as the presence of groundwater or aggressive chemical composition in the soil.	
· Where would you set the bar for the height of the following upward type walls?	
o MSE = 50 feet	o Gabion wall = I would not use a gabion wall for civil construction
o CIP = 25 feet	o Wire mesh wall = 25 feet
o Gravity wall = 8 feet	
· Where would you set the bar for the height of the following downward type walls?	
o Nailed wall = 35 feet, highly dependent on soil type	o Drill Shaft wall (w/ anchors) = 65 feet with anchors
o Tie Back wall = 55 feet	o Sheet pile wall = I would not use a sheet wall in most circumstances
o Drill Shaft wall (w/o anchors) = 45 feet, more with very good stratums	o Diaphragm wall = 100 feet with anchors or tie beams
· Which wall requires a higher supervision and designer expertise in your opinion?	
In my experience, anchored walls can lead to great complications if the design assumptions are not verified with proper field inspection and monitoring. Drill shaft walls also require experienced inspection for bearing stratum embedment.	
· For which types of walls is the groundwater a critical factor that makes them less appropriate?	
Definitely anchors and nails. For the rest of walls there are generally available solutions for groundwater control during and after construction.	
· What would be the three most common issues regarding the construction of the following wall types?	
o Cast in place = Improper formwork support, lack of proper drainage measures and insufficient concrete cover	o Sheet pile wall = I would not use a sheet wall in most circumstances
o Drill Shaft wall = Improper concreting operations, insufficient embedment due to incorrect stratum inspection during drilling, water intrusions.	o Diaphragm wall = Similar to drill shafts, with the specific concerns of oversized cages being lifted and moved before introduction in excavated panels

o MSE Wall = Non-compliant select backfill, incorrect drainage measures and excessive joint opening between precast panels	o Wire mesh wall = Lack of proper drainage, lack of the required filter fabric between rock and selected fill (then material washout occurs) and damaged wires.
o Tie Back wall = Damages to the corrosion protection measures, incorrect centralizers placement, deviations from design inclination/length.	o Gravity wall = Improper concrete practices with excessive free fall, out of plumb or improperly supported lateral formwork
o Nailed wall = Damages to the corrosion protection measures, incorrect centralizers placement, deviations from design inclination/length.	o Gabion wall = I would not use a gabion wall for civil construction
Could you please rank the following walls in order of construction difficulty? (1 most dif)	
o Cast in place = 6	o Sheet pile wall = 5
o Drill Shaft wall = 4	o Diaphragm wall = 1
o MSE Wall = 8	o Wire mesh wall = 9
o Tie Back wall = 2	o Gravity wall = 10
o Nailed wall = 3	o Gabion wall = 7
· **Which wall type do you believe to be more appropriate for fast-track needs for upward and downward construction?**	
When specialized equipment and personnel are available, nailed walls are a high production rate wall type for downward needs. For upward construction, under most circumstances and if the lateral space is sufficient, Mechanically Stabilized Earth Walls can be quickly erected.	
· **Which wall types do you believe to be result in increased maintenance needs?**	
Any wall that is subject to groundwater will require a high maintenance effort, particularly for walls that entail backfill such as MSE, wire mesh or Cast in place as improper drainage can lead to backfill being washed out and subsidence on the retained structure (building, roadway, etc.)	
· **What would you consider a "no-go" condition for the following types of walls (i.e. those factors that automatically discard the wall type as non-adequate for them)?**	
o Cast in place = Lack of space for proper footing	o Sheet pile wall = Would not use for permanent
o Drill Shaft wall = Potential for use of simpler walls or rock soil	o Diaphragm wall = Out of urban areas where lateral movement and groundwater control is not a requirement (for example in tunnels)
o MSE Wall = Lack of cost-efficient backfill	o Wire mesh wall = Permanent situation where aesthetic requirements exist
o Tie Back wall = Lack of specific needs, groundwater that requires control	o Gravity wall = Most cases would recommend cantilever instead.
o Nailed wall = Groundwater that requires control	o Gabion wall = I would not use a gabion wall for civil construction

· Which of the previously discussed wall types have, in your experience, been discarded or re-designed due to the lack of specialized equipment and/or materials?	
Tie back walls and diaphragm walls, the machinery and personnel constructing these walls is required to be proficient with these types	
· Would you please rank the following upward type walls in terms of unit cost of construction? (1 most expensive)	
o MSE = 3	o Gabion wall = 4
o CIP = 1	o Wire mesh wall = 5
o Gravity wall = 2	
· Would you please rank the following downward type walls in terms of unit cost of construction? (1 most expensive)	
o Nailed wall = 5	o Drill Shaft wall (w/ anchors) = 2
o Tie Back wall = 4	o Sheet pile wall = 6
o Drill Shaft wall (w/o anchors) = 3	o Diaphragm wall = 1
· Would you please rank the following upward type walls in terms of duration of construction? (1 slowest)	
o MSE = 3	o Gabion wall = 5
o CIP = 2	o Wire mesh wall = 4
o Gravity wall = 1	
· Would you please rank the following downward type walls in terms of duration of construction? (1 slowest)	
o Nailed wall = 5	o Drill Shaft wall (w/ anchors) = 2
o Tie Back wall = 4	o Sheet pile wall = 6
o Drill Shaft wall (w/o anchors) = 3	o Diaphragm wall = 1
· What would be a standard design life for the following wall types? (years)	
o Cast in place = 50	o Sheet pile wall = I would not use a sheet wall in most circumstances
o Drill Shaft wall = 50	o Diaphragm wall = 50
o MSE Wall = 50	o Wire mesh wall = 25 feet
o Tie Back wall = 50	o Gravity wall = 50
o Nailed wall = 25 unless justified otherwise in stable solid rock	o Gabion wall = I would not use a gabion wall for civil construction
• Is there any additional point that you believe needed to be included in this analysis?	
"Wall selection and design is not an easy task but it is not out of most engineer´s reach. On the other hand, the skills that make proper construction, via inspections and monitoring, result critical for the final product to be achieved. Also, groundwater and anchored walls should not be mixed unless experienced personnel are involved in the design and construction as well as movement control devices are used during and after construction"	
YOUR PARTICIPATION AND RESPONSES ARE GREATLY APPRECIATED	

<table>
<tr><th colspan="2"><u>RETAINING WALL SELECTION INTERVIEW TO EXPERT PERSONNEL</u></th></tr>
<tr><td>Name: Interview #4</td><td>Years of experience: 17</td></tr>
<tr><td>Position: Geotechnical Specialty Company Area Manager</td><td>Date: 03/04/2014</td></tr>
<tr><td>Area of expertise: Downward construction retaining structures</td><td>Location: Garland TX</td></tr>
<tr><td colspan="2">· What are the main 4 factors do you consider when determining the most appropriate types of walls for a certain location?</td></tr>
<tr><td colspan="2">Wall height, maximum unit cost, actual design life for project and subcontractor availability</td></tr>
<tr><td colspan="2">· Which are the areas where information is lacking for you to perform an appropriate design?</td></tr>
<tr><td colspan="2">Final Owner requirements, unforeseen site conditions and conflicts with other project activities, schedule requirements.</td></tr>
<tr><td colspan="2">· Where would you set the bar for the height of the following upward type walls?</td></tr>
<tr><td>o MSE = 50 feet</td><td>o Gabion wall = I would not use a gabion wall for civil construction</td></tr>
<tr><td>o CIP = 30 feet</td><td>o Wire mesh wall = 20 feet</td></tr>
<tr><td>o Gravity wall = 10 feet</td><td></td></tr>
<tr><td colspan="2">· Where would you set the bar for the height of the following downward type walls?</td></tr>
<tr><td>o Nailed wall = 40 feet</td><td>o Drill Shaft wall (w/ anchors) = 80 feet with anchors</td></tr>
<tr><td>o Tie Back wall = 65 feet</td><td>o Sheet pile wall = 25 feet</td></tr>
<tr><td>o Drill Shaft wall (w/o anchors) = 50 feet for rock bearing</td><td>o Diaphragm wall = 100 feet with anchors or tie beams</td></tr>
<tr><td colspan="2">· Which wall requires a higher supervision and designer expertise in your opinion?</td></tr>
<tr><td colspan="2">Diaphragm and drill shaft walls involve oversize rebar cages operations that can result in critical damages to personnel and workers and thus, proper inspection before lifting is critical</td></tr>
<tr><td colspan="2">· For which types of walls is the groundwater a critical factor that makes them less appropriate?</td></tr>
<tr><td colspan="2">Any wall that involves the introduction of an element of structural responsibility is highly affected by groundwater (i.e. nails or tie backs). Additionally, for vertical construction, washing of backfill can lead to wall movement or even failures</td></tr>
<tr><td colspan="2">· What would be the three most common issues regarding the construction of the following wall types?</td></tr>
<tr><td>o Cast in place = Incorrect rebar placement, lack of proper drainage measures, improper concrete vibration</td><td>o Sheet pile wall = I do not have experience with the construction of this type of walls</td></tr>
<tr><td>o Drill Shaft wall = Cage lifting and introduction, plumbness, soil intrusions and no use of tremie tubes</td><td>o Diaphragm wall = As for drill shafts Cage lifting and introduction, plumbness, soil intrusions and no use of tremie</td></tr>
<tr><td>o MSE Wall = Damaged straps due to machinery on tracks, deviation from strap length/angle and improper backfill /lift</td><td>o Wire mesh wall = Backfill, damage to wires and ripped fabric that leads to washing</td></tr>
</table>

o Tie Back wall = As for nailed walls damage to corrosion protective measures, inclination, insufficient bonded length. Recurrent issues during stressing and locking operations	o Gravity wall = Lack of concrete vibration, joints between placements, subgrade preparation
o Nailed wall = Damage to corrosion protective measures, inclination, insufficient bonded length	o Gabion wall = I do not have experience with the construction of this type of walls
Could you please rank the following walls in order of construction difficulty? (1 most dif)	
o Cast in place = 7	o Sheet pile wall = 5
o Drill Shaft wall = 2	o Diaphragm wall = 3
o MSE Wall = 8	o Wire mesh wall = 9
o Tie Back wall = 1	o Gravity wall = 10
o Nailed wall = 4	o Gabion wall = 6
· **Which wall type do you believe to be more appropriate for fast-track needs for upward and downward construction?**	
For downward construction and in absence of other constraints, definitely nailed walls. MSE walls are quickly constructed for upward needs	
· **Which wall types do you believe to be result in increased maintenance needs?**	
Anchored walls (tie backs, drill shafts and diaphragm with anchors) in high load situations require not only high maintenance but also load/movement monitoring	
· **What would you consider a "no-go" condition for the following types of walls (i.e. those factors that automatically discard the wall type as non-adequate for them)?**	
o Cast in place = Excessive height of lack of space for footing	o Sheet pile wall = Would not use for permanent
o Drill Shaft wall = Reduced height and availability of space	o Diaphragm wall = Absence of specific groundwater and movement control such as in urban areas
o MSE Wall = Corrosive soil, heights less than 15 feet	o Wire mesh wall = Would not recommend it in most circumstances unless temporary situations
o Tie Back wall = Remote areas with lack of specialized companies	o Gravity wall = Height over 5 feet, as cantilever results more economic
o Nailed wall = Corrosive soils and remote areas with lack of specialized companies	o Gabion wall = I would not use a gabion wall for civil construction
· **Which of the previously discussed wall types have, in your experience, been discarded or re-designed due to the lack of specialized equipment and/or materials?**	
Anchored walls due to lack of specialized equipment	
· **Would you please rank the following upward type walls in terms of unit cost of construction? (1 most expensive)**	
o MSE = 4	o Gabion wall = 2
o CIP = 3	o Wire mesh wall = 5
o Gravity wall = 1	
· **Would you please rank the following downward type walls in terms of unit cost of construction? (1 most expensive)**	

o Nailed wall = 6	o Drill Shaft wall (w/ anchors) = 1
o Tie Back wall = 4	o Sheet pile wall = 5
o Drill Shaft wall (w/o anchors) = 3	o Diaphragm wall = 2
· Would you please rank the following upward type walls in terms of duration of construction? (1 slowest)	
o MSE = 3	o Gabion wall = 4
o CIP = 1	o Wire mesh wall = 5
o Gravity wall = 2	
· Would you please rank the following downward type walls in terms of duration of construction? (1 slowest)	
o Nailed wall = 6	o Drill Shaft wall (w/ anchors) = 2
o Tie Back wall = 4	o Sheet pile wall = 5
o Drill Shaft wall (w/o anchors) = 3	o Diaphragm wall = 1
· What would be a standard design life for the following wall types? (years)	
o Cast in place = 50	o Sheet pile wall = Would not use for permanent, would say 5
o Drill Shaft wall = 50	o Diaphragm wall = 50
o MSE Wall = 50	o Wire mesh wall = 15
o Tie Back wall = 50	o Gravity wall = 50
o Nailed wall = 25/50 (soil/rock)	o Gabion wall = Would not use for permanent, would say 10
• Is there any additional point that you believe needed to be included in this analysis?	
"In my experience, the client needs are not clearly defined at the initial stages of the design process. This cause improper several changes to the original design that in most cases are performed by external companies not involved in the original studies. This can lead to complications during the construction. A clear and defined specification document during the proposal stage can lead to successful investigation, retaining wall selection, design and construction"	
YOUR PARTICIPATION AND RESPONSES ARE GREATLY APPRECIATED	

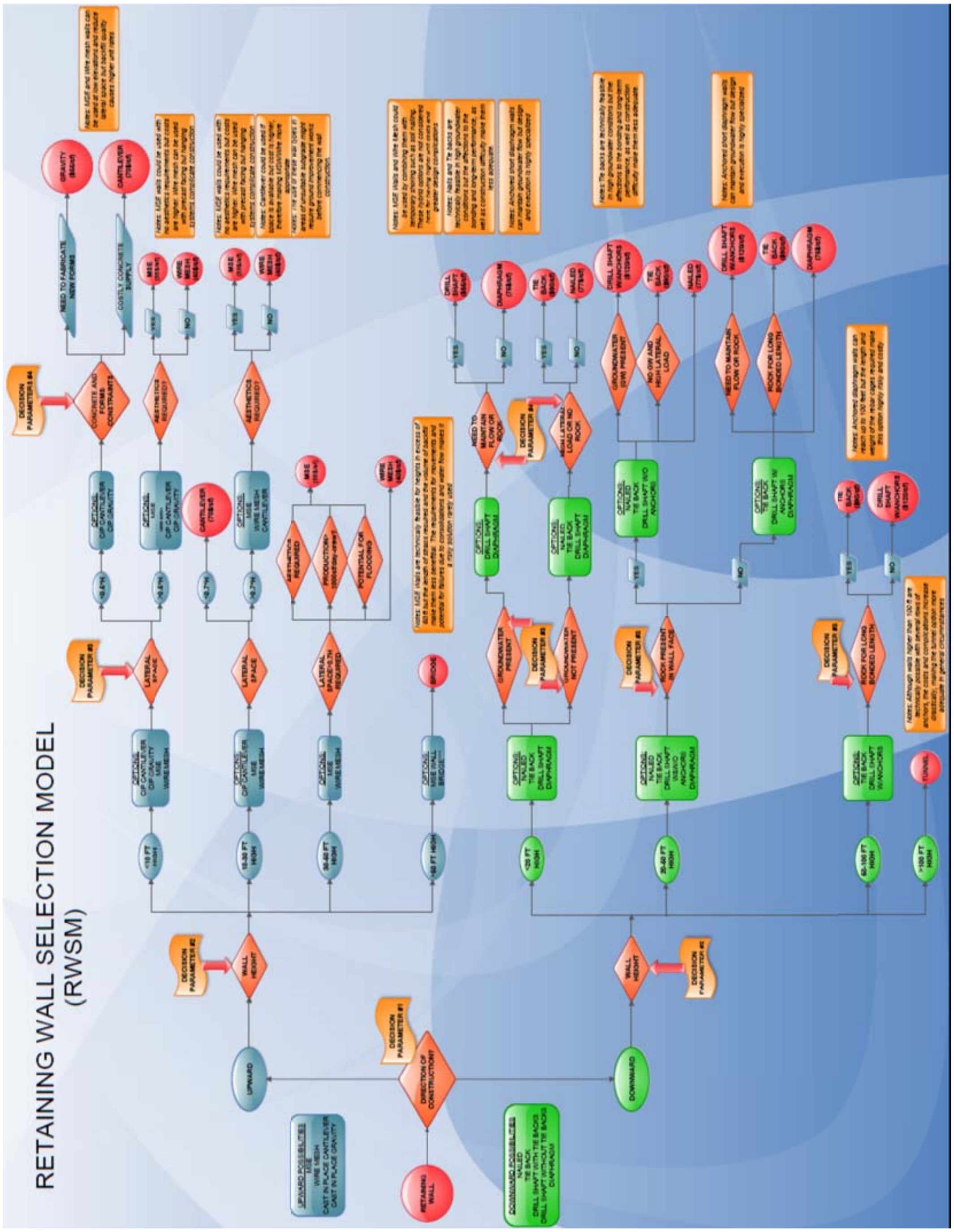
RETAINING WALL SELECTION INTERVIEW TO EXPERT PERSONNEL	
Name: Interview #5 P.E.	Years of experience: 21
Position: Geotechnical Design Firm Principal	Date: 02/27/2014
Area of expertise: Geotechnical design and engineering	Location: Dallas TX
· What are the main 4 factors do you consider when determining the most appropriate types of walls for a certain location?	
Soil type, maximum height, availability of horizontal space, presence of groundwater, maximum unit cost set by owner, and speed of construction required.	
· Which are the areas where information is lacking for you to perform an appropriate design?	
Proper geotechnical investigation, procurement constraints not present at the time of design and actual cost of materials for the particular project to make a proper cost evaluation that is later needed by Owners	
· Where would you set the bar for the height of the following upward type walls?	
o MSE = 45 feet	o Gabion wall = Can go up to 40 feet with high lateral space consumption
o CIP = 25 feet due to uneconomical formwork required	o Wire mesh wall = 25 feet with delicate construction and backfill control
o Gravity wall = 5 feet, if higher I would use cantilever	
· Where would you set the bar for the height of the following downward walls?	
o Nailed wall = 35 feet	o Drill Shaft wall (w/ anchors) = 65 feet
o Tie Back wall = 55 feet	o Sheet pile wall = 45 feet with the incorporation of anchors
o Drill Shaft wall (w/o anchors) = 40 feet in good bearing stratum such as unweathered rock	o Diaphragm wall = 90 feet with anchors or tie beams
· Which wall requires a higher supervision and designer expertise in your opinion?	
Any anchor involving active anchors, especially during the stressing and testing operations	
· For which types of walls is the groundwater a critical factor that makes them less appropriate?	
Anchors and nails are highly impacted by the groundwater and although some additional considerations can be taken into account, these walls do not provide any control over the groundwater intrusions in those cases where this is a design constraint. Most vertical construction walls are highly affected by water flows as it can cause backfill washing, especially in the MSE and wire mesh walls.	
· What would be the three most common issues regarding the construction of the following wall types?	
o Cast in place = Formwork system, drainage measures and joints between placements	o Sheet pile wall = Water infiltration, unforeseen boulders that difficult the driving processes and failing anchors
o Drill Shaft wall = Cleanness of the drilled hole, supervision of spoils to confirm design assumptions and soil intrusions/honeycombing.	o Diaphragm wall = Failing cages during lifting and introduction, excessive sand in slurry and soil intrusions in concrete/honeycombing

o MSE Wall = Improper compaction, unsuitable backfill and damage to straps	o Wire mesh wall = Plumbness, backfill washing and damage to fabric
o Tie Back wall = Deviation from angle of inclination, improper sleeve connection and incorrect testing practices	o Gravity wall = Cleanness of the area prior to concrete, support of formwork, excessive concreting speed which leads to improper consolidations and formwork blowouts
o Nailed wall = Damaged corrosion protection, improper locking processes and deviation from the required angle/length	o Gabion wall = Damage to wire baskets, out of plumbness and use of rock subject to weathering
Could you please rank the following walls in order of construction difficulty? (1 most dif)	
o Cast in place = 8	o Sheet pile wall = 5
o Drill Shaft wall = 4	o Diaphragm wall = 1
o MSE Wall = 6	o Wire mesh wall = 7
o Tie Back wall = 2	o Gravity wall = 10
o Nailed wall = 3	o Gabion wall = 9
▪ **Which wall type do you believe to be more appropriate for fast-track needs?**	
For upward construction MSE walls and for downward construction rock nails/tie backs	
▪ **Which wall types do you believe to be result in increased maintenance needs?**	
Wire mesh, mechanically stabilized earth and gabion	
▪ **What would you consider a "no-go" condition for the following types of walls (i.e. those factors that automatically discard the wall type as non-adequate?**	
o Cast in place = Height over 20 feet	o Sheet pile wall = Permanent construction
o Drill Shaft wall = Boulders exceeding shaft diameter	o Diaphragm wall = Less than 20 feet height except in high load cases or water control needs
o MSE Wall = Flowing water and corrosive soil/water	o Wire mesh wall = Potential water flow and need for lateral loading
o Tie Back wall = Creeping soils	o Gravity wall = Height over 10 feet, soft subgrade and difficult concrete supply
o Nailed wall = Corrosive soils	o Gabion wall = Height over 15 feet, reduced lateral ROW and lateral loads
▪ **Which of the previously discussed wall types have, in your experience, been discarded or re-designed due to the lack of specialized equipment and/or materials?**	
Tie back walls mostly but also drill shaft walls and diaphragm walls	
▪ **Would you please rank the following upward type walls in terms of unit cost of construction? (1 most expensive)**	
o MSE = 4	o Gabion wall = 1
o CIP = 2	o Wire mesh wall = 5
o Gravity wall = 3	

▪ **Would you please rank the following downward type walls in terms of unit cost of construction? (1 most expensive)**	
o Nailed wall = 6	o Drill Shaft wall (w/ anchors) = 2
o Tie Back wall = 5	o Sheet pile wall = 4 (higher if sheet stay)
o Drill Shaft wall (w/o anchors) = 3	o Diaphragm wall = 1
▪ **Would you please rank the following upward type walls in terms of duration of construction? (1 slowest)**	
o MSE = 2	o Gabion wall = 5
o CIP = 1	o Wire mesh wall = 4
o Gravity wall = 3	
▪ **Would you please rank the following downward type walls in terms of duration of construction? (1 slowest)**	
o Nailed wall = 5	o Drill Shaft wall (w/ anchors) = 1
o Tie Back wall = 6	o Sheet pile wall = 4
o Drill Shaft wall (w/o anchors) = 3	o Diaphragm wall = 2
▪ **What would be a standard design life for the following wall types? (years)**	
o Cast in place = 50	o Sheet pile wall = 10
o Drill Shaft wall = 75	o Diaphragm wall = 75
o MSE Wall = 50	o Wire mesh wall = 25
o Tie Back wall = 50	o Gravity wall = 50
o Nailed wall = 25/50 (soil/rock)	o Gabion wall = 25
• **Is there any additional point that you believe needed to be included in this analysis?**	
"Wall selection was historically driven by technical parameters but the advancements in technology, materials and design knowledge have shifted the owner requirements to those coming from economic and schedule constraints. Improved geotechnical investigations would allow more adjusted designs and longer lasting wall performances"	
YOUR PARTICIPATION AND RESPONSES ARE GREATLY APPRECIATED	

Appendix D

Completed Retaining Wall Selection Model. Flowchart.


RETAINING WALL SELECTION MODEL
(RWSM)

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*Surveys performed to Eight different professionals of the Construction Industry. February-March 2014.

*Interviews performed to Five different professionals of the Construction Industry. February-March 2014.

Biographical Information

Fernando Pizarro Quintanar was born in Ciudad Real, Spain on the 4th of June of 1985. He is the youngest son of Miguel Pizarro Barranquero and Rosario Quintanar Sanchez-Alarcos. He received his B.S. and M. Sc. Degrees in Civil Engineering with specialization in Geotechnical and Structural Engineering from the University of Castilla-la-Mancha (Spain) in 2008. Once graduated, he immediately joined Ferrovial-Agroman; Spain based Company with presence in four continents for construction and management of a variety of infrastructure projects. After three years as Quality and Production Manager in different construction Projects of the Spain-France High Speed Railway in the Barcelona area (Spain), the author was offered a position in the United States on to work in a major construction Project as the Design and Construction Quality Manager in 2011. With the support of his Company, the author enrolled the M. Sc. at the University of Texas at Arlington in September 2012 as a MS Candidate in Construction Management under the supervision of Dr. Mohammad Najafi.

The author's research interests include Construction Process Optimization, Improvement and Automation, Construction Quality, Project Management and Control, Public-Private-Partnerships (PPP) Contracting and Negotiation as well as technical topics in relation with Structural and Geotechnical Engineering.

Additionally to the technical and research ones, the author's interests include Finance, Management, Leadership and Strategy.