COMPARISON OF THE INSTALLATION OF STRAND WITH STEEL BAR TENDONS IN ANCHORED DRILLED SHAFT WALL

by

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Abstract

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Anchored drilled shaft walls are common in construction nowadays in the U.S. The use of either strand tendons or steel bar tendons as anchors in construction is approved. However, there is no information from a construction standpoint, of what type of tendon fits better depending on the field conditions or the project requirements. Nor is there any study reflecting the construction process and sequence of this type of retaining wall depending on the type of tendon.

This research will evaluate different consequences of the selection of the type of tendon. It will analyze the design aspects, construction scheduling, construction costs, and testing and instrumentation of anchored drilled shaft walls. Using a hypothetical anchored drilled shaft wall, this thesis will evaluate different sequences for the construction of these retaining walls.

With information provided by a case study, an evaluation of the reliability of each type of tendon will be presented. Different instrumentation readings will be provided to show the performance of each different type of tendon. The results of this thesis show

that strand anchors are, from a construction point of view, more cost and time efficient, and they have lower space limitations compared to steel bar anchors.

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Chapter 1

Introduction

1.1 Anchored Drilled Shaft Retaining Wall

Anchors, also known as tiebacks, are used nowadays in many construction applications, such as, protection of slopes, correction and prevention of landslides, retaining walls, shoring of excavations, and increasing the capacity of new or existing retaining walls. This thesis will focus on how tiebacks are used on the new construction of anchored drilled shaft walls, how they affect the construction process, and how they modify the construction costs.

As per the Federal Highway Administration’s (FHWA's) Geotechnical Engineering Circular No. 4 entitled “Ground Anchors and Anchored Systems” (Sabatini et al, 1999), an anchored drilled shaft wall is considered a soldier beam and lagging wall. Drilled shaft walls are anchored with tiebacks when the geotechnical conditions make anchoring necessary. The geotechnical conditions dictate if the use of ground anchors (soil or rock nail walls) is suitable when a retaining wall is built.

However, a cantilever drilled shaft wall could be built in most ground conditions. Decreasing the distance in between centers resolves the lateral pressure problems as well as increasing the diameter of the drilled shafts. In some occasions, if tie-backs are not feasible a "tangent" wall can be built, that is, a drilled shaft wall with a distance in between piers of one pier diameter (Sisson et al., 2004). However, inclusion of the anchors is done to reduce the costs of construction due to the use of larger diameter drilled shafts with greater embedment, with a greater amount of rebar, with less distance in between drilled shafts and with more concrete. Therefore, the combined solution of a tieback anchored drilled shaft wall is mostly accepted when the geotechnical conditions are not acceptable for the construction of a tieback anchored retaining wall, and to reduce the construction costs of a cantilever drilled shaft retaining wall.

The purpose of this thesis is to explain the differences in the construction process of the anchored drilled shaft walls depending on the type of tieback anchor used. The comparison will focus on the two types of anchors that are most widely used: the strand tendons and the steel bar tendons. In order to fully understand the differences between these two types of anchors, a complete understanding of the ground anchor components and their goals is needed. Then, when explaining the differences between the tendons, it will be easier to evaluate which ones are more critical and which ones are more irrelevant. It is also imperative to evaluate the differences in the construction process and the possible cost impacts for each type of anchor.

At the time of this thesis writing, the “*IH-635 Managed Lanes Project*” in Dallas, Texas, was constructing over 10,000 linear feet of anchored drilled shaft walls. Information provided from this project is used in this thesis. Although for the design and construction parts of this research, a hypothetical retaining wall is used, for the testing of the tiebacks and the instrumentation to evaluate the performance of the anchors, valuable data from the above mentioned project was analyzed. Figure 1.1 shows above-mentioned project for two of the anchored drilled shaft walls being built. Figure 1.2 shows a closer look of the northern wall of the two shown in Figure 1.1

Figure 1.1 Overview of the retaining walls of the "IH-635 Managed Lanes Project."

(Personal file, February 10, 2014)

Figure 1.2 A closer look at retaining walls of the "IH-635 Managed Lanes Project."

(Personal file, Jan 21, 2014)

1.2 Typical Construction Sequence

The construction process of a standard drilled shaft retaining wall is affected greatly by the inclusion of the tieback anchors. An explanation of the construction process is explained thoroughly in the following sections:

I. Installation of drilled shafts (soldier piles)
II. Construction of capping beam.
III. Excavation to anchor elevation.
IV. Drilling of anchor. Stressing and testing of the anchor as per the Post Tensioning Institute's recommendation (PTI, 2004).
V. Excavation to the next anchor level.
VI. Installation of anchor, stressing and installation of lagging (cast-in-place concrete facing when on permanent walls).
VII. Excavation to the next anchor level.
VIII. Installation of lagging (cast-in-place concrete facing when on permanent walls).
IX. Finish excavation.

Figure 1.3 shows each step of the construction process for an anchored concrete pile retaining wall as outlined above.

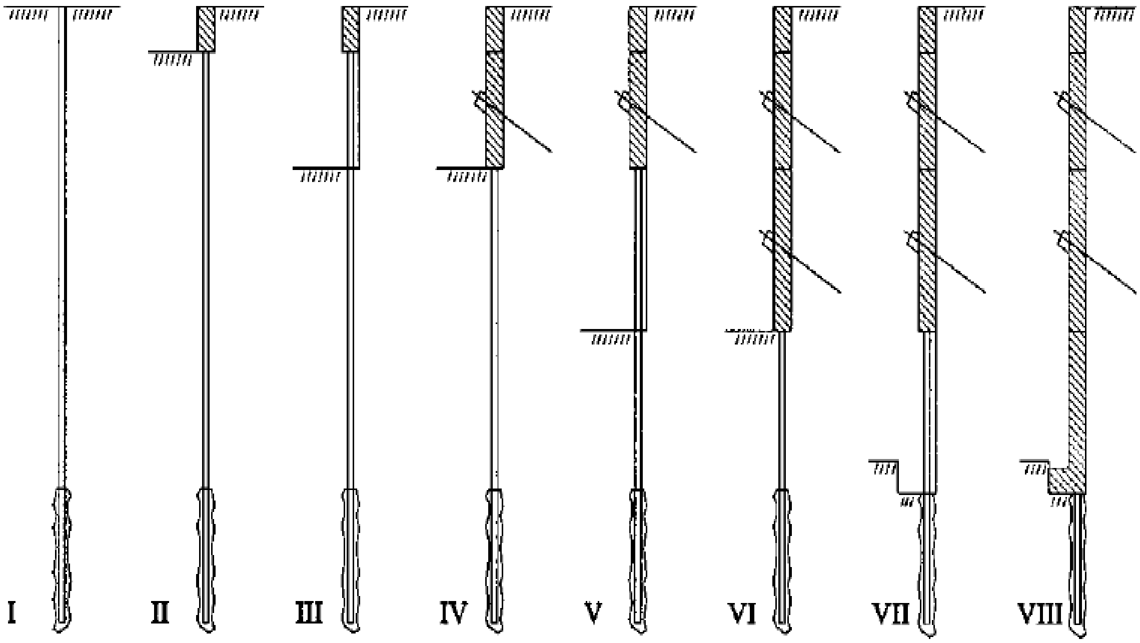


Figure 1.3 Construction sequence of an anchored concrete soldier pile retaining wall (Guerra et al., 2004)

1.3 Anchor Components

According to the FHWA's Geotechnical Engineering Circular No. 4 entitled “Ground Anchors and Anchored Systems” (Sabatini et al., 1999), the components of a ground anchor are different depending on the type of anchor installed. A review of the elements of each anchor is presented below.

1.3.1 Anchorage.

The anchorage is the system that transmits the prestressing force from the tendon to the supported structure. The anchorage system basics are the same for both a strand tendon and a bar tendon. Figure 1.4 shows all the components of a ground anchor. These components can be divided into main categories of Anchor Head, Bearing Plate, and Trumpet:

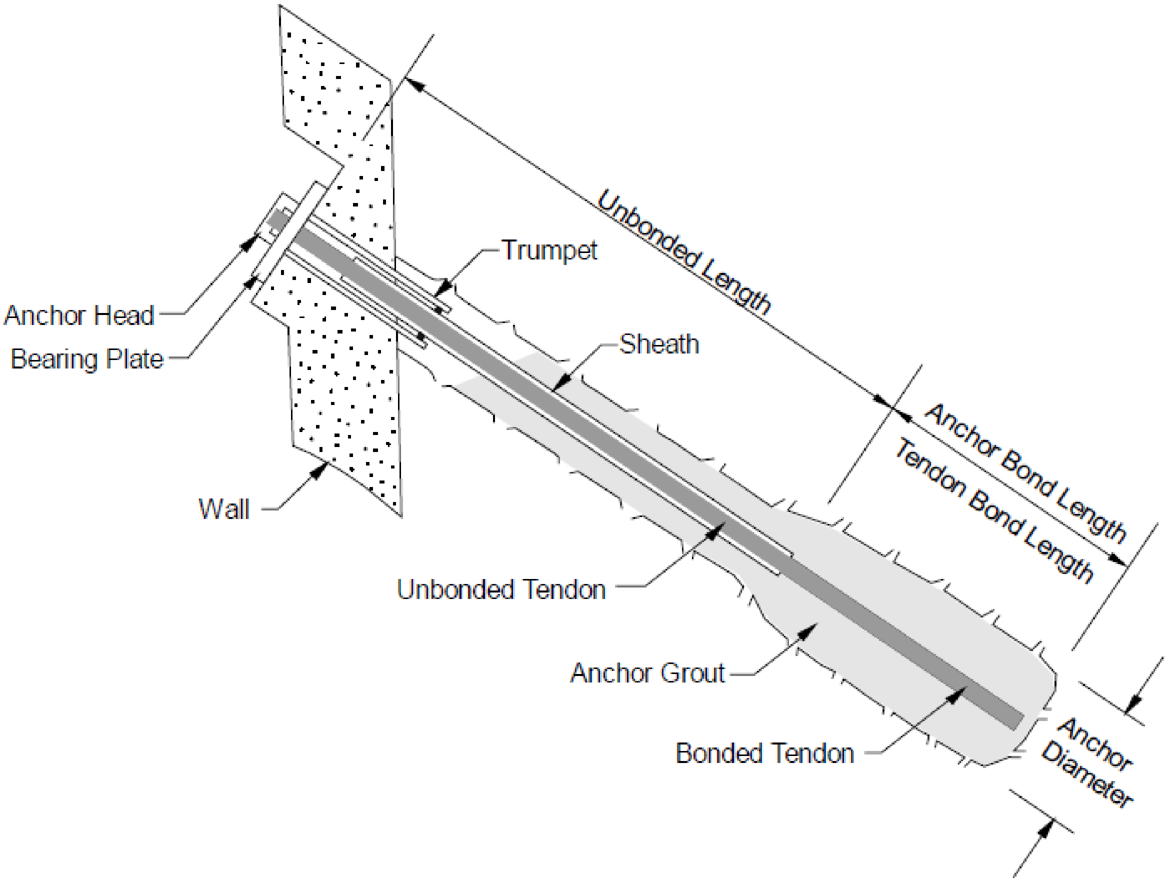


Figure 1.4 Components of a ground anchor

(Sabatini et al., 1999).

1.3.2 Tendon

The tendon includes the prestressing steel, corrosion protection, sheaths or sheathings, centralizers, and spacers. These elements are described for each different type of tendon. The tendon length can be divided in two areas:

a. Free stressing (unbonded) length: The unbonded length is the length of the tendon that is free to elastically elongate in order to transfer the resisting force to the structure. This unbonded length of the tendon is covered with a bond breaker to prevent the tendon from bonding to the grout. The bond breaker is usually referred as a sheathing and it consists of a smooth or corrugated tube or pipe plastic sleeve that is placed around the tendon's unbonded length.

b. Bond length of the tendon is the length that is bonded to the grout and is able to transmit the applied tensile load into the ground.

There are many variables depending on the type of tendons that are being used. Although there are other anchor types that are used in the United States, this thesis concentrates on the ones that are most widely used, the steel bar and the strand tendons.

i. Steel bar tendons. Steel bar tendons will need to comply with the specification from the American Society of Testing and Materials (ASTM) A722 (ASTM A722/A722M, 2012).

  - Bar anchors are available in 1" (26 mm), 1-1/4" (32 mm), 1-3/8" (36 mm), 1-3/4" (46 mm), 2-1/2" (66mm) and 3" (75 mm) nominal diameter, in lengths up to 60 feet (18.3 m) without couplers, with a guaranteed minimum ultimate tensile stress of 150 or 160 ksi (1034 or 1103 MPa) (DYWIDAG-Systems International, (2014)). For lengths greater than 18.3 meters or 60 feet, the use of couplers is mandatory.
  - Corrosion protection for steel bars depends on the class of protection that is needed, as follows:
    i. Class I protection is a double layer protection with an encapsulated tendon and it is used on soils that are aggressive on the bonded and the unbonded length.
      1. On the unbonded length, the protection consists on a grout filled sheath around the tendon, a bond breaker which is usually a smooth sheath that allows the prestressing steel to deform freely, and a grout encasement around the bond breaker that works as a second layer of protection. Protection of the couplers is done by applying either a corrosion proof

        compound or wax impregnated cloth tape and a smooth plastic tube.

    2. On the bonded length, corrugated encapsulation bonds the anchor to the outside grout and the second layer of grout is used as protection of the anchor.

- ii. Class II protection assumes a multilayer protection on the unbounded length of the anchor and a single layer protection on the bonded length of it.
    1. On the unbonded length, a smooth sheath plus a grout encasement is used around the anchors.
    2. On the bonded length, the anchor is just encapsulated with grout.
- iii. Class III no protection is used when the soil is known to be nonaggressive.

Figure 1.5 illustrates Class I corrosion protection for a steel bar tendon. The upper left section of Figure 1.5 (Section A) shows a cross section of the unbonded length of the anchor with its double layer of protection and the bond breaker. On the upper right corner of the figure (Section B), the cross section represents the bonded length of the anchor with its double layer of protection.

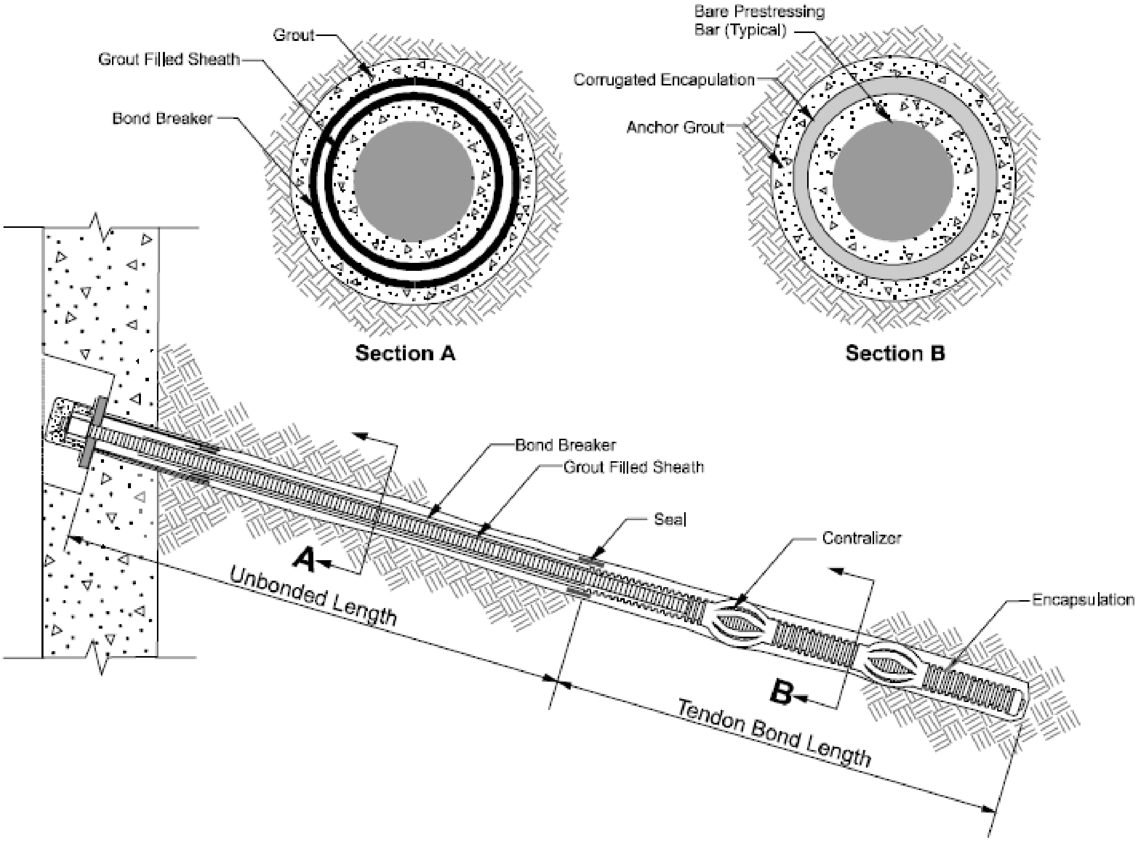


Figure 1.5 Corrosion protection Class I for bar tendons

(Sabatini et al., 1999).

- Due to its nature, bars are easier to stress and the load can be adjusted after lock-off.
- The anchorage system of the bar tendons are shown in Figure 1.6. The main difference of bars with the strand tendons is the locking system that in the case of the bar is an anchor nut. Figure 1.6 shows the components of the anchorage system for a steel bar tendon, the anchor nut and the bearing plate.

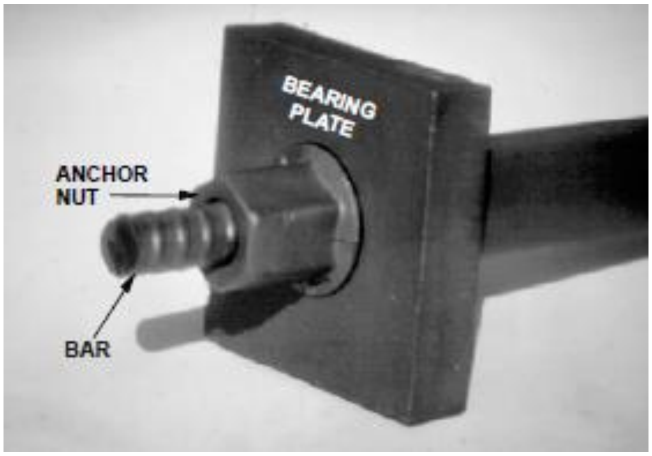


Figure 1.6 Anchorage components for a bar tendon

(Sabatini et al., 1999).

- Spacers and centralizers are used to ensure a minimum grout cover around the steel bars and are located typically every 3 meters.

ii. Strand tendons. ASTM A416 (ASTM A416/A416M-12a, 2012) specifies the requirements for strand tendons.

  - Strand tendons are comprised of multiple seven-wire strands that in the U.S. are commonly 15.2 mm diameter (DYWIDAG-Systems International 2014). Due to the fact that multiple strands can be used, there is not a practical load defined for them.
  - Due to its nature, strands do not have length limitations. Therefore, couplers are not commonly needed. Although they are available, they are not recommended because their diameter is much larger than that of the strands. Strand couplers are only recommended when tendons are to be repaired. When used, corrosion protection at the coupler location must be monitored and verified.
  - Corrosion protection for strand tendon anchors depends on the class of protection that is needed.

i. Class I protection is a double layer protection with an encapsulated tendon and it is used on soils that are aggressive on the bonded and the unbonded length.
    1. On the unbonded length, the protection consists of a grease filled strand sheath around each strand, a sheath that encapsulates the whole tendon, and a grout encapsulation around the smooth sheath.
    2. On the bonded length, corrugated encapsulation will bond the anchor to the grout, and a second layer of grout will be used as protection for the anchor.

ii. Class II protection assumes a multilayer of protection on the unbonded length of the anchor and a single layer of protection on the bonded length of it.
    1. On the unbonded length, a grease filled strand sheath is used around each strand plus a grout encasement will be used around the whole tendon.
    2. On the bonded length, the anchor will just be encapsulated with grout.

iii. Class III: No protection is used when the soil is known to be nonaggressive.

Figure 1.7 illustrates Class II corrosion protection for a strand tendon. Section A shows a cross section of the unbonded length of the anchor with its single layer of protection and the bond breaker. Section B shows the cross section of the bonded length of the anchor with its single layer of protection.

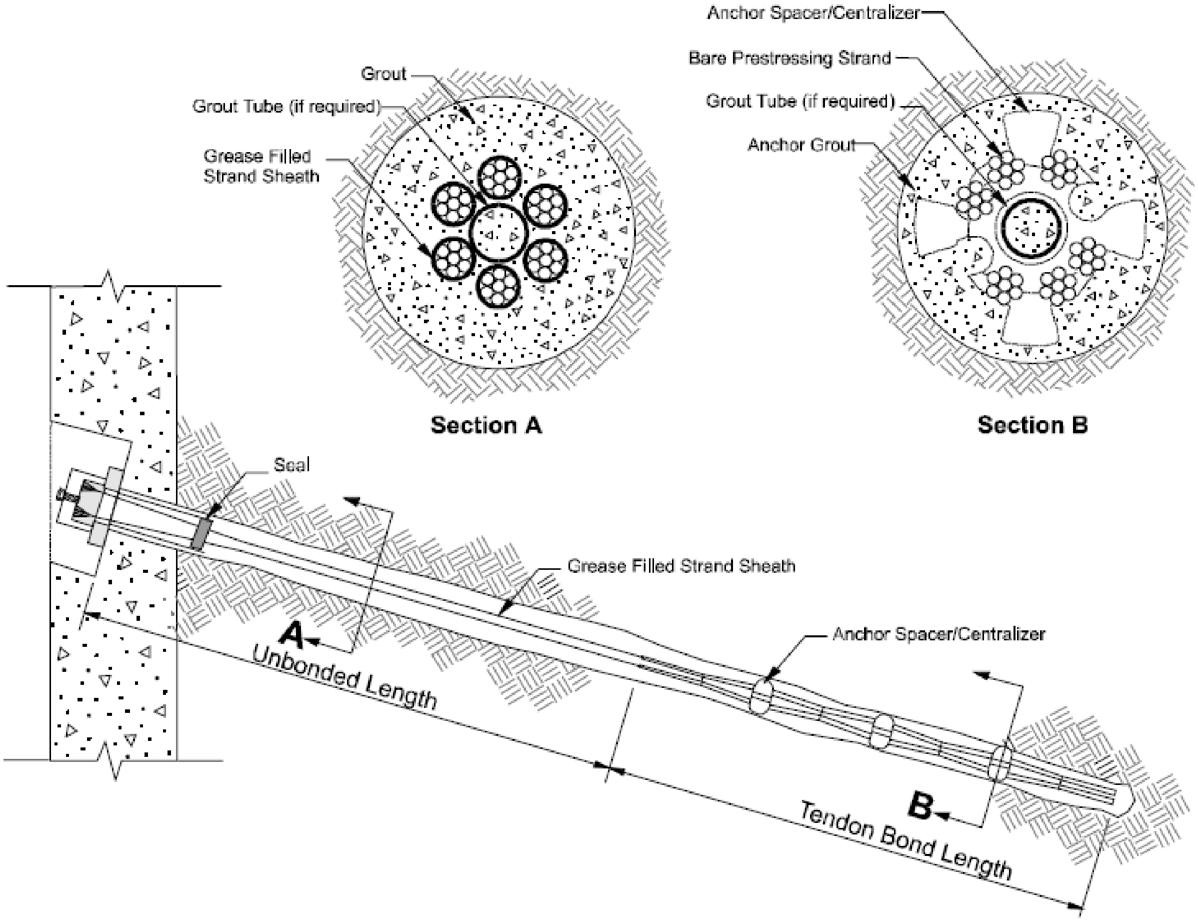


Figure 1.7 Corrosion protection Class II for strand tendon

(Sabatini et al., 1999).

- Spacers and centralizers are used to maintain the strand tendon on the center of the drill hole and to ensure a minimum amount of grout cover around the tendon. They are located typically every 3 meters. On strand tendons, an inter-strand spacer needs to be used to ensure a proper spacing between strands.
- The anchorage system of the strand tendons differs from the steel bar tendons on the locking system. On the strand tendons the locking system consists of a wedge plate and the wedges as shown in Figure 1.8. The bearing plate will complete the anchoring system.

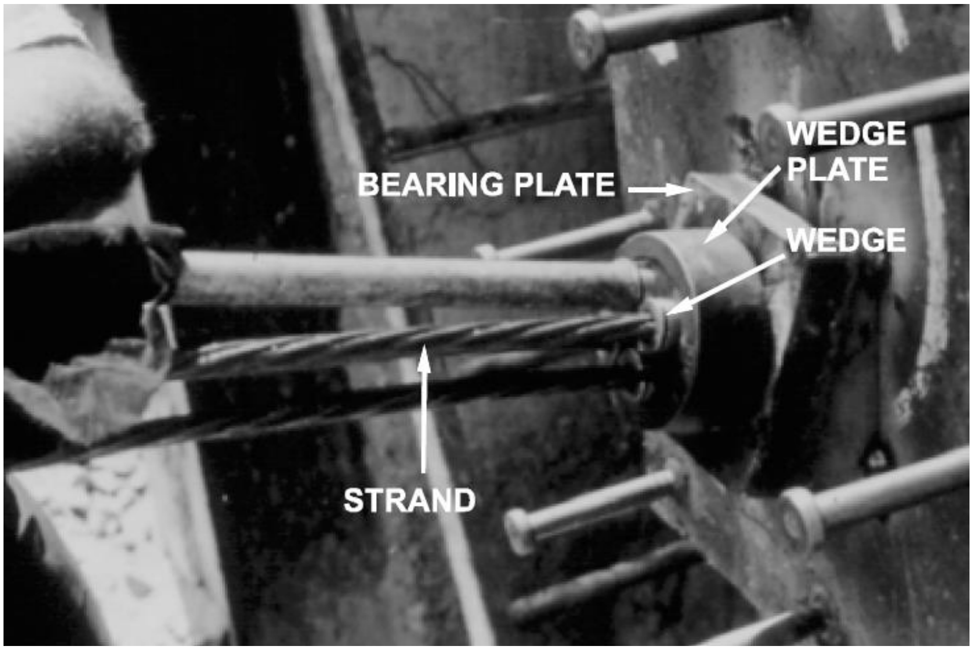


Figure 1.8 Anchorage components for a strand tendon

(Sabatini et al, 1999).

1.3.3 Grout

The grout is a mixture of Portland cement that transmits the load of the tendons to the ground and helps to protect the tendons against corrosion. The grout must conform to ASTM C150 (ASTM C150/C150M-12, 2012) with a water cement ratio between 0.4 and 0.55 by weight.

1.4 Objectives

The objectives of this thesis are:

- Explain the construction process of an anchored wall that uses either steel bar tendons or strand tendons and how this construction process can be improved to achieve a more effective construction.
- Compare the performance of the different type of anchors, strand tendons or steel bar tendons.

- Analyze the connection or relationship of the construction process to the anchor selection.
- Create a decision support system from which a contractor or designer can decide which type of anchor is suitable for each specific project and site conditions.

1.5 Scope of the Study

The scope of this research comprehends four different aspects of an anchored drilled shaft wall, which includes design, construction, testing and instrumentation. The impact of tendon selection to the above parameters is evaluated.

In this research, design of an anchored drilled shaft wall is not included. However it explains how the tendon is selected depending on the designed parameters. The construction phasing or sequence, the space needs for the construction, and the production rates and costs are evaluated for each type of tendon. The testing and the instrumentation is studied with data from the “IH-635 Managed Lanes Project.” This information is analyzed to conclude which tendon is more reliable.

The information analyzed in this research is site and project specific. Therefore, its conclusions cannot be extrapolated as general rules of thumb. This research relied on interviews with knowledgeable personnel and observations of field operations to come up with sufficient information to perform the work scope of it.

This thesis provides a decision support system to help engineers and contractors make retaining wall support decisions depending on the conditions of their projects, the type of tendon that needs to be used, and the construction sequence that needs to be followed.

1.6 Research Needs

Construction of anchored soldier pile walls is a common method in highway construction. It is being used all over the U.S. and around the world. In many cases, it is referred to as anchored drilled shaft walls, where the drilled shafts act as soldier beams and a shotcrete facing is set in between them in lieu of the timber lagging system.

Although the construction of anchored retaining walls is common practice and there is literature that refers to the construction process, in the end, the construction process is left to the designer or contractor. This thesis focuses on the most effective way to build these retaining walls and different possible sequences for building them are described. Although, it may occur that the construction sequences may not differ greatly from one process to another, the effects on the schedule and the cost related to the construction of the walls are tremendous. In the construction world, time and cost is everything. Therefore, this research will evaluate the most cost effective and time efficient way to construct these walls.

The different type of tendons used in the construction of anchored drilled shaft walls are not taken into consideration in any of the references used in this thesis. The selection of either strand tendons or steel bar tendons will have a huge impact on the construction process and its outcome. A case study of a hypothetical retaining wall is used to evaluate the cost and schedule differences due to the type of anchor selected. Using information from the *“IH-635 Managed Lanes Project,”* this thesis concludes specific answers regarding the reliability of each type of anchor.

No research was found that evaluates the differences created by selecting a type of anchor in both time and cost. Therefore, this research study is unique and necessary to probe the importance of the anchor selection.

1.7 Expected Outcomes

This research set out to establish guidelines for the use of strand tendons anchors and steel bar anchors for an anchored drilled shaft wall. Strand anchors were considered the preferable from the beginning because of their low rigidity, and easy handling. Strand tendons were also set forth as the best option in most cases. However the steel bar tendon was deemed capable of better results because of its ability to minimize onsite tasks (i.e., internal grouting is done off site), which can also serve to minimize potential problems.

Strand tendon installation is expected to be less expensive and more efficient than steel bar tendon installation. Therefore, strand tendons are expected to be the selected option for most applications.

1.8 Methodology

For this thesis, different sources of information were used: Literature research, interviews and field observations provided information to needed to develop the research topic. This thesis compares four different aspects of the anchored drilled shaft walls. All four aspects are evaluated herein depending on the type of anchor selected.

Because all research objectives are related to the construction of anchored retaining walls, the focus is mainly on tendon selection. The thesis research on the construction phase is divided into three different sections: (1) sequencing of construction, (2) availability of space, and (3) anchor installation. The anchor installation section evaluates productivity and costs of anchor installation.

The selection of tendons and construction methodology was evaluated using a hypothetical retaining wall while the testing of the anchors and the instrumentation to monitor the performance of the retaining wall used valuable information provided by the “IH-635 Managed Lanes Project” along with personal interviews and field observations.

1.9 Chapter Summary

This chapter presented an introduction and background of this thesis. The need for this study and its objectives as well as the methodology to fulfill those objectives and work scope were included.

This thesis will fill an existing gap by comparing the construction process of an anchored drilled shaft wall that uses strand tendons or steel bar tendons focusing on the costs, productivity and reliability of each type of tendon. It will perform this task by evaluating the design, construction, testing and instrumentation aspects of these walls. The goal is to provide contractors and designers with background information to help in the selection of the type of tendon needed for each construction process.

Chapter 2

Background and Literature Review

In this chapter, the author will provide the information needed to perform the work scope of this thesis. General background information about the construction of anchored drilled shaft walls will be provided. The design, construction, testing and instrumentation of this type of retaining walls will be reviewed to provide the sufficient backup information to support this thesis.

2.1 Background

Anchored walls were introduced in the 1930s in Europe and were widely applied to all major structures by the 1960s. There were, and still are, many reasons for the use of ground anchors.

At the beginning, ground anchors were mainly used for shoring excavations in European urban areas. Due to the compact and highly populated areas, excavation and retention techniques were needed, which could operate with minimum disturbance to land owners and to those needing to travel in the areas affected by construction. According to Cheney (1990) “Anchored walls substantially reduced the amount of land required for construction while also reducing the project cost.” (Cheney 1990)

However, at that time, there was almost no information established to be able to assess the actual permanent capabilities of these ground anchors, and they were considered a temporary solution (Cheney, 1990).

European agencies started investigating ways to obtain the information needed to be able to determine what conditions were suitable to install ground anchors in permanent construction. Using empirical data and long-term observation, these agencies published different codes regarding ground anchors. These codes did not only affect the ground anchor design but its construction as well, and contractors that were willing to use this construction methods were carefully evaluated for approval (Cheney, 1990).

In the United States, permanent ground anchors were not commonly installed until the late 1970s. Although, the first permanent ground anchor wall was constructed in Detroit, in 1961, public agencies were reticent to put ground anchors into practice for different reasons:

- The lack of experience on the construction and design of permanent ground anchor walls (Cheney, 1990).
- The preoccupation regarding the permanent features of ground anchors. The concerns basically affected corrosion and creep (Cheney, 1990).
- Lack of information for cost effectiveness applications (Cheney, 1990).
- The lack of tools from a contracting standpoint to warrant the quality of the product from the contractor (Cheney, 1990).

However, in 1979 the FHWA authorized a ground anchor demonstration project. The goal of the FHWA was to give the public agencies sufficient knowledge to use permanent ground anchors with confidence (Sabatini et al., 1999).

Nowadays, the construction of permanent ground anchor walls is a common technique that offers advantages over other more conventional systems. Some of these advantages are stated below (Sabatini et al., 1999):

- Excavations with no obstacles.
- Increase the capabilities of retaining walls to overcome larger pressures without increasing the wall thickness significantly.
- Elimination of temporary shoring for the excavation.
- Elimination of the select backfill in front of the wall.
- Reduce construction schedule.
- Reduce the right-of-way acquisitions.

On June 1999, the FHWA published the *“Geotechnical Engineering Circular No.4. Ground Anchors and Anchored Systems”*. With this circular the FHWA intended to give state-of-the-practice information on the ground anchors systems for highway applications (Sabatini et al.

1999). However, the authors admitted that design and construction of ground anchors and anchored systems was evolving, and this circular will have to be reviewed in the future with the addition of new technologies and methods.

2.2 Literature Review, Interviews, and Onsite Observations

For the completion of this research a large variety of documents were consulted. Publications on regulations and specifications from different US agencies as well as publications from regulatory agencies in other countries were consulted to ensure all perspectives on ground anchor use in construction were considered. Documenting the design part of the anchored drilled shaft walls was not as challenging due to the amount of research that has been done on this topic. However, gathering information regarding the construction process or sequencing of this kind of retaining walls was challenging because of the lack of research that has been done on it.

For the most part, articles usually reference construction as a simple activity, giving more importance to the design and testing parts, which are found to be more tedious. No author has ever conducted a study of how anchored drilled shaft walls need to be built in order to make their construction more efficient. Neither has anyone studied how the construction process is limited and varies depending the type of anchor that is being used. Therefore, in order to provide the information needed to fulfill the goals of this study, a number of interviews to professionals in the industry and a series of field observations were needed, and then sum up all the information gathered on those to evaluate the research objectives. Also, studies of production rates were conducted as well as material, equipment, and labor needs for the construction of these retaining walls. These observations were performed at the *"IH-635 Managed Lanes Project"* and they were used for *Appendix A: Calculations* in this thesis.

In order to provide a better understanding of the research paper and to facilitate its reading, the author has decided divide each part of it into four sections: design, construction, testing and instrumentation.

2.2.1 Design

This research study is not focusing on the design phase of an anchored drilled shaft wall. However, it is important for this study to evaluate the differences between strand tendons and steel bar tendons. From a design point of view, the selection of strand tendons or steel bar tendons is irrelevant. Therefore, the design will not be a factor to take into account when deciding which type of tendon is to be installed.

The design of an anchored wall was reviewed in the *"Geotechnical Engineer Circular No. 4 Ground Anchors and Anchored Systems"* of the FHWA (Sabatini et al., 1999). This Circular No.4 explains in detail the design process and defines the parameters that are to be followed. The following steps shown on Table 2.1 are explained by the FHWA Circular.

Table 2.1 Typical design steps for an anchored wall

(Sabatini et al., 1999).

Step 1	Establish project requirements including all geometry, external loading conditions (temporary and/or permanent, seismic, etc.), performance criteria, and construction constraints.
Step 2	Evaluate site subsurface conditions and relevant properties of in situ soil and rock.
Step 3	Evaluate design properties, establish design factors of safety, and select level of corrosion protection.
Step 4	Select lateral earth pressure distribution acting on back of wall for final wall height. Add appropriate water, surcharge, and seismic pressures and evaluate total lateral pressure. A staged construction analysis may be required for walls constructed in marginal soils.
Step 5	Calculate horizontal ground anchor loads and wall bending moments. Adjust vertical anchor locations until an optimum wall bending moment distribution is achieved.
Step 6	Evaluate required anchor inclination based on right-of-way limitations, location of appropriate anchoring strata, and location of underground structures.
Step 7	Resolve each horizontal anchor load into a vertical force component and a force along the anchor.
Step 8	Evaluate horizontal spacing of anchors based on wall type. Calculate individual anchor loads.
Step 9	Select type of ground anchor.
Step 10	Evaluate vertical and lateral capacity of wall below excavation subgrade. Revise wall section if necessary.
Step 11	Evaluate internal and external stability of anchored system. Revise ground anchor geometry if necessary.
Step 12	Estimate maximum lateral wall movements and ground surface settlements. Revise design if necessary.
Step 13	Select lagging. Design walers, facing drainage systems, and connection devices.

This research will only review the selection of the prestressing steel element. The selection of the tendon is determined by the following:

- The design load shall not exceed 60% of the specified minimum tensile strength, herein SMTS (PTI, 2004);
- the lock-off load shall not exceed 70% of the SMTS (PTI, 2004);
- the maximum test load shall not exceed 80% of the STMS (PTI, 2004);

- and in the case of strand tendons the lock-off load has to exceed 50% of the STMS to ensure the bite of the wedges. If needed, shims shall be used to achieve the load and to ensure this bite (PTI, 2004).

Once the design load and the maximum testing load of the ground anchors are determined, the tendons are selected using the following tables. An example calculation is provided on Appendix A.1. Table 2.2 describes the properties of the steel bar tendons depending on the diameter, while Table 2.3 shows the properties of the strand tendons depending on the number of tendons in the anchor.

Table 2.2 Properties of prestressing steel bars

(ASTM A722/A722M, 2012).

Steel grade	Nominal diameter	Ultimate stress f_{pu}	Nominal cross section area A_{ps}	Ultimate strength $f_{pu}\ A_{ps}$	Prestressing force		
					0.8 $f_{pu}\ A_{ps}$	0.7 $f_{pu}\ A_{ps}$	0.6 $f_{pu}\ A_{ps}$
(ksi)	(in.)	(ksi)	(in.^{2})	(kips)	(kips)	(kips)	(kips)
150	1	150	0.85	127.5	102.0	89.3	76.5
	1-1/4	150	1.25	187.5	150.0	131.3	112.5
	1-3/8	150	1.58	237.0	189.6	165.9	142.2
	1-3/4	150	2.66	400.0	320.0	280.0	240.0
	2-1/2	150	5.19	778.0	622.4	435.7	466.8
160	1	160	0.85	136.0	108.8	95.2	81.6
	1-1/4	160	1.25	200.0	160.0	140.0	120.0
	1-3/8	160	1.58	252.8	202.3	177.0	151.7
(ksi)	(mm)	(N/mm^2)	(mm^2)	(kN)	(kN)	(kN)	(kN)
150	26	1035	548	568	454	398	341
	32	1035	806	835	668	585	501
	36	1035	1019	1055	844	739	633
	45	1035	1716	1779	1423	1246	1068
	64	1035	3348	3461	2769	2423	2077
160	26	1104	548	605	484	424	363
	32	1104	806	890	712	623	534
	36	1104	1019	1125	900	788	675

Table 2.3 Properties of 15-mm diameter prestressing steel strands

(ASTM A416/A416M-12a, 2012).

Number of 15-mm diameter strands	Cross section area		Ultimate strength		Prestressing force					
					0.8 $f_{pu}A_{ps}$		0.7 $f_{pu}A_{ps}$		0.6 $f_{pu}A_{ps}$	
	(in.^{2})	(mm^2)	(kips)	(kN)	(kips)	(kN)	(kips)	(kN)	(kips)	(kN)
1	0.217	140	58.6	260.7	46.9	209	41.0	182	35.2	156
3	0.651	420	175.8	782.1	140.6	626	123.1	547	105.5	469
4	0.868	560	234.4	1043	187.5	834	164.1	730	140.6	626
5	1.085	700	293.0	1304	234.4	1043	205.1	912	175.8	782
7	1.519	980	410.2	1825	328.2	1460	287.1	1277	246.1	1095
9	1.953	1260	527.4	2346	421.9	1877	369.2	1642	316.4	1408
12	2.604	1680	703.2	3128	562.6	2503	492.2	2190	421.9	1877
15	3.255	2100	879.0	3911	703.2	3128	615.3	2737	527.4	2346
19	4.123	2660	1113.4	4953	890.7	3963	779.4	3467	668.0	2972

According to some research, the ultimate bond stress at the anchor-grout interface varies depending on the type of anchor. The differences are mainly due to the behavior that each anchor has in terms of load transfer mechanism. While on the steel bars the bond strength is mainly due to the mechanical interlock mobilized during the pullout movement, for the strand tendons the bond strength is due to chemical adhesion and a combination of friction and mechanical interlock (Benmokrane et al., 1995). The results of this study show that the shear bond stress at the grout-anchor interface for strand tendons are generally lower than those of steel bar anchors. This explains why the strand anchors have less resistance against pullout than the steel bar anchors.

As explained above, the type of anchor selected does not impact the design of an anchored drilled shaft wall. Although the design usually states what type of tendon is to be installed, this selection can usually be changed from strand to bar or vice versa. According to the literature that was reviewed for this research, steel bar tendons and strand tendons are easily interchangeable, and there are no design parameters that mandate which type of tendon is to be used for each situation. Therefore, the design cannot be taken as a parameter for the selection of the type of anchor.

2.2.2 Construction

Gathering information about the construction of anchored drilled shaft walls was the most challenging part of this research study for two main reasons. Firstly, the objectives of this research are all focused on the construction process and sequencing of the retaining wall. Therefore, a large amount of material was needed. Secondly, there is not a large variety of information published in articles, theses or dissertations that refer to the construction process of anchored drilled shaft walls. Moreover, there was no information found relating to the differences that the selection of the type of anchor create and their effect on the construction of retaining walls. The author had to rely on interviews with professionals in the trade and on field observations and measurements.

Due to the different objectives that this study wants to achieve, this section is divided in three different aspects.

2.2.2.1 Sequencing

The first goal of this research is to evaluate the most cost- and time-efficient way to build an anchored drilled shaft wall. In order to do so, the actual sequence of the work must be completely understood so that it can be evaluated.

An anchored drilled shaft wall is built from top down and uses elements anchored in the ground as support for the retaining wall. (Long et al., 1998). On many occasions, it uses soldier piles driven into the soil, but in this research the author will approach a situation were drilled shafts will be installed in lieu of these soldier piles.

Drilled shafts are cast in place piles that are used for deep foundations (Coduto, 2001). This is a very common deep foundation method and it has various advantages compared to soldier piles.

- Mobilizing in and out using a drilling rig is usually much cheaper than when using a pile driver (Coduto, 2001).
- There is less noise generated by the construction process (Coduto, 2001).

- The soil can be classified as it is being drilled by the engineer (Coduto, 2001).
- The length of the drilled shaft and even its diameter can be changed easily during construction due to unforeseen soil conditions (Coduto, 2001).
- The steel used can be pre-tied onsite and it is much easier to manage unlike H-Piles or steel piles that will need to be welded onsite for long soldier piles. Handling and transporting reinforcing steel is easier than H-Piles or steel piles (Coduto, 2001).

The construction of drilled shafts has some preliminary tasks that need to be done prior to the drill rig mobilization. The first task is to tie the steel for the drilled shaft. In most occasions, this tying is performed by a professional steel tying company.

Reinforcing steel is tied outside of the hole on top of a flat area. When drilled shaft steel is designed to be longer than 60 feet long, it is common to have the reinforcing steel shipped to the jobsite in two different pieces. These two pieces will have to be lapped with the proper splice length. Transporting material larger than 60 feet long requires special permits (oversize permits), predetermined routes and escorts. Most contractors and suppliers will try to avoid this type of shipments at all times to reduce costs and headaches. Figure 2.1 shows the length limitations for a truck semitrailer, and Table 2.4 shows the splice length requirements imposed by the Texas Department of Transportation.

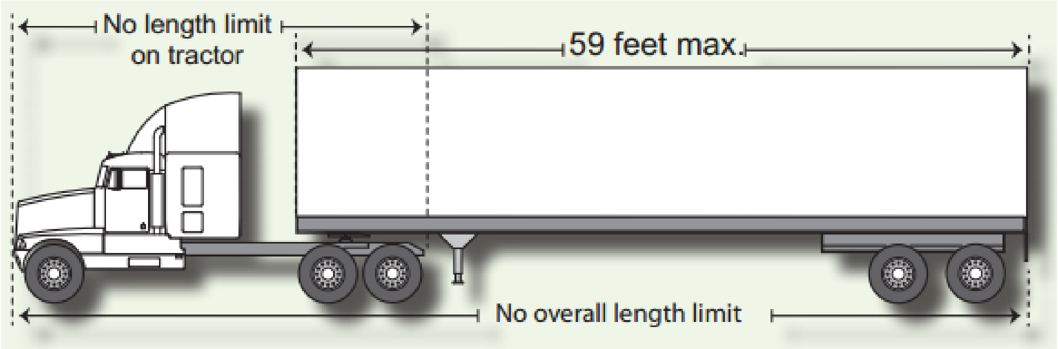
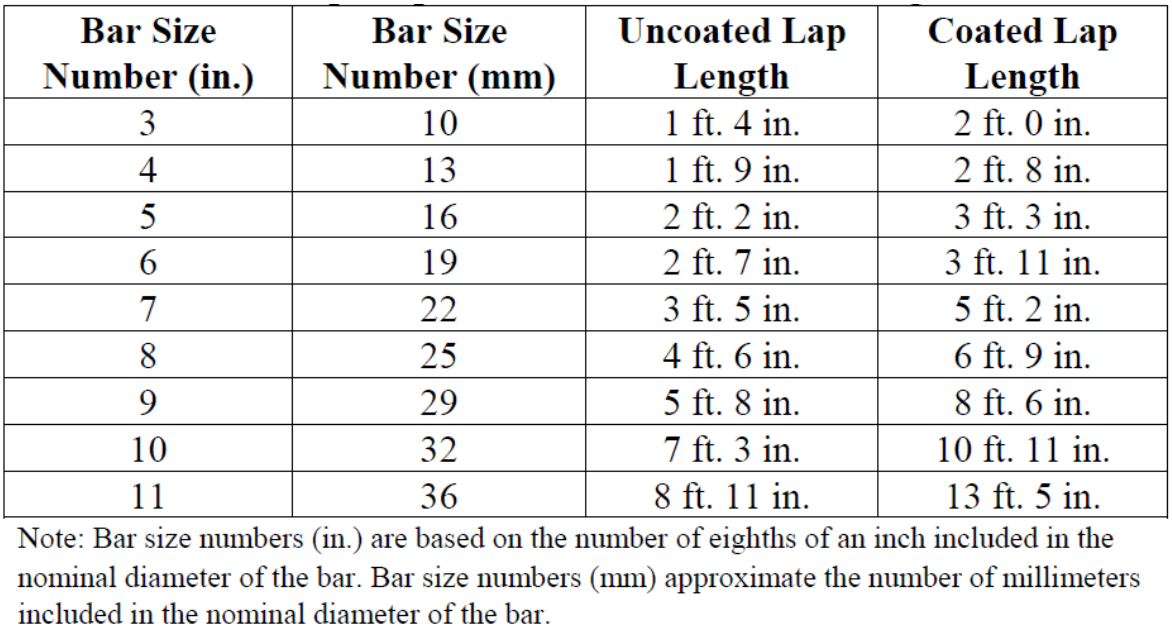


Figure 2.1 Length limitations for a semitrailer

(TxDMV 2014).

Table 2.4 Minimum Lap Requirements for Bar Sizes through No. 11 for the state of Texas (TxDOT, 2004).



Bar Size Number (in.)	Bar Size Number (mm)	Uncoated Lap Length	Coated Lap Length
3	10	1 ft. 4 in.	2 ft. 0 in.
4	13	1 ft. 9 in.	2 ft. 8 in.
5	16	2 ft. 2 in.	3 ft. 3 in.
6	19	2 ft. 7 in.	3 ft. 11 in.
7	22	3 ft. 5 in.	5 ft. 2 in.
8	25	4 ft. 6 in.	6 ft. 9 in.
9	29	5 ft. 8 in.	8 ft. 6 in.
10	32	7 ft. 3 in.	10 ft. 11 in.
11	36	8 ft. 11 in.	13 ft. 5 in.

Note: Bar size numbers (in.) are based on the number of eighths of an inch included in the nominal diameter of the bar. Bar size numbers (mm) approximate the number of millimeters included in the nominal diameter of the bar.

Traditional configuration of the steel for the drilled shaft is shown on Figure 2.2 below. However, due to the fact that the N-M interaction surface of an anchored drilled shaft wall does not demand symmetry, the longitudinal reinforcement of the piles could be optimized (Gil-Martin et al., 2012). Although this optimization will not be used for the research, it should be studied for future projects. Figure 2.3 shows different optimization examples for the reinforcement of a retaining wall drilled shaft. In Figure 2.3b. the steel is concentrated on the tensile area of the drilled shaft minimizing the total quantity of steel needed. In Figure 2.3c. two different sizes of steel are used, minimizing the total quantity of steel used in the drilled shaft.

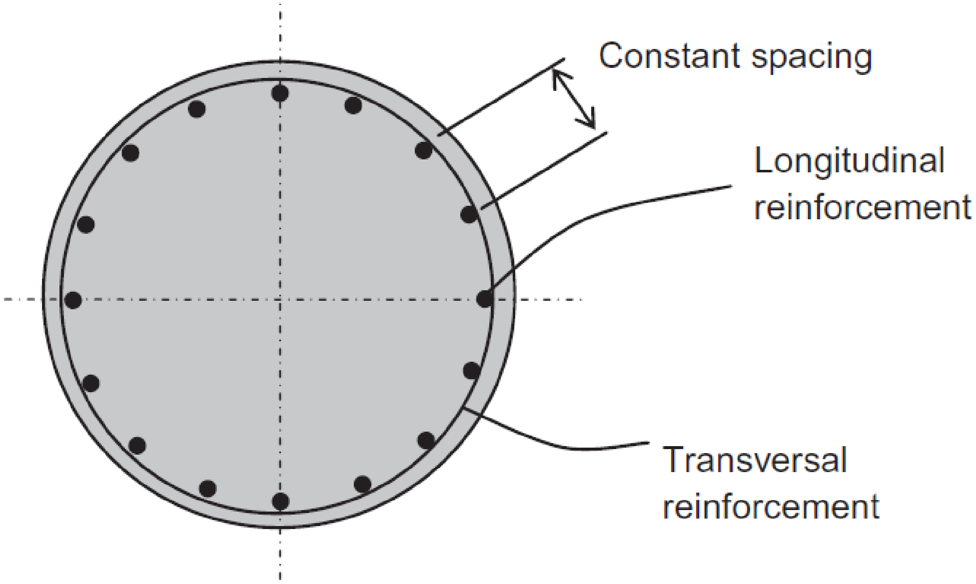


Figure 2.2 Traditional configuration of longitudinal steel

(Gil-Martin et al., 2012)

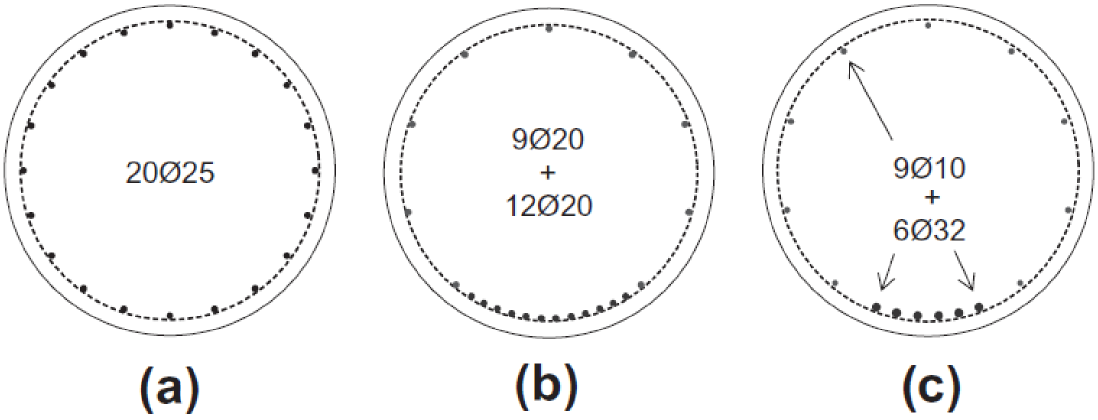


Figure 2.3 Optimization of longitudinal steel. (a) conventional reinforcement; (b) optimized reinforcement using a single bar diameter; (c) optimized reinforcement using a two bar diameter (Gil-Martin et al., 2012).

Although the optimization of the longitudinal reinforcement may reduce greatly the costs for material (reinforcing steel) and labor (tying of the steel), it may not be an applicable solution for an anchored drilled shaft wall. The extra reinforcement located on the tensile zone of the drilled shaft will prevent the installation of the required trumpet for the tieback. Figure 2.4 shows the actual location of the trumpet in red, in a cross section of a drilled shaft.

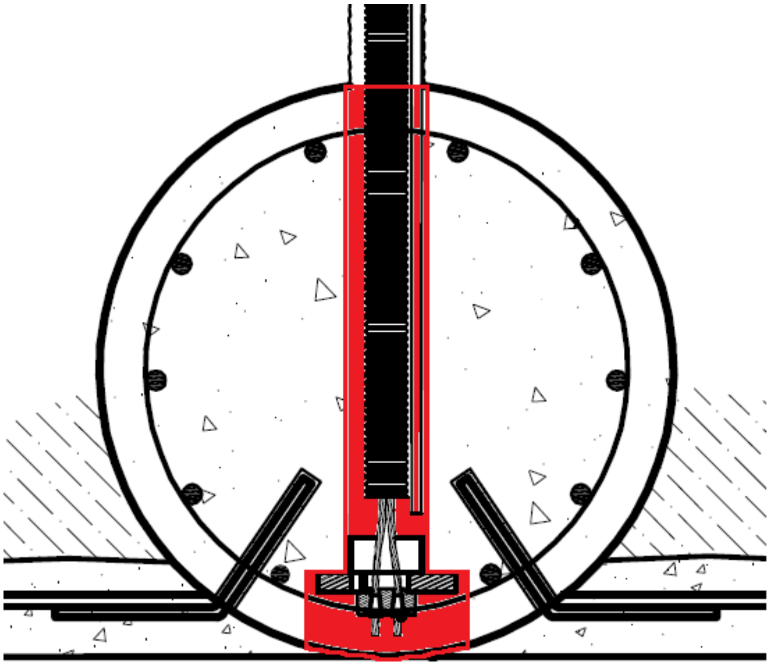


Figure 2.4 Plan view of a drilled shaft with a strand anchor installed; trumpet outline is in red (Personal file, February 24th, 2014).

Either the steel tiers or the ground anchor contractor will proceed with the installation of trumpets once the steel cages are tied. These trumpets will work as a block out inside the drilled shafts for the installation of anchors (O.O., Interview 1, February 3rd, 2014). These trumpets are critical because they are part of the anchorage system of the anchored wall, and its location will directly affect the installation of the tiebacks. Elevation, inclination with the vertical and with the horizontal needs to be measured with precision so that the anchor is drilled within tolerance (JIL, Interview 2, January 24th, 2014). Figure 2.5 shows how the trumpets are pre-installed in a drilled shaft steel cage to be installed as the reinforcing steel for the pier.

Figure 2.5 Trumpet installation on drilled shaft reinforcing steel

(Personal picture, January 16th, 2014).

After the preparatory work for the drilled shaft installation is complete, the drilling rig will mobilize to the jobsite along with the auxiliary equipment needed for the drilling operations (crane to set the steel and loader to remove the spoils and move reinforcing steel as it is shown in Figure 2.6). Depending on the type of soil and its conditions the drilling method will be chosen. There are three different methods: the dry method, the casing method and the wet method.

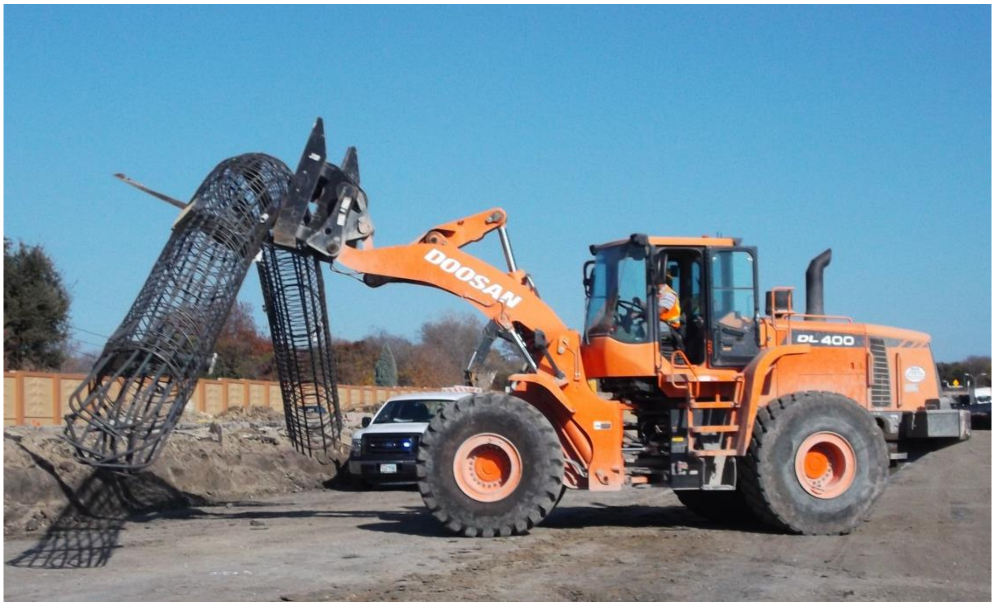


Figure 2.6 Loader handling reinforcing steel

(Personal picture, December 3rd, 2012).

The drilling sequence for the dry method is described below:

i. Drill the shaft with the drilling rig (Coduto, 2001).
ii. Clean the base using a bucket or flat bottom tool to remove debris and possibly any water (Brown et al., 2010).
iii. Depending on the design, concrete may need to be poured on the bottom part of the drilled shaft (Coduto, 2001).
iv. Install the pre-tied steel cage with the trumpets in it using either a crane or the drilling rig (Coduto, 2001).
v. Pour concrete into the top of drilled shaft (Coduto, 2001).

Figure 2.7 shows the different sequence steps for the dry method installation of drilled shafts. Pouring concrete on the bottom is not needed for this example.

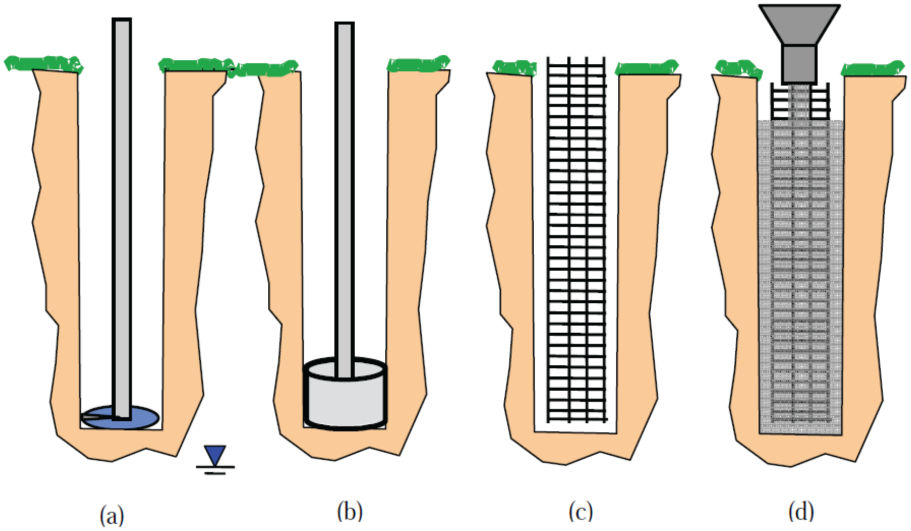


Figure 2.7 Dry Method of Construction: (a) Drill the hole; (b) Clean the Base; (c) Place Reinforcement; (d) Place Concrete

(Brown et al., 2010).

For this thesis's purposes it will be assumed that the dry method will be used. Figure 2.8 and Figure 2.9 show onsite reinforcing steel installation. Figure 2.8 shows how the steel is inserted inside the drill hole, and Figure 2.9 shows how it is picked up with the help of a crane. Handling of the steel needs to be done with extreme care to ensure that the cage is not damaged during its movement. Moreover, the inclusion of trumpets inside of the reinforcing cage makes this handling an even more critical operation.

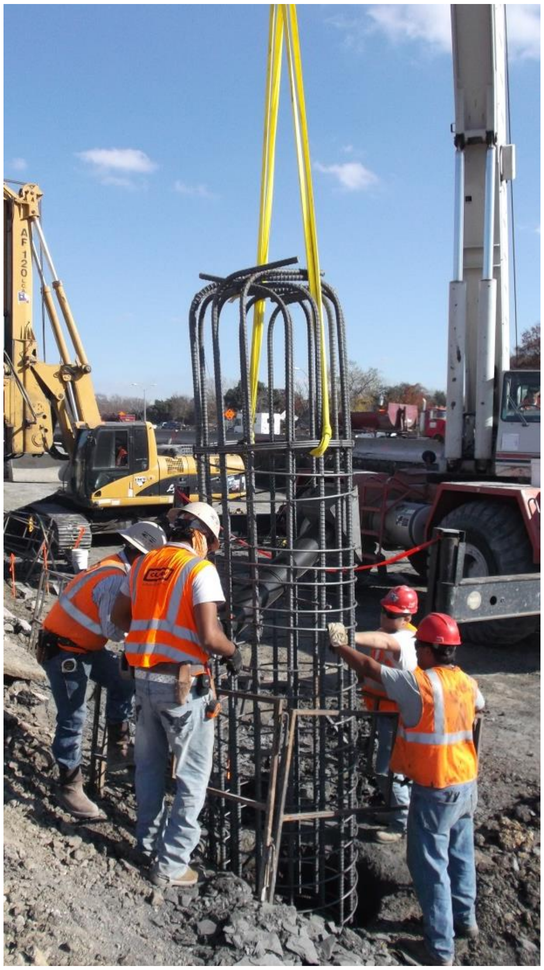


Figure 2.8 Reinforcing steel being installed in the drilled shaft

(Personal file, December 3rd, 2012).

Figure 2.9 Crane picking up reinforcing steel (Personal picture, January 12th, 2014).

Following the drilled shaft installation, a cap beam is constructed to tie all the drilled shafts together so that if one of the anchors fails, the excess stress is compensated by the anchored drilled shaft beside it (JIL, Interview 2, January 24th, 2014). The cap beam construction procedure is described below.

i. Clean the drilled shaft top and the projection reinforcement.
ii. Set bottom forms as shown in Figure 2.10.
iii. Tie reinforcing steel in place.

iv. Set forms and verify grade as shown on Figure 2.11.

v. Pour concrete.

Figure 2.10 Preparation of drilled shaft for construction of cap beam

(January 10th, 2014)

Figure 2.11 Cap beam ready to be poured

(Personal file, July 18th, 2013).

In some occasions, and depending on the design, an anchor may be located at the cap beam elevation (JIL, Interview 2, January 24th, 2014). In that case, a trumpet shall be installed at the same time as the reinforcing steel prior to setting the forms.

The completion of the cap beam will finalize all the work needed previous to beginning excavation. The construction sequence follows:

i. Excavation to the first row of anchors (Long et al., 1998).
ii. Installation of the cast in place concrete facing (shotcrete) instead of timber lagging (Long et al., 1998).
iii. Installation of the first row of anchors (Long et al., 1998).
iv. Grouting of the anchor to the ground (Long et al., 1998).
v. Once the grout has reach the necessary strength, the anchor will be load tested to the required load and locked-off (Long et al., 1998).
vi. Repeat steps 1 to 5 until the bottom of excavation is achieved (Long et al., 1998).
vii. Once the excavation is completed the installation of the drainage system is done (Long et al., 1998).
viii. Installation of the permanent, reinforced, cast-in-place or precast face is constructed from the bottom up (Long et al., 1998).

Figure 2.12 illustrates a scheme of the sequence for the excavation plus the installation of the anchor.

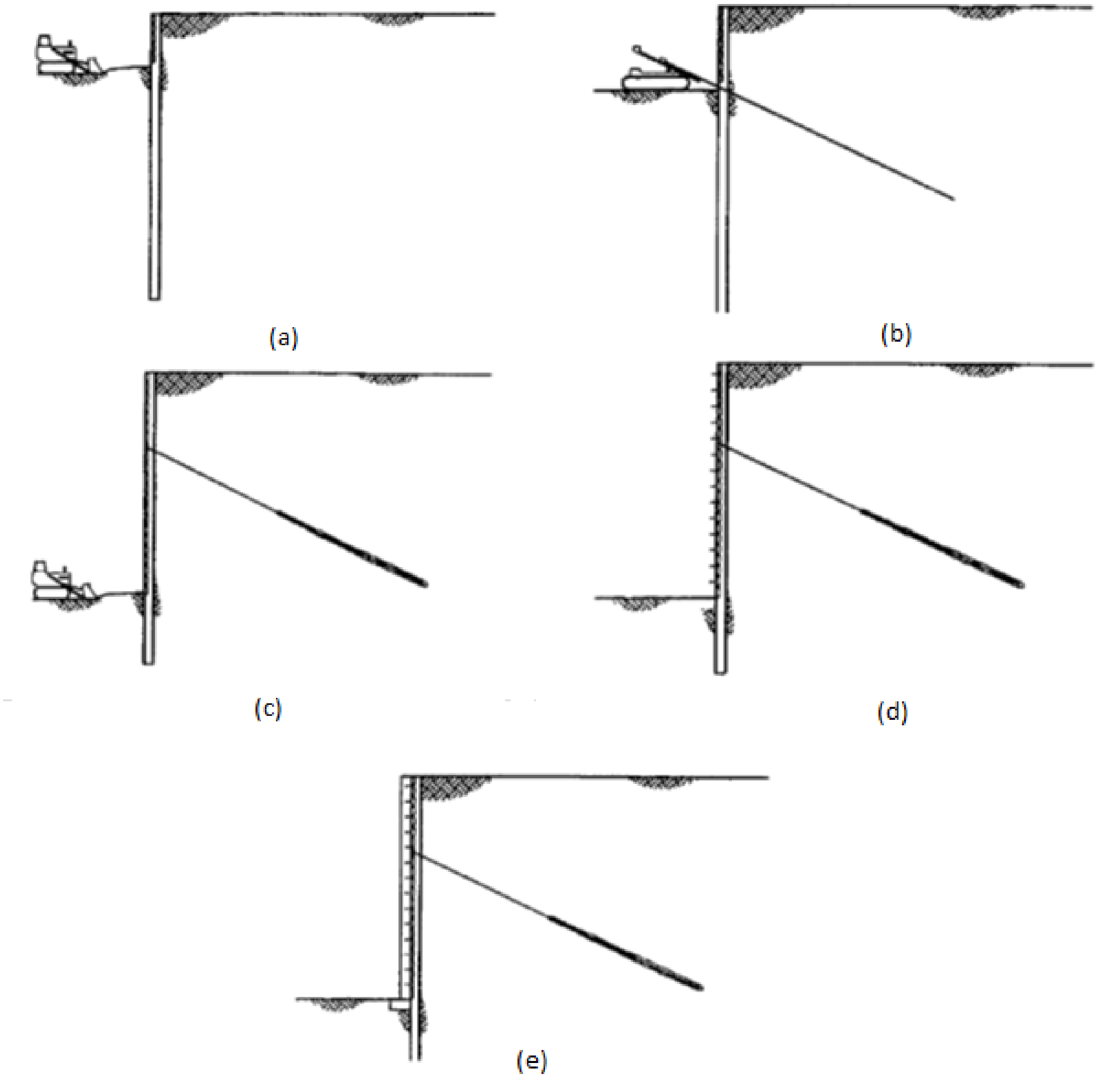


Figure 2.12 Excavation-anchor installation sequence. (a) Excavate and install support system; (b) install ground anchor; (c) complete excavation; (d) install headed studs and prefabricated drainage; (e) Install cast-n-place or precast facing wall. (Long et al., 1998).

This construction process is often determined by the engineer, who sets the excavation limits and gives the go ahead to the excavation once the row of tiebacks is locked-off. Although the engineer is the one that determines these factors (Sabatini et al., 1999), in some states the Department of Transportation (DOT), has set up some limitations to the excavation within their own projects. As an example, you can read below the limitations from the North Carolina DOT.

- Excavate in front of the drilled shafts from the top down with a maximum lift height of 5 feet (NCDOT, 2013).
- Install the temporary support (timber lagging or shotcrete) in less than 24 hours (NCDOT, 2013).
- If excavation becomes unstable, stop anchored wall construction and place an earth berm up against the face of the wall. Proceed with the appropriate corrective methods (NCDOT, 2013).
- Remove material in between the drilled shafts to install the shotcrete or timber lagging. At least 3 inches of horizontal contact between the shotcrete or timber lagging and the drilled shafts is needed (NCDOT, 2013).
- Proceed with the next excavation lift once the temporary support has been accepted (NCDOT, 2013).

The installation of the ground anchors and their testing will be explained in greater detail on the following subparts.

An overall view of the construction sequence for anchored drilled shaft walls is:

i. Tying of the reinforcing steel
ii. Installation of the anchor trumpets in the reinforcing steel.
iii. Drilling of the drilled shafts.
iv. Construction of cap beam.
v. Excavation to row of anchors.
vi. Installation of temporary support (timber lagging or shotcrete)
vii. Installation of ground anchors.
viii. Stressing of ground anchors.
ix. Repeat steps 5 through 8 until bottom of excavation is achieved.
x. Installation of drainage system of the wall.
xi. Installation of precast or cast-in-place facing of the wall.

For the purpose of this project steps 10 and 11 are not going to be evaluated, because although they affect the schedule and the cost of the retaining wall, those activities occur after the installation of the anchors which is the main objective of this study.

After surveying many contractors of the different areas, a production chart was established showing the production rates per day and per crew for each of the operations. The drilling of anchors will depend on the type of anchor chosen for the project and this will be shown in the following sections. Production rates were asked for to accommodate three different situations, i.e., the three scenarios that the thesis compares.

- Scenario 1: Construction site is1,000 feet long by 60 feet wide, and only one trade works at a time. For this situation, the maximum production rates provided by the different contractors are used. Table 2.5 shows the production rates assumed for Scenario 1.

Table 2.5 Production rates for the different activities for Scenario 1

ACTIVITY	UNIT	Per crew and day
Steel tying	lbs	50,000
Trumpets	Ea	30
Drill Shafts	LF	480
Cap Beam	LF	80
Excavation	CY	4,500

- Scenario 2: The same construction site is used as in Scenario 1 and is divided into two areas. Area 1 from station 0+00 to 5+00 and Area 2 from 5+00 to 10+00. One trade will enter Area 1 once the previous contractor has started working on Area 2. Therefore, the area will not be shared but the construction site will be more crowded. This extra work on the area will decrease the production rates of the contractors for different reasons. Depending on the activity, the production rates are adjusted differently, but there are reasons that apply to all the activities. During field observations, it has been registered that due to the extra crowded work area, working safely requires extra care. More equipment, personnel and extra hazards created by other subcontractors will reduce the production rate. The approach to production rates was done using an adjustment factor. Table 2.6 shows the production rates and the production loss factor for Scenario 2.

- Steel tying production is reduced due to other trades working behind them. The reinforcing steel deliveries must run through the whole area and the area is congested with our personnel and activities. Moving in and out of the work area is slower as well moving the reinforcing steel around the work area.
- The trumpet installation is not greatly influenced by steel tying. Possible steel deliveries and equipment moving around the area during the steel tying affects the installation rates. Also, when the drilling operations start, concrete trucks and extra equipment appears on the job site.
- Drilling of the piers is affected by all the work that precedes and follows it. An extra crowed work area makes every activity reduce their production. It is a larger activity, with larger equipment and more space constraints than both the trumpet installation and the cap beam construction.
- Cap beam construction is affected by both the predecessor and successor activities. The construction of the cap-beam is faster than the drilling of the anchors. Therefore, at some point both activities will share the area. Also, the excavation activities with all the trucking will decrease the production rates of the concrete workers, because it is

assumed that the trucks will enter the jobsite on Area 1 and will exit through Area 2. Therefore, once the excavation starts all trucks run next to the cap-beam workers.

  - Excavation is the activity that is most damaged by other trades. As stated before, it is assumed that the trucks for the excavation enter the jobsite at Station 0+00 and exit it at 10+00. Therefore, the trucking will be in direct contact with all the activities on both areas. The same situation repeats once the anchor drilling starts in Area 1, as the excavation is performed in the area where the drillers are working, and its production rates decreases.

Table 2.6 Production rates, production factors for the different activities for Scenario 2

ACTIVITY	UNIT	Per crew and day	Factor	Final Production
Steel tying	lbs	50,000	0.75	37,500
Trumpets	Ea	30	0.75	23
Drill Shafts	LF	480	0.75	360
Cap Beam	LF	80	0.75	60
Excavation	CY	4,500	0.70	3,150

- Scenario 3: Similarly to Scenario 1, the jobsite is not divided, and it is assumed as a whole area of work. However, the approach to this option is that of a continuous work area. Therefore, the activities will be schedule according to their production rates, and to those of their predecessor. An activity will start, once it is known that is going to be completed with no interruption. In this scenario the activities take a longer time to complete, but there will not be any down time with no work. It is assumed that these activities will have lower production rates due to having even more trades in their areas of work. The reasons for these lower production rates are similar as those for Scenario 2. The production rates for this scenario are shown on Table 2.7.

Table 2.7 Production rates, and factors of production for the different activities for Scenario 3

ACTIVITY	UNIT	Per crew and day	Factor	Final Production
Steel tying	lbs	50,000	0.75	37,500
Trumpets	Ea	30	0.50	15
Drill Shafts	LF	480	0.50	240
Cap Beam	LF	80	0.50	40
Excavation	CY	4,500	0.35	1,575

On the methodology part, it is explained how this information is to be used and how the author will evaluate each scenario.

2.2.2.2 Availability of space

Space is a precious asset at construction sites, and the lack of it requires the engineer and contractors to have imaginative solutions. However, there are some activities that require a minimum amount of space, and without it they cannot occur. In this section, only the space requirements needed for the anchor installation activity are evaluated. It also explains how the selection of the type of anchor affects space requirements.

When dealing with equipment, space is always an important aspect to take into account (O.O., Interview 1, February 3rd, 2014). In order to work productively, a piece of equipment must have enough space to not only perform its assigned task but to be able to move around the work area without any space constraints. “When you think about a piece of equipment, you will need to think in 3-D not in 2-D” (O.O., Interview 1, February 3rd, 2014), the project manager of an important tieback company explains. Length and width are important, but height clearance is even more critical because operators cannot usually see all the parts of their equipment. Therefore, when dealing with a clearance issue a spotter will be needed, and the operation will have a production rate decrement and a cost increment.

In order to determine what will be the space needs for a piece of equipment, it is mandatory to know the piece of equipment that will be used and the work that it will be performing. A specific piece of equipment was chosen for this thesis, the CAT 320D L with a 25 feet long excavator mounted drill shown in Figure 2.13.

Figure 2.13 CAT 320D with 25 feet excavator mounted drill

(Personal file, January 13th, 2014)

As seen in the previous section, excavation is always done prior to the installation of the anchors. Usually the excavation for the wall face is done full length, although in some occasions due to geotechnical reasons designers want the excavation to be staggered (JIL, Interview 2, January 24th, 2014). In this research, the assumption was that the excavation can always proceed full length, and it can only be done in 5 feet deep lifts (NCDOT, 2013).

In order to determine the possible clearance requirements, the inclination of the anchors must be known because that determines how high the excavator mounted drill needs to be. The proposed design will be followed to compute the clearances and platform width needs for the piece of equipment selected. Simple trigonometry was used to evaluate the height of the drill and the width of the drill.

$$Height\ of\ the\ drill\ (ft) = Length\ of\ the\ drill\ (ft) * \sin(angle\ of\ anchor)$$

$$Width\ of\ the\ drill\ (ft) = Length\ of\ the\ drill\ (ft) * \cos(angle\ of\ anchor)$$

To evaluate the clearance and width, extra requirements must be met. To account for height, at least an extra 3 feet is needed to maneuver and maintain the production rates (P.G., Interview 3, February 5th, 2014). If there is not a 3 feet window, the production rates will be reduced. Also, the drill hole has to be at least 2 feet higher than the ground to maintain water away from it in case it rains (P.G., Interview 3, February 5th, 2014). Therefore, the total distance to an overhead obstacle will have to be:

$$Total\ height = Height\ of\ drill\ hole\ above\ the\ ground + Height\ of\ drill\ hole + 3\ feet\ to\ maneuver$$

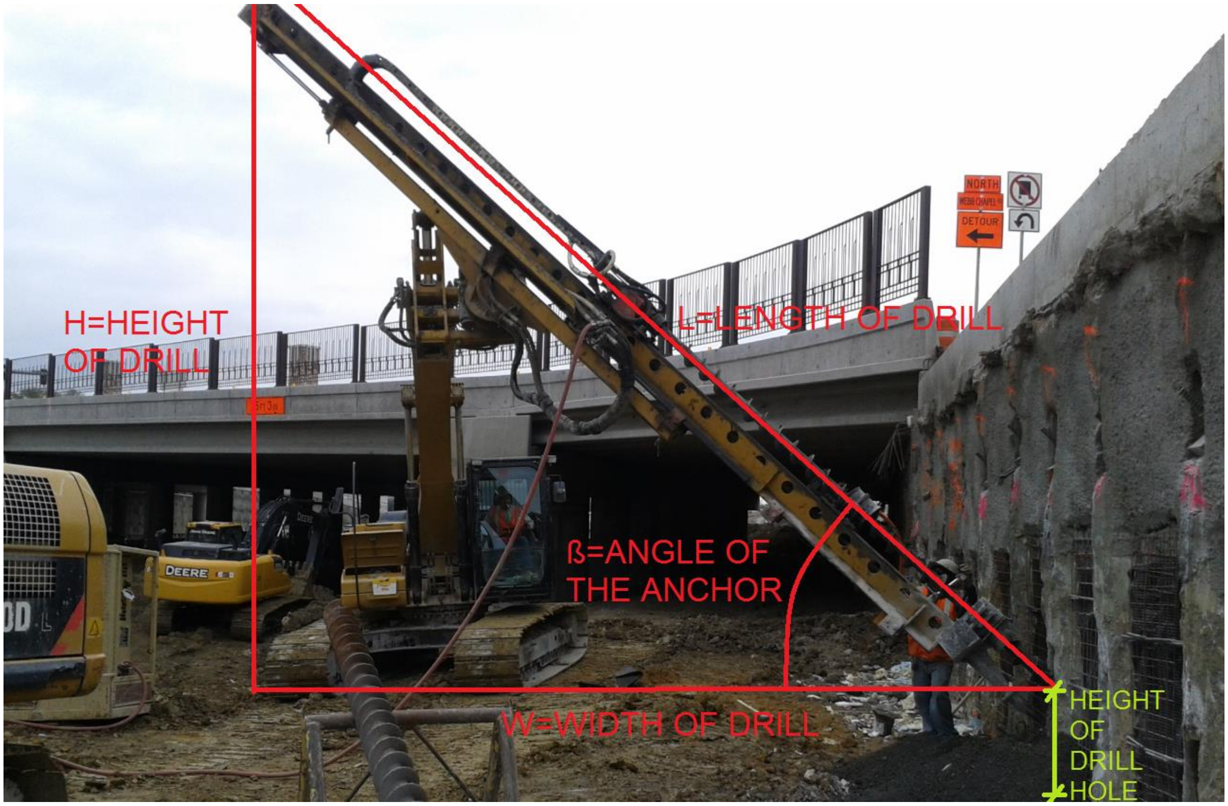


Figure 2.14 Excavation mounted drill: Dimension of drill

(Personal file, March 5th, 2014)

Figure 2.14 shows the drilling operation with the above mentioned piece of equipment. Dimensions and description are identified by writing the parameters over the picture. These include the height and width of the drill along with the angle of the anchor.

Length and height have already been covered on the previous paragraphs. Width depends on the type of machine that is being used. A proper width must be provided to maneuver and maintain production. In order to set up the drilling machine, an extra 3 feet of width is set up(P.G., Interview 3, February 5th, 2014). The formula used to compute the platform width is:

$$Platform\ width\ (ft) = Width\ of\ drill(ft) + 3\ ft\ to\ maneuver$$

The main goal of this research study is to evaluate the construction differences that the selection of the type of anchor will create. As mentioned previously, the two main types of anchors are strand tendon anchors or steel bar tendon anchors.

Strand tendons are flexible tendons made up of a number of seven-wire strands, with six wires helically wound to a long pitch around a center wire (Corven and Moreton, 2013). Depending on the needs of the anchor, a different number of seven-wire strands can be installed on the tendon. Strand length and sizes are not limited (Sabatini et al., 1999), and it is important to note when delivered strand tendons are not grouted (O.O., Interview 1, February 3rd, 2014). For this research, a low number of strands were needed per tendon. Therefore, their storage and handling did not require a large space.

A storage area must be provided where the material will be protected from any mechanical damage, corrosion, contamination with dirt, and exposure to moisture and ultraviolet light (PTI, 2004). Pallets 4 feet by 4 feet are used to store the strand tendons and 3 strands can be store per pallet (see Figure 2.16). Prior to its installation, a strand tendon is straightened to inspect its condition and to prepare it for its installation. Any dent, pit or crack could be a reason for failure (CaDOT, 2005) The space needed for this preparation is directly proportional to the strand tendon length. However, no extra room is needed for handling the material because it can be easily transported by a loader as seen in Figure 2.15., and straightened.

Due to the tendon flexibility, its insertion in the borehole will be less space limiting than the actual drilling of the hole. Therefore, clearance and widths are limited by the machine and not by the tendon.

Figure 2.15 Loader handling a strand anchor

(Personal picture, January 13th, 2014).

Figure 2.16 Storage area for strand tendons

(Personal file, March 24th, 2014)

On the other hand, steel bar tendons are rigid steel bars that vary in diameter from 16 mm (5/8 in.) to over 50 mm (2 in.) (Corven and Moreton, 2013). Their lengths are limited so that transportation is easier, the restriction is usually 18 m (60 feet) (Sabatini et al., 1999). For lengths longer than 18 m, bars are joined together with couplers (Sabatini et al. 1999). The installation of these couplers must be closely monitored and each bar has to be engaged in the coupler for half the coupler length (PTI, 2004). Figure 2.17 shows couplers already installed on one of the steel bars highlighted with red circles.

Figure 2.17 Coupler installation

(Personal file, February 20th, 2014)

The space needed for storing the steel bars has to be at least 18 m long. The steel bar tendon handling is more tedious because of their rigidity. In order to avoid dragging the steel bar tendon, two pieces of equipment are needed to move them when longer than 60 feet (P.G., Interview 3, February 5th, 2014). A greater handling area is needed for this type of tendons, because they need to be coupled on site and the use of larger equipment is needed to move them. The anchor insertion needs more space than the drilling operation, and space requirements will depend on the tendon length and anchor angle. A simple formula using trigonometry will allow us to know the space limitations depending on the tendon length. If tendons are shorter than 60 feet one piece of equipment is used on the insertion.

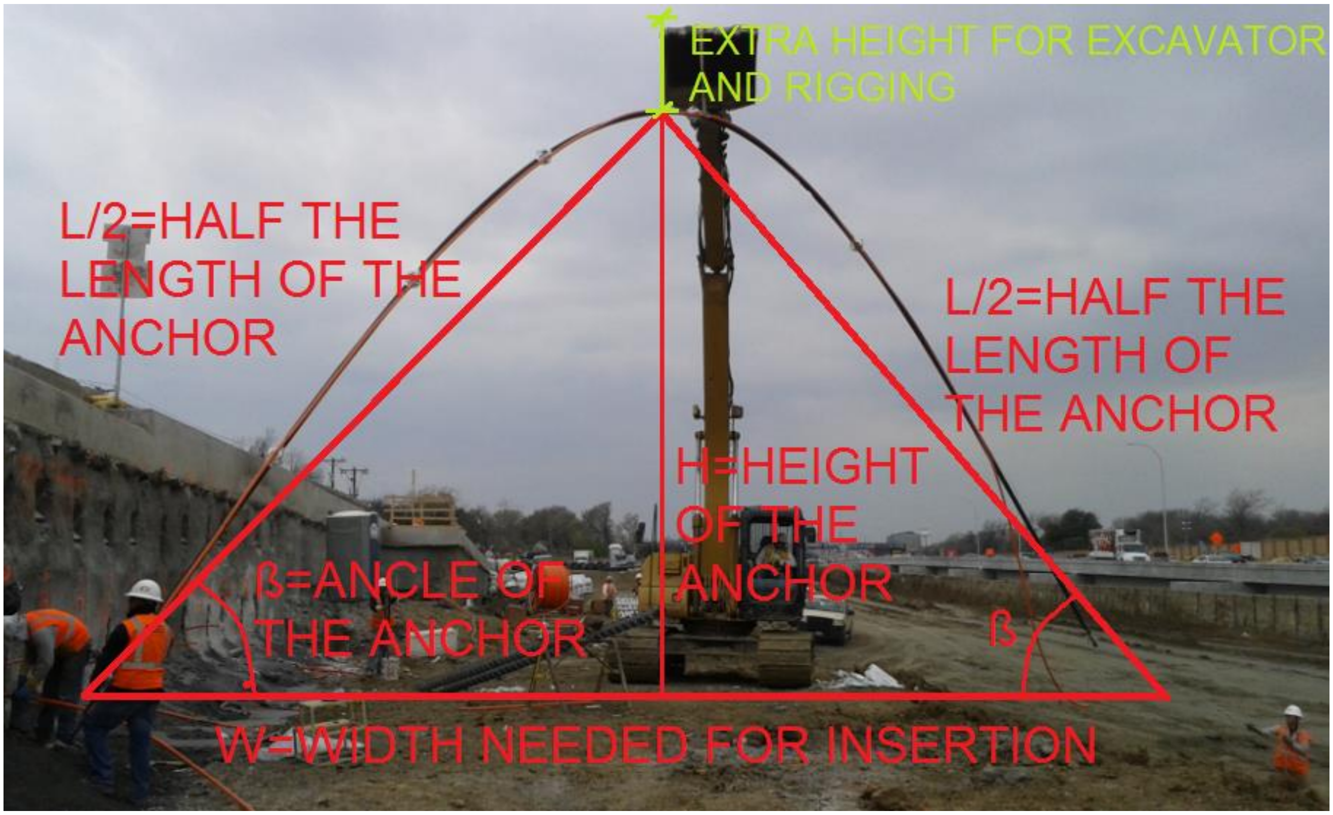


Figure 2.18 Insertion of steel bar anchor. Dimensions

(Personal picture, March 26th, 2014).

For width limitations:

$$W(ft) = Anchor\ Length\ (ft) * cos(ß)$$

where W is the width limitations in feet.

For clearance limitations:

$$Clearance\ (ft) = H\ (ft) + Extra\ height\ for\ excavator\ and\ rigging\ (ft) + Height\ of\ drill\ hole\ (ft)$$

where H is the height of the anchor in feet

$$H(ft) = \frac{Anchor\ Length\ (ft)}{2} * \sin(ß)$$

where ß is the angle of the anchor and the extra height for excavator and rigging is 8 feet (P.G., Interview 3, February 5th,2014), for anchors smaller than 60 feet long and 5 feet wide; however, two excavators are used to install the anchors on anchors longer than 60 feet. This distance is smaller because the rigging equipment is tied to the anchor at a specified distance from the center.

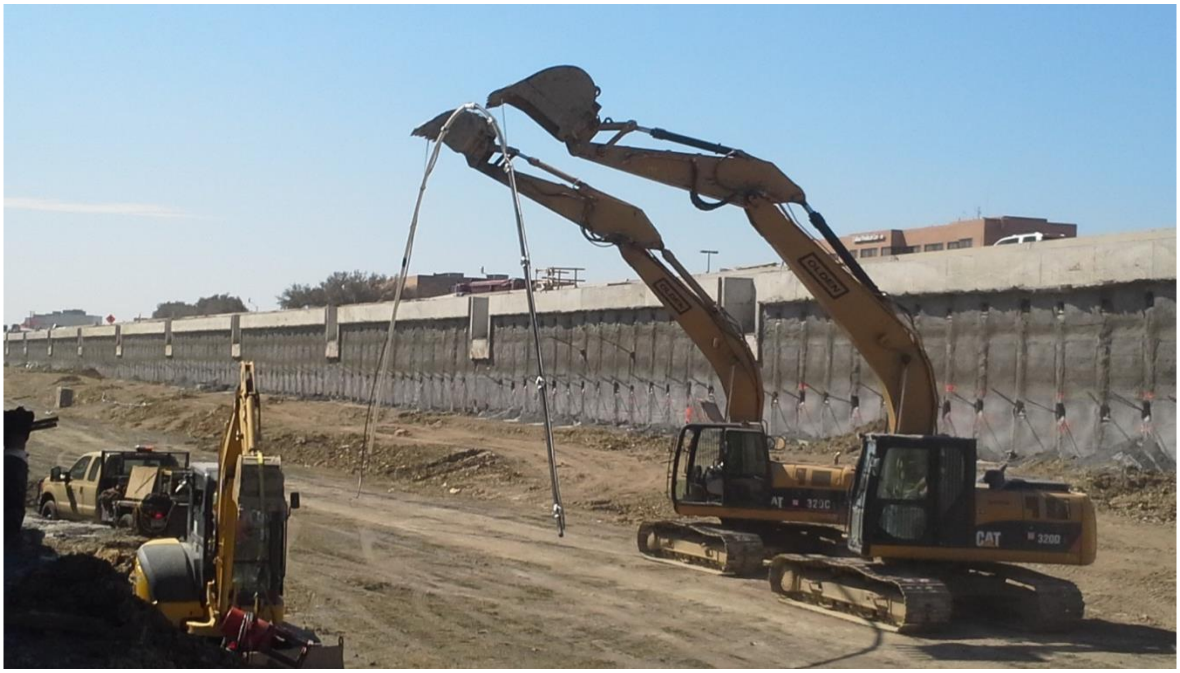


Figure 2.19 Two excavators handling a steel bar anchor longer than 60 feet

(Personal file, March 3rd, 2014).

These two formulas give the actual limitations, but a maneuver factor must be applied. This maneuver factor is added to the width and clearance, and for clearance purposes, it must be at least 1 foot wide to be feasible and have a 3 feet clearance to maintain the production rates in addition to 5 feet for platform widths (P.G., Interview 3, February 5th,2014).

When installation of the steel bar tendons is not feasible due to space constraints, the contractor will have to use shorter bars and more couplers. The coupling operation must be done once the first piece of steel bar is inside the borehole. The insertion will be done one piece at a time.

Space limitations are a critical factor for installation of the ground anchors. They affect the equipment selection, the material selection, and they also affect the material delivery if space for storage and preparation is limited. Steel bar tendons are more affected by space limitation than strand tendons.

2.2.2.3 Anchor installation.

In the construction process of an anchored drilled shaft wall, the anchor installation is the critical activity, and it is the one that will determine the success in the construction of the anchored wall. The process of anchor installation is divided into four phases, and each of them is analyzed depending on the anchor type selection.

The first phase depends on the anchor hole drilling. The means and methods of the drilling operations are left to the contractor to decide (Sabatini et al., 1999). On most occasions, the contractor will overdrill the hole to allow a better drill hole cleaning (Sabatini et al. 1999). The drill hole needs to be within tolerance of location and inclination, and those tolerances are set by the Post-Tensioning Institute. Deviations of the “as-drilled holes” are usually inconsequential except if those deviations create conflict between anchors (PTI, 2004). Some states have decided to impose more restrictive tolerances for these drill holes. As an example, the state of Connecticut has a tolerance of ±3 inches for the location of the drill hole, and ±3 degrees on the horizontal and/or vertical orientation (CTDOT, 2004). An excessive deviation inside the bore hole may affect the tendon insertion. Although strand tendons will not be affected by this issue, steel bar tendons will. The rigidity of steel bar tendons may be the actual limitation of the anchor drill hole. If the drill hole is drilled with excessive curvature the steel bar tendon will not fit inside it, and the drill hole will have to be redrilled (CTDOT, 2004). Therefore, the use of steel bar tendons has as a consequence smaller tolerances for the anchor hole drilling. Also, if any geotechnical constraint is encountered while drilling, the solution may be to extend the length of the anchor. Since strand tendons cannot be lengthened, this solution makes the tendon useless. However, steel bar tendons can extend with the use of another coupled bar.

The second phase is tendon insertion. The insertion of the tendon must be done after the preparation of it has been completed. Strand tendons must be straightened to look for any possible damage to the strands, coatings, sheaths and encapsulations (Sabatini et al., 1999); the lengths of the unbounded length and the bonded length are inspected (Sabatini et al., 1999); the strand spacer is checked for proper placement to ensure a proper grout cover around each strand, and installation of centralizers is checked for each strand length. These centralizers will ensure that a proper cover is left around the tendon so that grout can surround it (Sabatini et al., 1999), and then the external grouting tube can be installed. Special care must be taken on strand tendons regarding corrosion protection, loose flaky rust has to be removed, because if rust has penetrated the tendon, it will not be suitable for use (Sabatini et al., 1999).

For steel bar tendons most of the procedures described above apply; hence, there is an inspection for damages, proper length inspection, installation of centralizers and an external grouting tube, and corrosion protection inspection. Although corrosion has to be taken into account, steel bars are less affected by it due to their lower strength compared to strand steel. This is due to a larger diameter and smaller ratio of exposed surface to cross section area (Corven and Moreton, 2013). One extra inspection is needed on the steel bar tendons, that is, the coupler inspection. Couplers need to be properly installed and properly protected against corrosion. Their installation is done on site producing extra time for preparation. Note that no coupler shall be installed on the bonded length of the anchor according to the European specification (CEN, 2009). This steel bar tendon preparation is shown on Figure 2.20 below. This shows how the grout tube is attached to the anchor and how the centralizers are installed.

Figure 2.20 Steel bar tendons preparation

(Personal file, March 24th, 2014).

Tendon insertion comes after the inspection is completed. For strand tendons the insertion is done with the help of a piece of equipment, usually an excavator with a sling, and the tendon is straighten by hand (CTDOT, 2004). This tendon insertion is shown in Figure 2.21. where a piece of equipment has to be used to ensure the proper insertion of the steel bar tendon into the borehole. Depending on the length of the anchor, one or two pieces of equipment will be needed. This will affect the production rates and the cost (O.O., Interview 1, February 3rd, 2014). Tendons of up to 60 feet long can be handled with just one piece of equipment (see Figure 2.21), but a longer tendon requires the use of two pieces of equipment (P.G., Interview 3, February 5th, 2014). As explained in the previous section, if there is a space constraint, shorter pieces of tendon must be coupled together, and the couplers are installed with the previous tendon section already inside the drill hole.

Steel bar tendons are much more difficult to insert in the drill hole. They must often be handled with two pieces of equipment, and they require more inspections and preparation.

Figure 2.21 Steel bar tendon insertion

(Personal file, March 26th, 2014).

Anchor grouting is the third phase of the anchor installation and it does not really differ greatly when considering the different types of anchors. As explained above, and for the purpose of this study, strand tendons are assumed not be pregrouted, while steel bar tendons are already grouted when delivered to the construction site. Therefore, grouting operations will take longer time and require a larger amount of grout on strand anchors than on steel bar tendons. Due to the high power of the pumps that are used onsite, the main difference in the pumping process will not depend on the quantity of grout but the time spent connecting the grout pipe to two different conduits instead of just one. Strand tendons must first connect to the inner conduit to grout the inside and then connect to the outside conduit. For steel bars, only the second connection is needed (O.O. Interview, February 4th, 2014). Although these differences may seem trivial for a single anchor, they will have to be taken into account when the number of anchors is large.

The last phase of the anchor installation is the anchorage installation. Due to the differences on the anchorage system, the strand tendons anchorage system takes longer to place, because the wedge plate must be inspected and the wedge holes cleaned of any rust, grout and dirt (PTI, 2004). This inspection and cleaning plus having to set each strand through each wedge hole makes this operation longer for the strand tendons.

Timber lagging installation or shotcrete facing, wall drainage system installation, horizontal drains and the precast or cast-in-place wall facing installation are not evaluated in this research because they do not depend on the type of tendon that is being installed.

Several contractors were surveyed for production rates for each phase depending on the type of anchor used and the approximate cost for each anchor installation. In Appendix A, there are many tables that show the different rates and costs for each phase of the anchor installation. These values were used in this thesis to compare the benefits of each type of anchor and to evaluate which one is more efficient.

2.2.3 Testing

Testing of anchored drilled shaft walls is critical, and it is analyzed by itself due to its importance. The design criteria of an anchored drilled shaft wall will always specify a design load for an anchor and a lock-off load function of the design load. Every single anchor has to be load tested to verify its capabilities (Sabatini et al., 1999).

The testing process does not differ depending on the type of testing that is being performed. However, the selection of strand tendon or steel bar tendon is of critical importance to the production rate during testing. On the preparation for the testing, the first step is to clean the anchor. Removing the dirt, rust, and excess grout from the strands is a much longer activity than doing the same on the steel bar. The installation of the jack at beginning of testing also takes more time when working with strand tendons because each anchor needs to be inserted through one of the wedge holes, and until the jack gets up to a certain tension a piece of equipment must keep the tails of the strands in place while the steel bar supports itself (O.O., Interview 1, February 4th, 2014).

Figure 2.22 Testing a strand anchor

(Personal file, February 20th,2014).

Figure 2.22 shows a testing jack installed on a strand tendon performing a proof test.

Three tests determine the acceptance or rejection of the ground anchors. Each test is briefly explained herein although its importance is not really critical for this research. It is important to note that the testing process is the same for all the anchors, and the testing itself does not differ when using strand tendons or steel bars.

2.2.3.1 Performance test.

Performance tests are done on a small amount of anchors no greater than 5% (PTI, 2004). The tests determine:

- If the anchor is able to carry the sufficient load (PTI, 2004);

- if the apparent free tendon length has been established (PTI, 2004),
- if there is residual movement (PTI, 2004), and
- if the creep rate stabilizes within the limits (PTI, 2004).

The performance test is conducted by loading cyclically the anchor according to the figure below. On every cycle the load needs to be decreased to the Alignment Load (AL) (PTI, 2004). Different readings of the movement are done. If the creep movement between minute 1 and minute 10 is higher than 0.04 inches, then the test will have to be longer and readings taken at intervals of 10 minutes, 20, 30, 40, 50 and 60 minutes (PTI, 2004).

2.2.3.2 Proof test.

Every anchor not tested in a performance test must be tested using a Proof Test. The proof test is used to determine quickly and economically:

- If the anchor is able to carry the sufficient load (PTI, 2004),
- if the apparent free tendon length has been established (PTI, 2004).
- if the creep rate stabilized with the limits (PTI, 2004).

The deformations must be checked in the same way as the performance test and when failing to meet the requirements, the longer test is done (PTI, 2004). The loading in this case will not be cyclical but linear.

2.2.3.3 Extended creep test.

For extended creep testing, the Plasticity Index of the soil needs to be above 20 (PTI, 2004). The loading for this test follows the same chart as the performance tests. The difference between both tests is that the loads must be held for up to 300 minutes unless the creep rate stabilizes before 0.08 inches.

2.2.3.4 Lock-off.

Once every anchor is tested, it has to be locked to the lock-off load specified by the designer. However, this load should never be greater than 70% of the ultimate design load (PTI, 2004). The lock-off limitations differ depending on what type of anchor is being used. For strand anchors, the lock-off load needs to be at least 50% of the design load. If this is not so, the use of shims under the wedge plate will be needed. The reason for this minimum load factor on the strands is the need for the wedges to bite the strand. Lock-off loads have to account for losses that are called seating losses. For steel bar tendons it is common to account for losses of 5% while for strand tendons the seating losses are greater due to the wedge losses (JIL, Interview 2, January 24th, 2014).

2.2.3.5 Lift-off test.

At some point, the load of a specific anchor needs to be checked for design, construction or quality purposes. When this happens a lift-off test will be needed. Lift-off tests are done by pulling on the anchor until either plate moves without untying the nut on the steel bar anchor. For a strand tendons, the lift-off test will finish once the plate lifts without unseating the wedges.

2.2.3.6 Acceptance criteria.

The acceptance criteria is established by PTI, and it is shown in Figure 2.23 below.

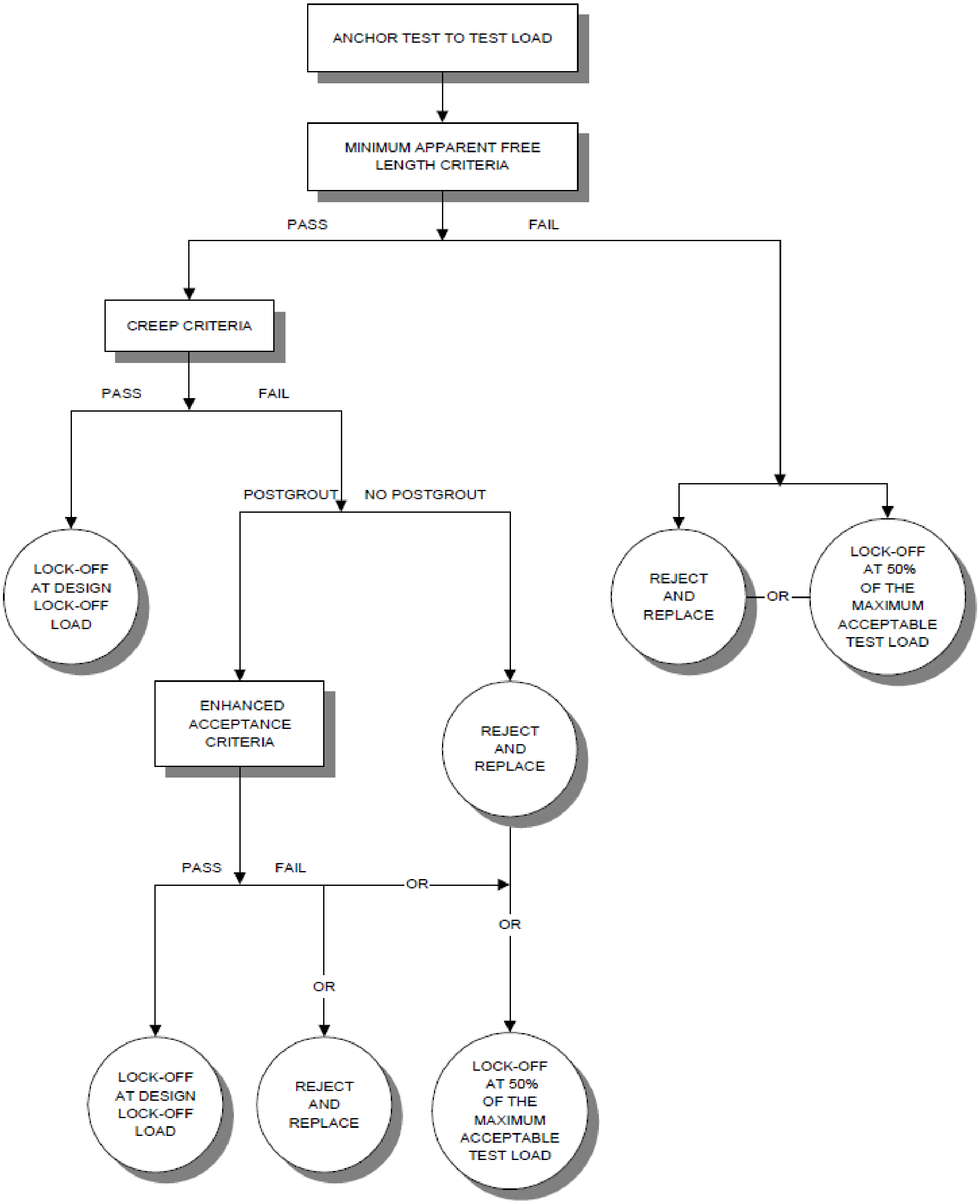


Figure 2.23 Ground anchor testing acceptance criteria

(Sabatini et al., 1999)

2.2.4 Instrumentation

Monitoring anchored drilled shaft walls is critical to understanding their behavior and to ensuring that the design reflects the reality. Monitoring also means records are kept on whether or not the retaining wall works according to how it was designed. Instrumentation of wall performance is a key element to improving the wall design (Winter et al. 2010). There are many ways to monitor a retaining wall, and it is not the subject of this research to explain each of them. However, this subject is written to reflect the importance of instrumentation and how it explains wall movements.

On projects where soil behavior is a critical factor, the design of retaining walls should account for instrumentation during the construction phase and once the construction is done; it shall also specify how the retaining wall is to be monitored and where the monitoring systems are to be located (FDOT, 2004). Inclinometer readings and survey inspections are the standard practices used to monitor anchored drilled shaft walls, although there are other systems such as strain gauges, settlement plates or pendulums.

2.2.4.1 Inclinometers

Inclinometers are generally used to measure the lateral movement of a retaining wall (Brahana et al., 2007). They are installed attached to the soldier pile or drilled shafts, and in some cases they are installed just behind the retaining wall.

Inclinometers consist on a of a grooved plastic or metal pipe casing that is installed An inclinometer casing consists of a grooved metal or plastic tube installed as explained above and its bottom needs to be on the bottom of the drilled shaft, that is supposed to be fixed (no movement). An instrument that measures deflection is sent down the casing (FDOT, 2004).

The equipment used to measure the wall deflections is very precise. The system accuracy is around ±6 mm per 25 m of casing with the Digitilt Classic Inclinometer System from Slope Indicator (Durham Geo-Enterprises, 2014)). Readings of the inclinometer are taken in two perpendicular planes and the information is registered at certain intervals of depth (Ding and

Qin, 2000). Monitoring the inclinometer is done periodically, and the information is presented in comparison to the previous measurements. The first measurement shall be done prior to excavation so that the deflection is related to a real situation. A sensing probe is lowered down into the tube and deflection of the tube is measured.

Inclinometers are the best tool to measure deflections on anchored drilled shaft walls, and their installation is reasonably cheap because they can be installed attached to the steel of the drilled shaft. However, they require maintenance, because it is fairly common that in a construction site, with all the equipment and personnel, the inclinometer casing gets damaged.

2.2.4.2 Optical survey

Optical survey is an easy way to monitor wall movements. A set of survey bullseyes are installed on the top of the wall prior to the excavation commencement (Sabatini et al., 1999) and on the lower part of the wall as the excavation progresses. Periodic readings are taken to check the wall movement. It is necessary that the installation of these survey bullseyes is done in a timely manner to prevent extra costs of installation. A survey department qualified for the task must be appointed.

As is done with the inclinometer readings, the survey readings are compared to the previous ones to analyze the wall movement.

2.3 Chapter Summary

During this chapter a review of all the necessary information for the completion of this thesis were described. Special attention was given to the construction aspects of this review. The sequencing of the anchored drilled shaft wall construction, its space needs and the anchor installation were explained and all the differences depending on the type of tendon were noted. An overview of the different tests done to the ground anchors and of the standard practices for instrumenting a drilled shaft wall were also included in this chapter.

Chapter 3

Methodology

As was done in the literature review, the methodology has been divided into the same subparts or subsections.

3.1 Design

Design of ground anchored drilled shaft walls is complex and cannot be overlooked. Due to the fact that it is not the objective of this study to evaluate the design phase of an anchored drilled shaft wall, this research will only evaluated the type of tendon selection for the wall.

The retaining wall used on this project is illustrated with three figures. Figure 3.1 shows the typical profile of the retaining wall, Figure 3.2 presents the plan view, and Figure 3.3 illustrates the typical section.

The construction site used has the following dimensions:

- 1,000 feet long. In order to evaluate the situation as a real life evaluation the stationing has been given for the wall. It runs from station 0+00 to station 10+00.
- 60 feet wide. This distance will allow construction traffic through the job site while the anchored drilled shaft wall is being constructed.
- 18 feet high. The distance from the top of the cap beam to the final grade level is 18 feet. However, the cap beam is 3 feet high. This means that only 15 feet will have to be excavated starting from bottom of the cap beam to the final grade.

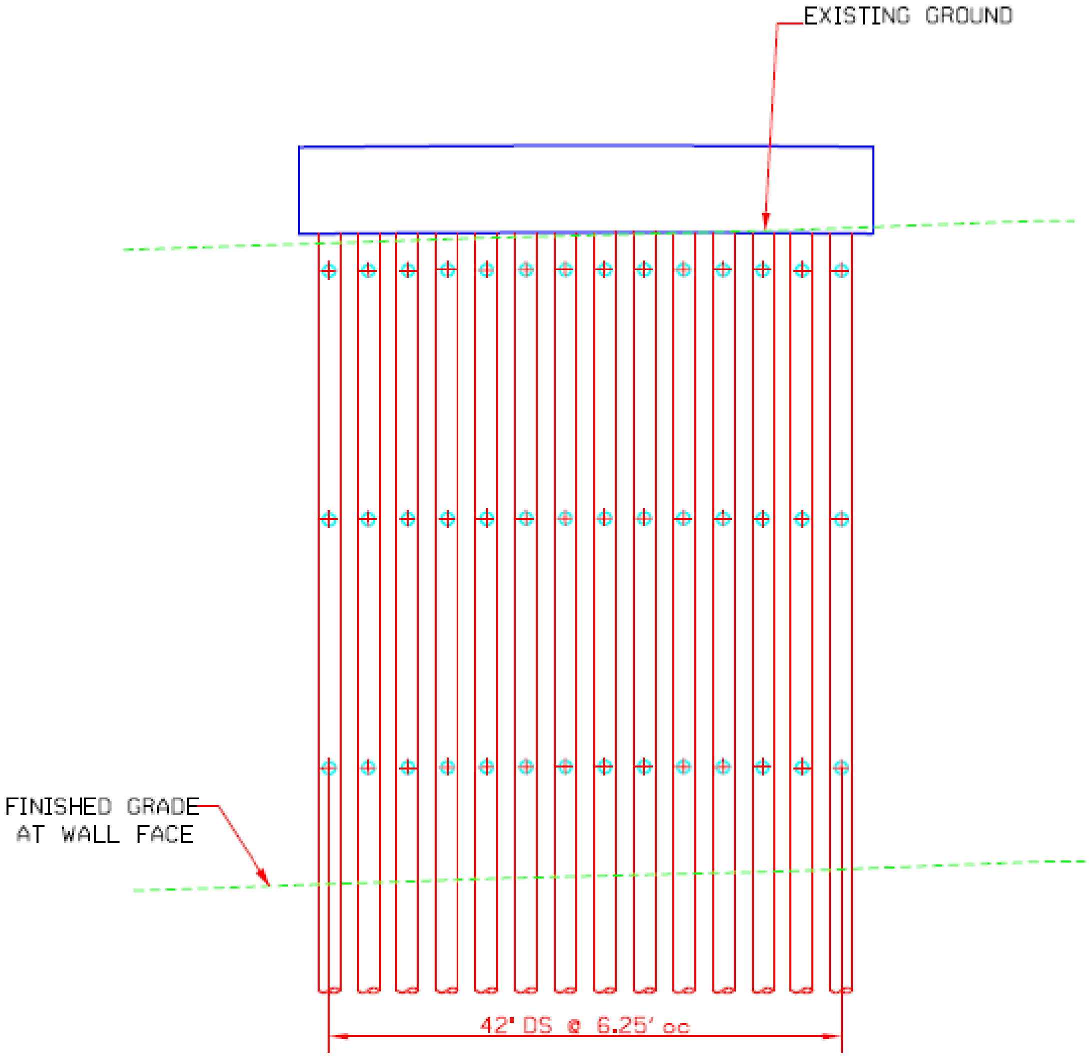


Figure 3.1 Typical profile of the proposed retaining wall

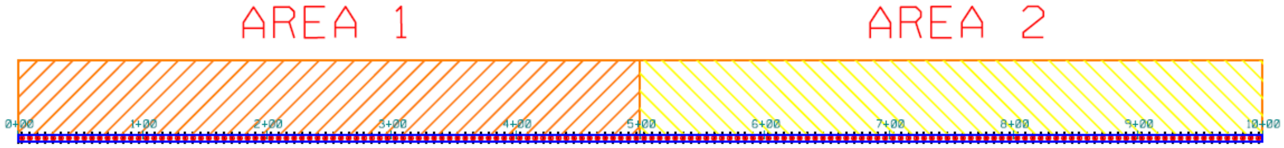


Figure 3.2 Plan view of the proposed construction site for the Scenario 2 with the work area divided in two.

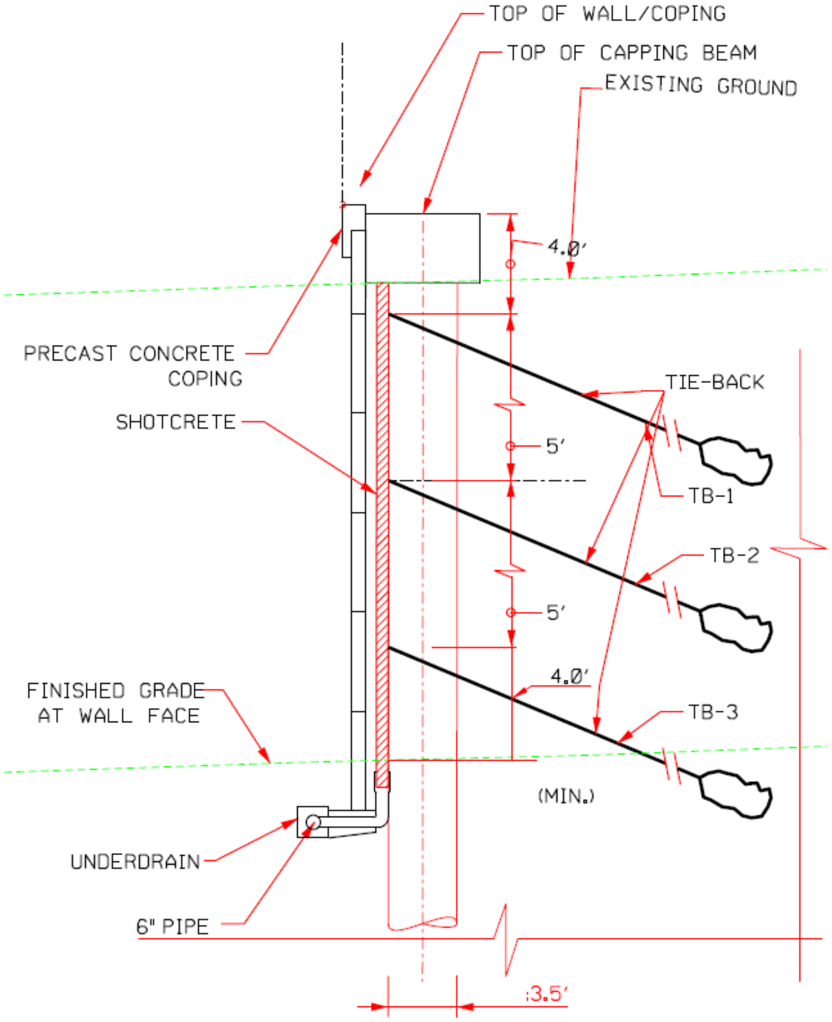


Figure 3.3 Typical section of the proposed retaining wall

The following consideration are assumed for the proposed wall.

- The drilled shafts have a diameter of 3.5 feet, a length of 60 feet, and are spaced 6.25 feet apart. Each drill shaft needs 8,000 pounds of reinforced steel.
- The cap beam is 3 feet high, 5 feet wide, and the whole beam is1,000 feet long.

- Each drilled shaft has 3 anchors. Each anchor is skewed 30 degrees with the horizontal, and they are 100 feet long (anchors usually decrease their length as they go down, but for this study, all anchors have the same length). The distances between the anchors are shown on Figure 3.3.

In order to select the tendon to be used, the following proposed loads were made available and are shown in Table 3.1.

Table 3.1 Design data for the anchor testing

	LOCK-OFF LOAD	PERFORMANCE TEST LOAD	PROOF TEST LOAD
TB-1	120	175	175
TB-2	120	175	175
TB-3	120	175	175

With the information above the type of tendon was selected.

3.2 Construction Process

3.2.1 Sequencing

Although the sequencing of the construction of the wall does not vary depending on the type of anchor selected, the author intentions are to ensure that the most cost effective and least time consuming way for their installation is explained. In order to do so, three different options are evaluated for the wall already described in the design section above.

For the purpose of this study and considering the design, it was assumed that the soil is an easy soil to excavate and to drill into, that no water would be encountered neither in the drilled shafts nor in the drill holes for the anchors. Excavation can proceed only in five feet lifts due to soil properties to allow for the installation of tiebacks; furthermore, testing of tiebacks can only start once the grout cylinders have been tested (after a 7-day break) and after the strength is confirmed; then the excavation of the next lift can continue once the testing has been finalized. Production rates have already been explained in previous sections of this study.

All the production rates stated previously were obtained by field observation and from surveying different contractors. At the time of the surveys, the contractors were prompted for pricing as well. For the purpose of the research and to maintain anonymity, the names of the companies and personnel are not identified and will be referred to as Company A, Company B and Company C. However, a price per unit was given and then it was averaged to obtain the pricing below. Note that the pricing for steel tying and supplying was given by the pound and that an average weight of 8,000 pounds per drilled shaft was assumed. The cost computed for this research is that of the direct costs. Costing was also done from the perspective of a general contractor who does not perform any actual on-the-job tasks. Therefore, the total cost of the retaining wall from the general contractor's point of view varies due to indirect costs. Consequently, the indirect cost is more dependent on the time it takes to build the wall. The anchor installation is studied in depth because depending on the type of anchor to be installed, costs will vary as well as the time spent on their installation. The rest of the activity will always be the same, and a cost analysis will only be needed to have an overview of the overall cost of the wall. Excavation costs are included as part of the retaining wall costs because the excavation is not part of the retaining wall itself. The unit costs are shown on the Table 3.2.

Table 3.2 Unit costs by activity

ACTIVITY	UNIT	PRICING ($/UNIT)
STEEL TYING	lbs	$0.50
TRUMPET INSTALLATION	EA	$485.00
DRILLING 42" DRILLED SHAFTS	LF	$70.00
INSTALLATION OF CAP-BEAM	LF	$140.00

Three different approaches will be done to evaluate the study.

- Scenario 1: The first approach was done proposing the wall as a single area where construction would take place with only one operation taking place at the same time. This situation will maximize each contractor's production, but the author anticipates that the project will have a longer duration that will at the end increase the overhead cost; therefore, the total cost will be increased as well.
- Scenario 2: The second approach will evaluate the area as divided into two job sites (see Figure 3.2). All the operations would follow the same sequence.

  Each activity starts once the predecessor has change from one area to the other and as long as each work crew can complete their activity without being interrupted. A loss of productivity factor will be applied to this operation, and this loss of productivity factor was surveyed among professionals of each sector, verified by field observations, and differs depending on the operation.

- Scenario 3: The construction site is not be divided into two different areas and contractors start once their predecessor has advanced sufficiently for them to perform their activity continuously until completion. This third approach has a lower factor of productivity that can decrease the performance of each subcontractor.

All three scenarios were studied and a schedule of completion was done for each of them. Those schedules were done for both options of tendon selection with the same amount of resources to maintain the costs.

3.2.2 Availability of Space

Construction efficiency is directly proportional to availability of space. The smaller the space the lower the production is. Space is needed for storage of materials, for handling of the materials, and for operating equipment.

For the construction of an anchored drilled shaft wall, the contractor or designer should value the availability of space because it may be the critical factor for the selection of the type of anchor (strand or steel bar tendon).

Using the proposed wall as an example, the study will compute the possible space constraints due to storage, handling and/or preparation of the anchors. As expressed above, steel bar tendons require more space for their installation than strand tendons. Depending on the anchor length the space may impede the construction process by requiring installation of couplers for the steel bar anchors piece-by-piece once they are in the hole lowering the production rate. All these space constraints are calculated using a CAT 320 drilling machine with a 25-ft long excavator mounted drill as the machine used on the example project.

With the results from the previous study an evaluation of the space limitation was done depending on the type of tendon.

3.2.3 Anchor Installation

The main goal of this research was to evaluate the differences from a construction standpoint when the retaining wall is built using strand anchors or steel bar anchors. With this in mind, the comparison between them had to be done in terms of time and money. Therefore, the methodology of the study which includes production rates and production costs is detailed below.

3.2.3.1 Production Rates

As explained in the literature review, production rates vary significantly when using steel bar anchors and strand anchors. A comparison for the production rates is done using the proposed wall. Two different schedules were done for the same wall using a different type of anchor. A relation between each type of anchor installation was done depending on the three activities below:

- Drilling of the borehole.
- Tendon insertion including preparation of the tendon.
- Grouting the anchor.

The schedules were done for a one-crew scenario and for a two-crew scenario. This way an easy comparison could be done of both types of anchors for two different situations.

3.2.3.2 Construction Costs

In order to evaluate the differences in costs when installing the different types of anchors, the study assumed that the production had to be the same for both systems. The construction costs were divided into two different aspects:

- Materials. The cost of materials was quantified. The anchor cost included grout cost and corrosion protection. However, for the steel bar tendons the coupler cost has to be taken into consideration as well.
- Equipment and labor. Drilling equipment, handling equipment, installation equipment and all the labor associated with it was evaluated to get a true estimate of equipment cost.

With these two aspects concerning the cost for each of the anchors and assuming the same production rates, differences in costs between steel bars and strands were evaluated.

3.3 Testing

Testing is a critical aspect in the construction of an anchored drilled shaft wall because it is the testing that gives the acceptance criteria for installation of the tiebacks. Therefore, once testing is done the excavation for the next row of anchors is released.

As seen in the sequencing part, testing is time consuming and it is to be taken into account when planning the construction schedule of an anchored wall; hence, it was included in the schedules described above.

The testing specification (PTI, 2004) does not specify any differences in the testing process depending on the type of anchor. Therefore, the testing will not be affect by the anchor selection.

On the other hand, the preparation for testing depends greatly on the anchor selection as has been explained previously. This preparation includes installation of the anchorage, and the differences depending on the anchor were evaluated to compare the production and cost.

Due to the importance of testing, its production rates have been separated from installation production rates. They are also evaluated on a time and cost basis.

In the cost evaluation, it is assumed that production is the same. Therefore, the resources will have to vary and with them the costs.

Testing results are presented for one of the walls of the *“IH-635 Managed Lanes Project”*. Using these results the author computed a percentage of failures per type of tendon which enabled an evaluation of the reliability of each type of anchor.

3.4 Instrumentation

Instrumentation of a wall is normally mandated by the designers to monitor the wall movement and to prevent future problems. Anchored drilled shaft walls instrumentation is installed in the construction phase, and it is monitored during construction and once the construction is done or until the monitoring devices are no longer accessible.

Instrumentation is used in this research to evaluate wall response depending on the types of anchors. As an example, one of the walls from the *“IH-635 Managed Lanes Project”* that was constructed using steel bar tendons with strand tendons was used to evaluate the different responses of the types of tendons.

Inclinometer readings were presented on the above mentioned wall in two different areas of approximately the same height and material but located around the two different type of anchors. These readings were used to evaluate the movement of the wall at both locations.

Chapter 4

Results

After all the calculations that are shown in Appendix A, the following are the results that this research has obtained for the proposed hypothetical retaining wall.

4.1 Design

Following the calculations in Appendix A.1 the tendons parameters that are suitable for this retaining wall are:

- 4-strand tendon
- 1-3/8 inches nominal diameter steel bar tendon

Although greater anchor sizes may be used, the more cost effective option will be those noted above.

4.2 Construction

4.2.1 Sequencing

The sequencing evaluation is shown in Appendix A.5. The results of this evaluation are resumed on Table 4.1. The table specifies the durations for two different activities, the preparation for the anchor installation (steel tying, trumpet installation, drilled shafts and cap beam) and for the anchor installation (excavation, drilling and testing) for each scenario and tendon.

Table 4.1 Results of the schedule by type of tendon and scenario

SCENARIO	TENDON	PREPARATION FOR ANCHOR INSTALLATION (DAYS)	ANCHOR INSTALLATION (DAYS)	TOTAL DAYS
Scenario 1	Strand tendon	33	51	84
	Steel bar tendon	33	60	93
Scenario 2	Strand tendon	27	52	77
	Steel bar tendon	27	68	93
Scenario 3	Strand tendon	23	53	71
	Steel bar tendon	23	80	98

4.2.2 Availability of Space

The space availability is evaluated in Appendix A.4. This evaluation is divided in three subparts storing, handling, and installing the anchor. The last one was studied for two different activities the drilling of the borehole, and the actual anchor installation.

4.2.2.1 Storage Room

The storage room needs were evaluated for a whole row of anchors, that is, a total of 16,000 linear feet of anchors. Two different situation were studied, one for strand anchors and a second one for steel bar anchors.

- Strand anchors will need a total surface of 864 square feet to be stored properly.
- Steel bar anchors will need a surface of 1,600 square feet.

4.2.2.2 Handling Space

Although no calculations were made for this subpart, based on the following field observations and feedback from professionals that were consulted, it was determined that in order to handle steel bar tendons with the same productivity as strand tendons, the space needs for the first type of tendons will double the requirements of the strand tendons.

4.2.2.3 Installation of the Anchor

As previously mentioned, the installation of the anchor was divided into two different activities.

Drilling the borehole will require some space and clearances to allow the piece of equipment enough room to perform productively. This evaluation does not depend on the type of tendon selected because the same machine will be used to install both types of tendons.

In order to provide enough space for the drilling operation, the platform will need to be greater than 22 feet. If productivity is to be maximized, a platform at least 25 feet wide will be needed.

Clearances for selected equipment are determined by the length of the drill and by the angle of the anchor. The clearance needed for the proposed case is 14.5 feet, and in order to maintain productivity, a clearance of 17.5 feet or greater is needed.

The platform needs for the insertion of the anchor only apply to the steel bar tendons. In the case of strand tendons, the platform needs for its insertion are smaller than those needed for the drilling of the borehole. Therefore, in this study it has only been evaluated for the requirements of steel bar tendons.

The steel bar tendon insertion for this case study needed a clearance of at least 32 feet and in order to maintain the productivity, a clearance over 35 feet was needed. The platform had to be at least 87 feet wide to allow the insertion with the tendon precoupled, and it will have to be 5 feet larger to ensure that production rates are maintained.

4.2.3 Anchor Installation

4.2.3.1 Production Rates

The production rates for the anchor installation were calculated in Appendix A.2 and were evaluated depending on the type of tendon selected. The anchorage installation is going to be evaluated as part of the testing.

Table 4.2 summarizes the relations that were obtained by field observation for each activity that depends on the anchor installation. This table shows for a same amount of time how many of each type of anchors can be installed. A final relationship is given between both types of anchors.

Table 4.2 Relations on production rates for the different tendons

OPERATION	TENDON	
	Strand	Steel bar
Drilling borehole	1	1
Tendon insertion	3	1
Grouting	1	2
Overall relation	**3**	**2**

A schedule was done as part of this research for the installation of 1 row of tiebacks with 1 or 2 crews and depending on the type of tendon that was chosen. The results are summarized on Table 4.3.

Table 4.3 Durations for the installation of one row of anchors depending on the number of crews and type of tendon selected.

	Duration (days)	
Tendon	1 Crew	2 Crews
Strand	18	9
Steel Bar	27	13

4.2.3.2 Construction Costs

The construction costs were quantified depending on the tendon selected but assumed the same production rates for both tendons. Table 4.4 shows the cost for all the tendons on one row of anchors of the proposed wall depending on the type of tendon. Tables 4.5 shows the labor and equipment costs for the installation of that same row. Table 4.6 summarizes the total costs for the whole wall of materials and labor and equipment. Table 4.7 gives the unit rates for each installation of anchors depending on the scenario and the type of anchor by linear feet.

Table 4.4 Tendon costs for one row of anchors

Tendon	Material	Freight	Couplers	**Total Cost ($)**
Strand	$119,200.00	$16,000.00	$0.00	**$135,200.00**
Steel Bar	$140,000.00	$12,800.00	$4,800.00	**$157,600.00**

Table 4.5 Labor and equipment costs of installation of one row of anchors depending on the scenario

		Labor and equipment costs
Scenario 1	Strand	$46,293.33
	Steel bar	$56,604.44
Scenario 2	Strand	$57,866.67
	Steel bar	$70,755.56
Scenario 3	Strand	$77,155.56
	Steel bar	$94,340.74

Table 4.6 Total anchor installation costs for the whole wall by scenario and tendon

		Material costs	Labor and equipment costs	TOTAL COST
Scenario 1	Strand	$405,600.00	$138,880.00	$544,480.00
	Steel bar	$472,800.00	$169,813.33	$642,613.33
Scenario 2	Strand	$405,600.00	$173,600.00	$579,200.00
	Steel bar	$472,800.00	$212,266.67	$685,066.67
Scenario 3	Strand	$405,600.00	$231,466.67	$637,066.67
	Steel bar	$472,800.00	$283,022.22	$755,822.22

Table 4.7 Unit costs ($/LF) by scenario and type of tendon

		Unit Cost
Scenario 1	Strand	$11.34
	Steel bar	$13.39
Scenario 2	Strand	$12.07
	Steel bar	$14.27
Scenario 3	Strand	$13.27
	Steel bar	$15.75

4.3 Testing

Testing production rates and its costs depending on the type of tendon were evaluated in Appendix A.2. However, the evaluation of the testing results and the analysis of the reliability of each type of anchor is included in Appendix A.7.

4.3.1 Production Rates

Table 4.8 summarizes the results obtained with this research study. It determines the number of days needed to test one row of the proposed wall depending on the type of tendon and the number of crews.

Table 4.8 Duration for the testing of one row of anchors by type of tendon

	Duration (days)	
Tendon	1 Crew	2 Crews
Strand	11	6
Steel Bar	6	3

4.3.2 Construction Costs

Construction costs related to the testing operations are shown on Table 4.9, and Table 4.10 gives unit costs per anchor tested depending on the type of tendon.

Table 4.9 Total testing cost for the whole proposed retaining wall depending on the type of tendon

	Labor and equipment costs
Strand	$47,001.60
Steel bar	$23,500.80

Table 4.10 Unit costs ($/Ea) for the testing depending on the type of tendon.

	Unit Cost
Strand	$97.92
Steel bar	$48.96

4.3.3 Reliability

After evaluating the testing results of one of the retaining walls of the "IH-635 Managed Lanes Project" the following reliability depending on the type of tendon was determined (see Table 4.11).

Table 4.11 Reliability depending on the type of tendon

	Reliability
Bar	99%
Strand	95%

4.4 Instrumentation

The graphs shown in Appendix A.8 show 5 different readings on 2 inclinometers. An analysis of these two graphs will be done in the following chapter.

Chapter 5

Analysis of the Results

All the previous parts of this research have been divided in four different subsections. However, for the analysis of the results, in order to comprehend all the aspects of the study, no such division will be made. First, the productivity of the construction sequence for each scenario and tendon selection will be analyzed, then the cost for each type of anchor will be shown, and space requirements for each type of tendon described. The analysis will end with a reliability and performance evaluation based on the nature of the tendon.

5.1 Productivity

In this research study, a total of six different cases were observed. Three different scenarios were established with two different anchors for each scenario described—each of them with different conditions and requirements.

For each case, the author decided to split the retaining wall construction in two different phases, one that will not depend on the anchor selection (Preparation for anchor installation) and one that will (Anchor installation). Table 4.1 shows the durations for each case. The first phase varies depending on the scenario but not on the tendon selection, as expected. The second phase varies for every case.

In the "Preparation for the anchor installation" phase, by overlapping as much as possible, all the activities decreased in duration down to a 70%, while the productivity reduced to a 50% for all the activities except the steel tying. For a general contractor who pays by the unit, the only important factor is the schedule because that rules the budget. The longer it takes to perform the job, the higher the indirect and total costs are. Therefore, for this phase, Scenario 3 was the most time efficient for both types of tendons.

In the second phase the "Installation of the anchor," the duration was affected by the scenario and by the type of tendon. For both tendons, Scenario 1 is the most favorable, the one that takes less time. In this phase overlapping many activities does not decrease its duration. On the contrary, the more activities you overlap, the longer the duration of this phase is. The reason for this behavior is that the relations that the activities in this phase have with their predecessor and their successors have time lapses. For example, between the testing of the anchors and its installation, a minimum of 7 natural days is needed. Another example would be that the excavation cannot proceed until the testing of the anchors has been done. These constraints in the relationship between the activities in this phase makes this phase less time efficient when the activities are overlapped.

Steel bar tendons are even more affected by the reduction of production rates because the installation of steel bars takes longer and the testing takes less time. Lower testing durations is actually not beneficial for the schedule. If the testing cannot be interrupted and it has to finish in at least seven natural days after the drilling, it means that the testing will have to delay its start. Due to the fact that the excavation has a longer duration than the testing; hence, the excavation begins just after the testing starts. Then, all the delays on testing will affect the excavation commencement and, therefore, the next row of tiebacks.

For the strand tendons, the best case is Scenario 3 where its duration is the shortest one. However, for the steel bar tendons the best cases can be either Scenario 1 or Scenario 2 since both of them have the same duration. A hybrid solution may be the best case for both types of tendons. Combining the conditions on the scenarios for each phase will be the most time efficient way to improve the overall duration. For both types of tendons, a solution combining the "Preparation of anchor installation" phase of Scenario 3 with the "Anchor installation" phase of Scenario 1 will accomplish shorter durations.

To summarize, for every scenario the strand tendon installation is faster than the steel bar tendon installation. The fastest way to complete the wall will be installing strand tendons in Scenario 3. However, a solution combining Scenarios 1 (Installation of the anchor) and 3

(Preparation for the anchor installation) will compute a shorter schedule for both types of tendons.

5.2 Cost Analysis

While the costs for installation of the anchors are more convenient when the tendon chosen is the strand tendon, the costs of testing are exactly the opposite. An overall study was performed and, and it is shown on Appendix A.3. Table 5.1 below summarizes the information obtained in that Appendix.

Table 5.1 Summary of the costs by Scenario and tendon

		Material costs	Installation of anchor Labor and equipment	Testing Labor and equipment	TOTAL COST
Scenario 1	Strand	$405,600.00	$138,880.00	$47,001.60	$591,481.60
	Steel bar	$472,800.00	$169,813.33	$23,500.80	$666,114.13
Scenario 2	Strand	$405,600.00	$173,600.00	$47,001.60	$626,201.60
	Steel bar	$472,800.00	$212,266.67	$23,500.80	$708,567.47
Scenario 3	Strand	$405,600.00	$231,466.67	$47,001.60	$684,068.27
	Steel bar	$472,800.00	$283,022.22	$23,500.80	$779,323.02

Table 5.2 Unit cost ($/anchor) for each scenario and tendon selection

		Unit Cost
Scenario 1	Strand	$1,232.25
	Steel bar	$1,387.74
Scenario 2	Strand	$1,304.59
	Steel bar	$1,476.18
Scenario 3	Strand	$1,425.14
	Steel bar	$1,623.59

The differences in cost were mainly due to the materials. The installation costs are small compared to those of the materials. For every scenario the strand tendon was cheaper than the steel bar tendon on the installation costs. Even though, testing was more expensive on the strand tendons, the extra costs of installation of the steel bar tendons overcame the testing differences.

When analyzing direct costs, durations are critical factors. The longer it takes to complete the operation and the lower the production rates are, the more expensive that scenario will be. Therefore, Scenario 3 was more expensive than Scenario 2, which was also more expensive than Scenario 1. The most cost effective solution was the use of strand tendons on Scenario 1.

5.3 Space Requirements

According to the field observations and to the results obtained in this research, strand tendons will have smaller space constraints for every aspect of their installation.

Strand tendons are easier to store due to their flexible nature. They can be coiled in the storage area and set one on top of another. Their storage requirement is almost half that of steel bar tendons. This may be relevant on small construction areas with a large number of anchors.

Strand tendons are easier to handle and to prepare because they can be moved and transported with just the help of a single piece of equipment. For this same reason, they are easier to insert in the borehole. The space requirements for the insertion of the anchor in the borehole are much larger for the steel bar tendons than for the strand tendons.

On a construction site with clearance constraints and a small availability of space, strand tendons will be the preferable option for the contractor.

5.4 Reliability and Performance

The reputation for reliability of anchors that are less probable to fail in their testing phase has been earned based on over 1,000 tests where steel bar tendons proved more reliable than the strand tendons. Although both of them have a high reliability, failures attributed to steel bar tendons appear less than 1% of the time compared to strand tendons failures, which have a failure rate that can go as high as 5%. This situation makes steel bar tendons a more reliable anchor than strand tendons.

The performance of both anchors was analyzed by monitoring a retaining walls. In Appendix A.8, two different figures for two different inclinometers are shown. In Figure A.18, almost no movement of the wall was reflected. While in Figure A.19, movements were reflected, although minor, and they are greater than those of the first inclinometer. Movements on the top part of the graphs are not taken into account because on many occasions the inclinometer gets damaged in this area. Therefore, the top readings should be discarded.

For each figure, are two graphs are shown. One is for movement perpendicular to the wall (graph A) and the other is for movement along the wall (graph B). For the first inclinometer located on the area with all the steel bar anchors, the maximum movements recorded are smaller than 1/8 of an inch. It can be said that this wall is not moving.

On the second inclinometer, the movements recorded are larger. The greatest recording during the last reading showed movement to be less than half an inch. Between the third and fourth reading there was a movement increase due, probably, to the excavation of the lower portion of the retaining wall.

Evaluating the readings provided by the “IH-635 Managed Lanes Project”, it seems that the performance of the steel bar tendons was better than that of the strand tendons, because a lower amount of movement was recorded on the inclinometer located on the steel bar tendon area.

Chapter 6

Conclusions and Recommendations for Future Research

6.1 Conclusions

Upon completion of this research several conclusions are found:

- Overlapping activities will only expedite the schedule when the relations between the activities are not fixed to specific waiting times. In those cases, maximum productivity should prevail in order to improve the duration of the project.
- Hybrid solutions with overlapping activities and nonoverlapping activities were found to be the best construction sequence for the construction of anchored drilled shaft walls.
- On almost all occasions, the best solution for the tendon selection was the strand tendons. The installation of strands is faster, cheaper, and needs less space. There are no size limitations for the strand anchors. From a construction standpoint, there are no reasons to choose the steel bar anchors over the strand anchors.
- Installation of steel bar tendons is more expensive due to the extra cost of the materials and installation costs. Extra equipment and personnel needed to prepare, handle, and insert the anchor in the borehole makes the anchor installation less cost effective compared to the strand tendon.
- Testing of steel bar tendons was more cost effective than the testing of strand tendons. However, this small difference was not sufficient to overcome the extra costs of installation.
- Overall a steel bar anchored retaining wall is more expensive than the strand anchored one.
- Strand tendon installation is done at a greater rate than the steel bar tendon installation. Although testing strand anchors is more time consuming than testing steel bar anchors,

the differences in time are not enough to overcome the differences created by the anchor installation. Therefore, the strand tendon installation is more time efficient.

- Space needs are greater for the installation of steel bar tendons. Greater clearances and widths of platforms will be needed if the steel bar is the tendon chosen.
- Steel bar tendons account for less failures during testing.

Table 6.1 shown below can serve as a decision support system for contractors that are trying to choose what anchor will best fit their situation for permanent purposes.

	Strand tendon	Steel bar tendons
Existing space constrains	X	
Schedule runs the project	X	
Cost runs the project	X	
Reliability of the anchors is critical		X
Performance of the anchors		X Further research needed

6.2 Future Recommendations

Although the scope of this study is large and a great number of observations were made, the study could easily be extended to approach a better understanding of the different type of tendons and their uses. Below are some recommendations for future studies:

- Conduct a comparative study of scenarios governed by critical path activities with those activities given extra attention.
- Seek more reliable statistics with the use of different retaining walls constructed by different subcontractors. Although 1,000 tests were used, all of them were on the same retaining wall and were performed by the same contractor.
- Provide cost comparisons and schedules including the reliability factors for each tendon to probe that the testing failure of tiebacks incurs in extra cost and time.
- Perform a statistical analysis on the type of testing failures resulting from the tendon that is tested.

- Further research should be conducted on the performance of each type of tendon. Inclinometer readings from different retaining walls should be taken where it is known the type of anchor that was used.
- Durability researches are needed to ensure that strand tendons are as durable as steel bars. Analyses should be conducted of old anchored retaining walls and their conditions should be evaluated depending on the nature of the tendon that was used.

Appendix A:

Calculations

A.1 Selection of the Type of Tendon Given the Proposed Tendon Loads

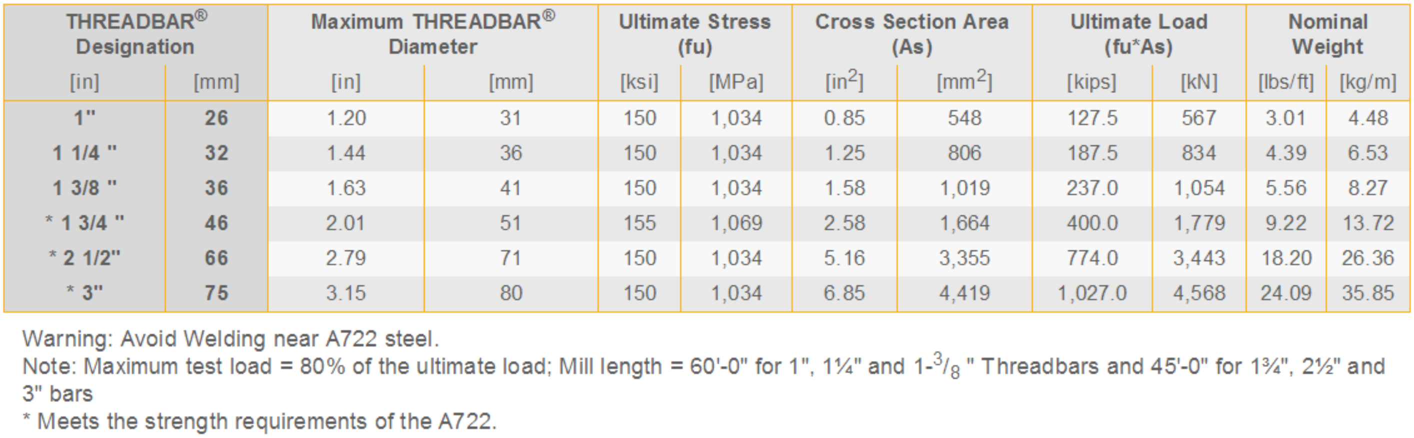
On Table A.1 the information for the proposed anchors of the retaining wall is established.

Table A.1 Proposed loads for the anchors.

	LOCK-OFF LOAD	PERFORMANCE TEST LOAD	PROOF TEST LOAD
TB-1	120	175	175
TB-2	120	175	175
TB-3	120	175	175

With this information and using the tables provided ASTM A722 shown on Table A.2 below.

Table A.2 ASTM A722 (Grade 150) for steel bar anchors provided by DSI (http://www.dsiamerica.com/products/geotechnic/tierods/bar-properties.html, March 4th, 2014)

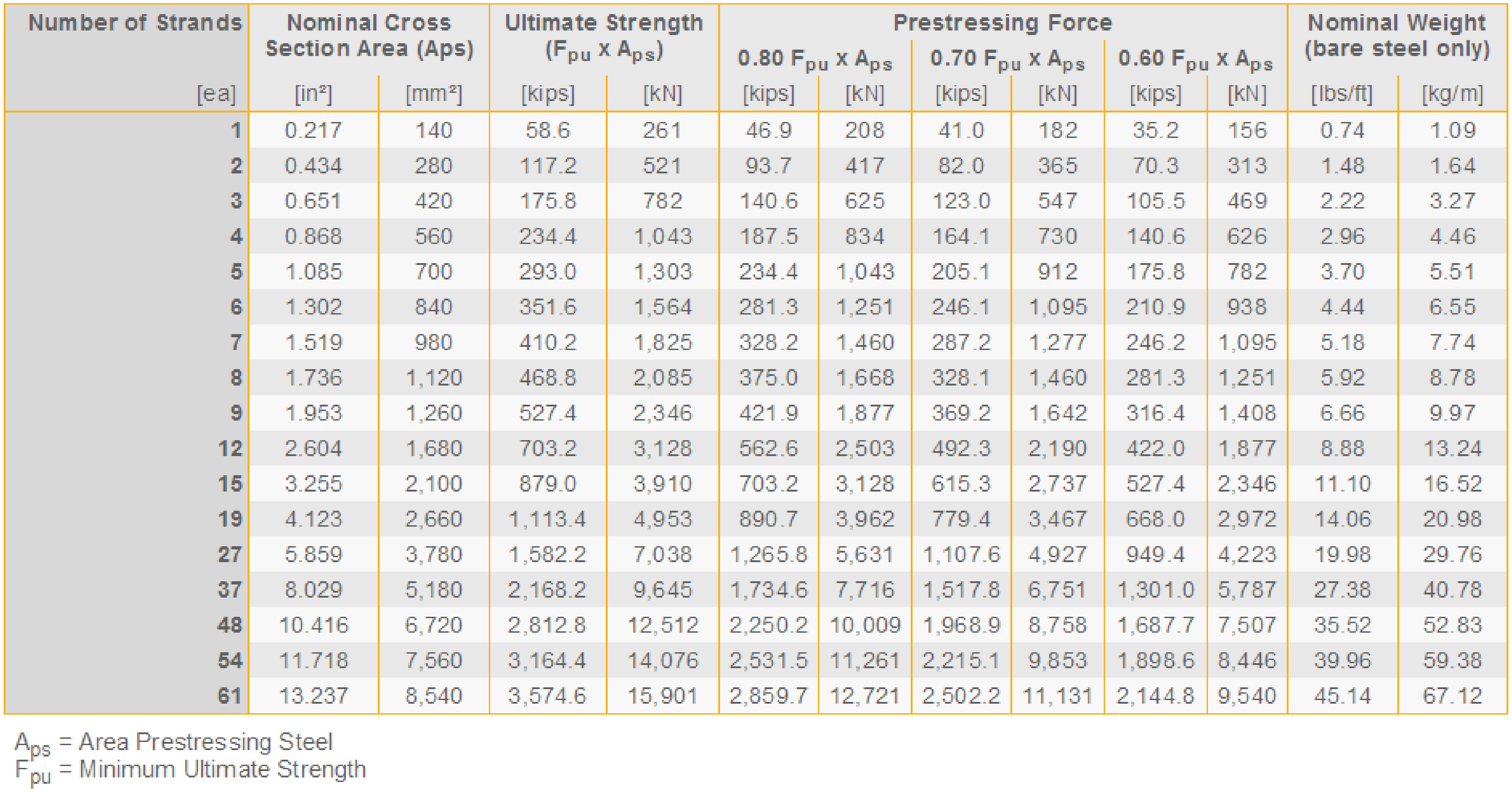


THREADBAR® Designation		Maximum THREADBAR® Diameter		Ultimate Stress (fu)		Cross Section Area (As)		Ultimate Load (fu*As)		Nominal Weight	
[in]	[mm]	[in]	[mm]	[ksi]	[MPa]	[in^2]	[mm^2]	[kips]	[kN]	[lbs/ft]	[kg/m]
1"	**26**	1.20	31	150	1,034	0.85	548	127.5	567	3.01	4.48
1 1/4 "	**32**	1.44	36	150	1,034	1.25	806	187.5	834	4.39	6.53
1 3/8 "	**36**	1.63	41	150	1,034	1.58	1,019	237.0	1,054	5.56	8.27
*** 1 3/4 "**	**46**	2.01	51	155	1,069	2.58	1,664	400.0	1,779	9.22	13.72
*** 2 1/2"**	**66**	2.79	71	150	1,034	5.16	3,355	774.0	3,443	18.20	26.36
*** 3"**	**75**	3.15	80	150	1,034	6.85	4,419	1,027.0	4,568	24.09	35.85

Warning: Avoid Welding near A722 steel.
Note: Maximum test load = 80% of the ultimate load; Mill length = 60'-0" for 1", 1¼" and 1-$^3/_8$ " Threadbars and 45'-0" for 1¾", 2½" and 3" bars
* Meets the strength requirements of the A722.

Table A.3 ASTM A416 (bare strand) for strand tendons provided by DSI

(http://www.dsiamerica.com/products/geotechnic/dywidag-strand-anchor-systems/strand-anchor-properties.html, March 4th, 2014)



Number of Strands	**Nominal Cross Section Area (Aps)**		**Ultimate Strength (F_{pu} x A_{ps})**		**Prestressing Force**						**Nominal Weight (bare steel only)**	
					0.80 F_{pu} x A_{ps}		**0.70 F_{pu} x A_{ps}**		**0.60 F_{pu} x A_{ps}**			
[ea]	[in²]	[mm²]	[kips]	[kN]	[kips]	[kN]	[kips]	[kN]	[kips]	[kN]	[lbs/ft]	[kg/m]
1	0.217	140	58.6	261	46.9	208	41.0	182	35.2	156	0.74	1.09
2	0.434	280	117.2	521	93.7	417	82.0	365	70.3	313	1.48	1.64
3	0.651	420	175.8	782	140.6	625	123.0	547	105.5	469	2.22	3.27
4	0.868	560	234.4	1,043	187.5	834	164.1	730	140.6	626	2.96	4.46
5	1.085	700	293.0	1,303	234.4	1,043	205.1	912	175.8	782	3.70	5.51
6	1.302	840	351.6	1,564	281.3	1,251	246.1	1,095	210.9	938	4.44	6.55
7	1.519	980	410.2	1,825	328.2	1,460	287.2	1,277	246.2	1,095	5.18	7.74
8	1.736	1,120	468.8	2,085	375.0	1,668	328.1	1,460	281.3	1,251	5.92	8.78
9	1.953	1,260	527.4	2,346	421.9	1,877	369.2	1,642	316.4	1,408	6.66	9.97
12	2.604	1,680	703.2	3,128	562.6	2,503	492.3	2,190	422.0	1,877	8.88	13.24
15	3.255	2,100	879.0	3,910	703.2	3,128	615.3	2,737	527.4	2,346	11.10	16.52
19	4.123	2,660	1,113.4	4,953	890.7	3,962	779.4	3,467	668.0	2,972	14.06	20.98
27	5.859	3,780	1,582.2	7,038	1,265.8	5,631	1,107.6	4,927	949.4	4,223	19.98	29.76
37	8.029	5,180	2,168.2	9,645	1,734.6	7,716	1,517.8	6,751	1,301.0	5,787	27.38	40.78
48	10.416	6,720	2,812.8	12,512	2,250.2	10,009	1,968.9	8,758	1,687.7	7,507	35.52	52.83
54	11.718	7,560	3,164.4	14,076	2,531.5	11,261	2,215.1	9,853	1,898.6	8,446	39.96	59.38
61	13.237	8,540	3,574.6	15,901	2,859.7	12,721	2,502.2	11,131	2,144.8	9,540	45.14	67.12

A_{ps} = Area Prestressing Steel
F_{pu} = Minimum Ultimate Strength

In order to select the type of tendon to be used in the proposed retaining wall, it is important to remember the rules that exist for tendon testing:

- The design load shall not exceed 60% of the Specified Minimum Tensile Strength, herein SMTS (PTI, 2004);
- the lock-off load shall not exceed 70% of the SMTS (PTI, 2004);
- the maximum test load shall not exceed 80% of the STMS (PTI, 2004);
- and in the case of strand tendons the lock-off load has to exceed 50% of the STMS to ensure the bite of the wedges. If needed, shims might be used to achieve the load and to ensure the bite (PTI, 2004).

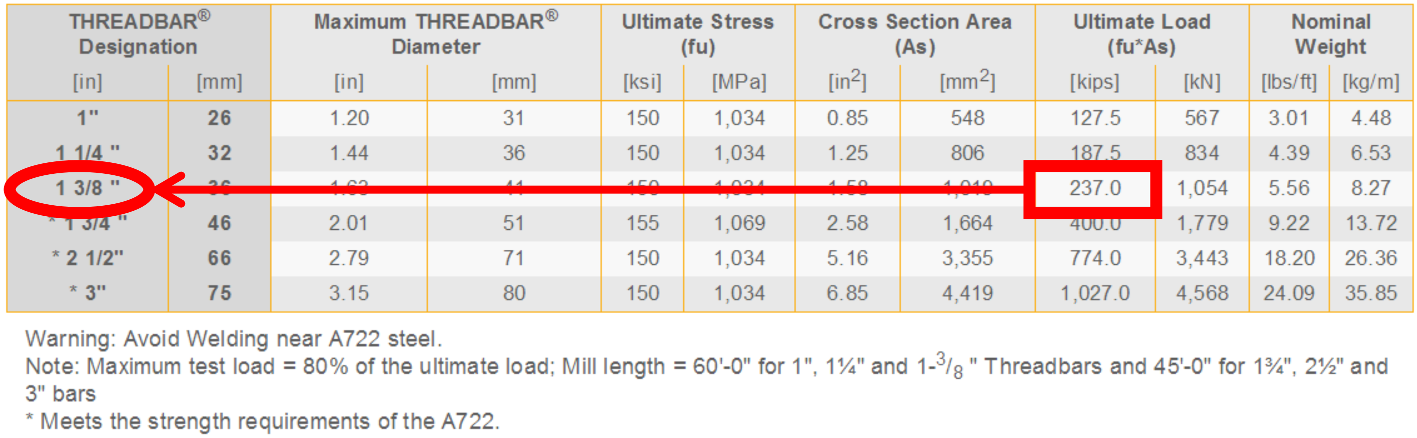
Using the given information on Table A.1 and the conditions provided by the PTI, the following table was calculated.

Table A.4 Design loads needed for the proposed anchors

	LOCK-OFF LOAD	PERFORMANCE TEST LOAD	PROOF TEST LOAD	DESIGN LOAD (DL=Lock-off/0.7)	DESIGN LOAD (DL=Performance Test/0.8)	DESIGN LOAD (DL=Proof Test/0.8)
TB-1	120	175	175	171.43	218.75	218.75
TB-2	120	175	175	171.43	218.75	218.75
TB-3	120	175	175	171.43	218.75	218.75

Using the higher value from columns 4, 5 and 6 and Table A.2, a steel bar that will fit this retaining wall was found.

Table A.5 Proposed steel bar to be used on the retaining wall



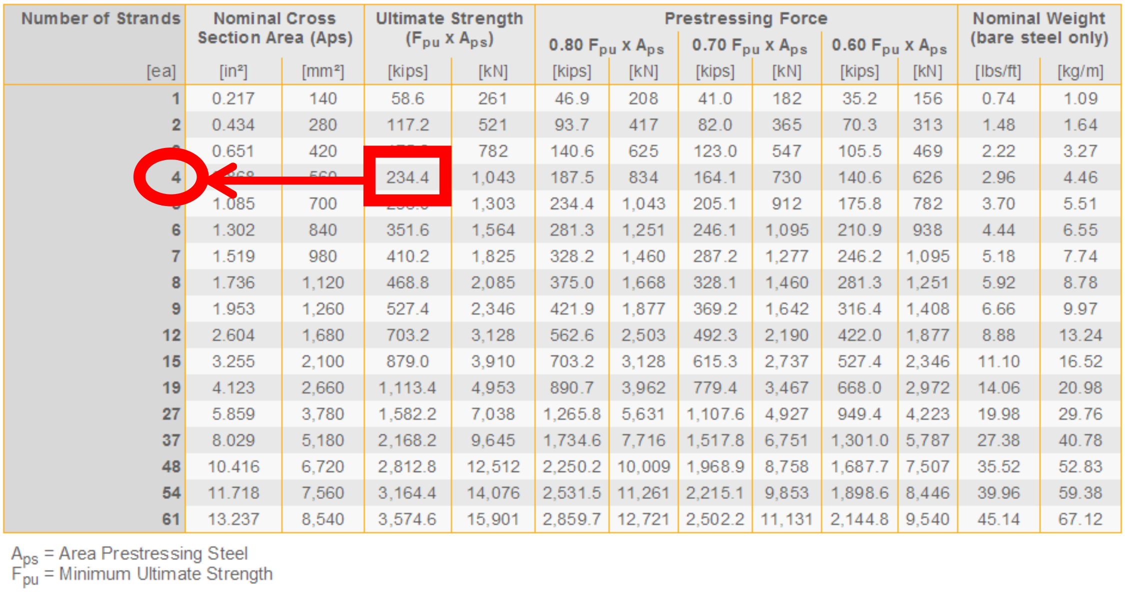
THREADBAR® Designation		Maximum THREADBAR® Diameter		Ultimate Stress (fu)		Cross Section Area (As)		Ultimate Load (fu*As)		Nominal Weight	
[in]	[mm]	[in]	[mm]	[ksi]	[MPa]	[in^2]	[mm^2]	[kips]	[kN]	[lbs/ft]	[kg/m]
1"	**26**	1.20	31	150	1,034	0.85	548	127.5	567	3.01	4.48
1 1/4 "	**32**	1.44	36	150	1,034	1.25	806	187.5	834	4.39	6.53
1 3/8 "	**36**	1.63	41	150	1,034	1.58	1,018	237.0	1,054	5.56	8.27
*** 1 3/4 "**	**46**	2.01	51	155	1,069	2.58	1,664	400.0	1,779	9.22	13.72
*** 2 1/2"**	**66**	2.79	71	150	1,034	5.16	3,355	774.0	3,443	18.20	26.36
*** 3"**	**75**	3.15	80	150	1,034	6.85	4,419	1,027.0	4,568	24.09	35.85

Warning: Avoid Welding near A722 steel.
Note: Maximum test load = 80% of the ultimate load; Mill length = 60'-0" for 1", 1¼" and 1-$^3/_8$ " Threadbars and 45'-0" for 1¾", 2½" and 3" bars
* Meets the strength requirements of the A722.

Therefore, in this case the steel bar of 1 3/8" will have to the one to be used.

The same process is done for the strand anchors and it is shown in Table A.6.

Table A.6 Proposed number of strands for the retaining wall



Number of Strands	Nominal Cross Section Area (Aps)		Ultimate Strength (F_{pu} x A_{ps})		Prestressing Force						Nominal Weight (bare steel only)	
					0.80 F_{pu} x A_{ps}		0.70 F_{pu} x A_{ps}		0.60 F_{pu} x A_{ps}			
[ea]	[in²]	[mm²]	[kips]	[kN]	[kips]	[kN]	[kips]	[kN]	[kips]	[kN]	[lbs/ft]	[kg/m]
1	0.217	140	58.6	261	46.9	208	41.0	182	35.2	156	0.74	1.09
2	0.434	280	117.2	521	93.7	417	82.0	365	70.3	313	1.48	1.64
3	0.651	420	175.8	782	140.6	625	123.0	547	105.5	469	2.22	3.27
4	0.868	560	234.4	1,043	187.5	834	164.1	730	140.6	626	2.96	4.46
5	1.085	700	293.0	1,303	234.4	1,043	205.1	912	175.8	782	3.70	5.51
6	1.302	840	351.6	1,564	281.3	1,251	246.1	1,095	210.9	938	4.44	6.55
7	1.519	980	410.2	1,825	328.2	1,460	287.2	1,277	246.2	1,095	5.18	7.74
8	1.736	1,120	468.8	2,085	375.0	1,668	328.1	1,460	281.3	1,251	5.92	8.78
9	1.953	1,260	527.4	2,346	421.9	1,877	369.2	1,642	316.4	1,408	6.66	9.97
12	2.604	1,680	703.2	3,128	562.6	2,503	492.3	2,190	422.0	1,877	8.88	13.24
15	3.255	2,100	879.0	3,910	703.2	3,128	615.3	2,737	527.4	2,346	11.10	16.52
19	4.123	2,660	1,113.4	4,953	890.7	3,962	779.4	3,467	668.0	2,972	14.06	20.98
27	5.859	3,780	1,582.2	7,038	1,265.8	5,631	1,107.6	4,927	949.4	4,223	19.98	29.76
37	8.029	5,180	2,168.2	9,645	1,734.6	7,716	1,517.8	6,751	1,301.0	5,787	27.38	40.78
48	10.416	6,720	2,812.8	12,512	2,250.2	10,009	1,968.9	8,758	1,687.7	7,507	35.52	52.83
54	11.718	7,560	3,164.4	14,076	2,531.5	11,261	2,215.1	9,853	1,898.6	8,446	39.96	59.38
61	13.237	8,540	3,574.6	15,901	2,859.7	12,721	2,502.2	11,131	2,144.8	9,540	45.14	67.12

A_{ps} = Area Prestressing Steel
F_{pu} = Minimum Ultimate Strength

The two options that will need to be evaluated in a cost comparison will be:

- Installation of 1 3/8" steel bar anchor
- Installation of 4 strand anchors

A.2 Production Rates for the Different Types of Tendon Selected

Due to the lack of information of production rates on the construction of anchored retaining walls, the information provided on this research has been computed with the information provided by professional of the sector that has been verified with field observations. The production rates for the different type of tendons selected were divided into two main sections.

A.2.1 Anchor Installation

The anchor installation will comprehend the drilling of the borehole, the tendon installation and the grouting process. The anchorage installation most commonly used has been included on the following section.

A.2.1.1 Drilling of the Borehole.

The drilling operation is not different from one tendon to another. Its production rates basically depend on the operators' expertise and on-the-ground conditions. Assuming ground conditions that are suitable for anchor installation (no collapsing holes, or ground water), no difference was found on production rates. It is worthy to note that if worse geotechnical conditions are encountered, such as ground water at the bonded length, the anchor shall be extended. When using steel bar anchors, this may not have a big impact because they can be extended easily. However, strand tendons are not that easily extended and a geotechnical problem may end up having the contractor rejecting the anchor that was to be used in that borehole, and a new and longer one chosen for installation instead.

An operator with poor experience may have more trouble when working with steel bar tendons due to their lack of flexibility. This lack of flexibility reduces the tolerances within the borehole. This means that the borehole inclinations will have more restrictive tolerances when using bar tendons. However, for this research it has been assumed that the operators are experts and that no differences on the production rates will arise from drilling operations.

A.2.1.2 Tendon Insertion.

Tendon insertion requires preparation of the tendons. It is this preparation that makes the biggest differences in the production.

Strand tendons are easily handled due to their flexibility, and all the preparatory work they need is also needed for steel bar tendons. Some of this work includes installation of centralizers, attaching the external grouting conduit, protecting the end of the tendon, straightening the tendon for inspection and getting it ready for the installation.

On the other hand, steel bar tendons need more preparation work and are not as easy to handle. To all the operations noted on the previous paragraph, the steel bar tendon adds the installation of couplers and corrosion protection. Due to this activity along with the difficulties that this type of tendons present, the production rates for strand tendon preparation are higher than those for steel bar tendons.

For the same crew, the preparation time of one steel bar tendon (100 feet long) is the same as the time expended preparing 3 strand tendons.

The insertion is also affected greatly by the rigidity of the steel bar tendons. For lengths over 60 feet, two pieces of equipment are needed to move the tendon. This operation is much simpler for strand tendons that once ready are move close to the borehole with no need for even one piece of equipment.

For the same crew, the relation between both types of tendons will be the same. For one steel tendon an insertion of 3 strand tendons can be installed.

A.2.1.3 Grouting.

Grouting is the only operation of the anchor installation that is more time consuming on the strand tendons than on the steel bar ones. The main reason is that steel bar tendons arrive at the jobsite with the internal grout already installed. Therefore, the onsite grouting naturally takes up more time on the strand tendons as operators wait for grout to be pumped. However, when using high pressure pumps, these differences are as noticeable because of the amount of grout this equipment can pump per second. Nevertheless, the fact that the pump will have to be connected to two different grouting tubes on the strand tendon (internal and external), compared to only one pump for steel bar tendons (external application only) makes a large impact on the time expended during the grouting operation.

Overall, the difference in time has been approximately 2 to 1. While grouting one strand tendon, two steel bar tendons can be grouted.

The production relations seen above are resumed on the table below.

Table A.7 Relations on production rates for the different tendons accounting just for anchor installation

OPERATION	TENDON	
	Strand	Steel bar
Drilling borehole	1	1
Tendon insertion	3	1
Grouting	1	2
Quantity install in one day per one crew (LF)	900	600

A.2.2 Testing of the Anchor

From a production standpoint the anchorage installation will be accounted for during testing. This anchorage installation and the preparation for the testing (jack installation and plate installation) are more time consuming on the strand anchor.

There are two main reasons for this difference as noted during the production of both type of tendons.

- Rigidity of the steel bar anchor helps the installation process of equipment needed for stressing. While on the strand tendon, a small excavator needs to hold the strand until they reach enough stress; however, on the steel bar tendons the excavator is not needed except for installation of the jack.
- The larger number of strands per number of steel bars, increases the amount of cleaning that needs to be done prior to the testing. Also inserting each strand through

each wedge hole is less time effective than inserting the steel bar through the plate hole.

For these two reasons, and by field observations it is determined that on a regular day of testing, the same testing crew will be able to test 14 strand tendons or 25 steel bar tendons. This is approximately a 2 to 1 ratio.

A.2.3 Overall.

To serve as an example, and using the production rates described above, a simple schedule for one of the rows of tiebacks from the proposed wall is used. The schedule is done for two different cases:

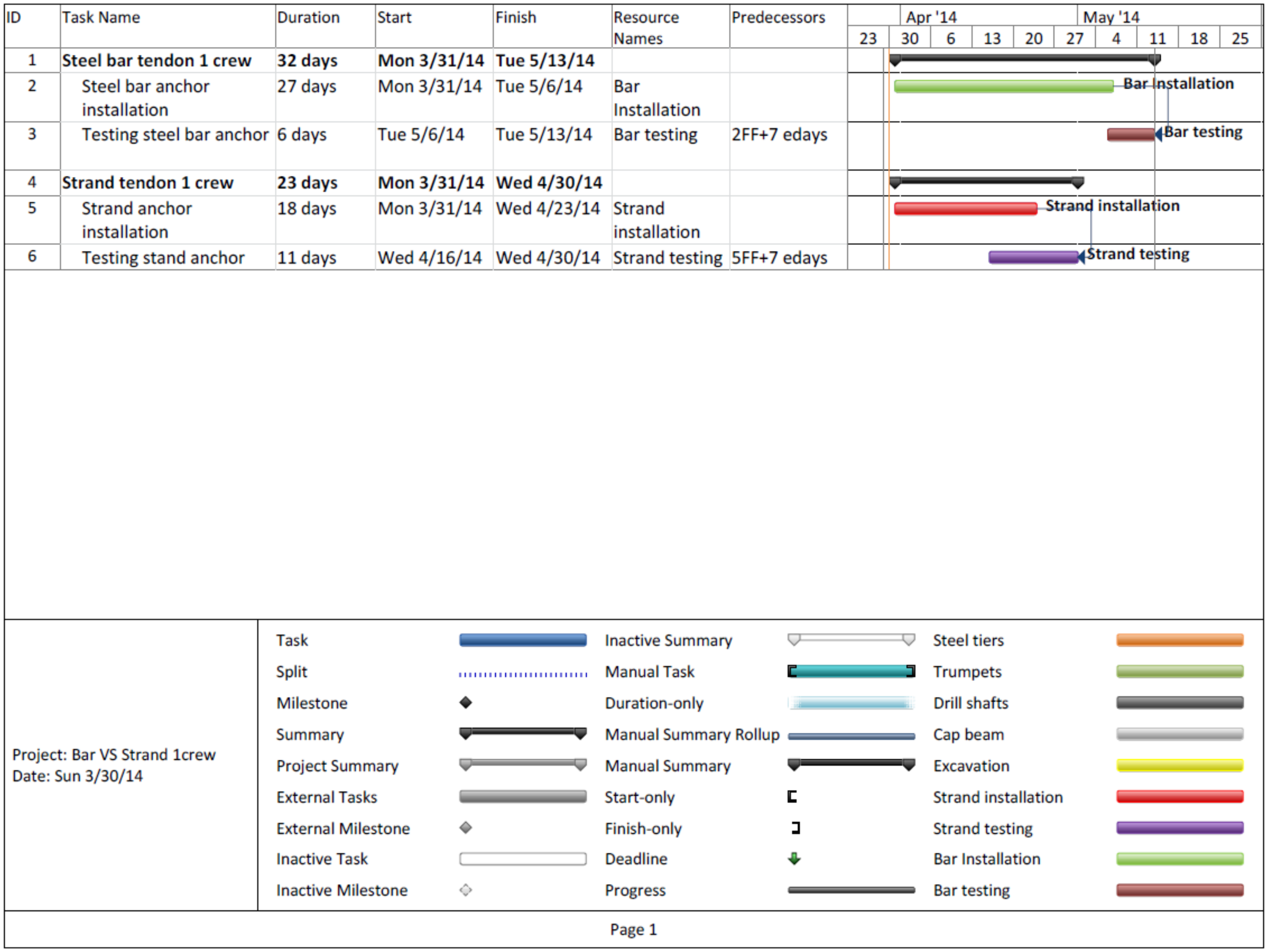
1. One crew per operation
2. Two crews per operation

The total quantities for one row of tiebacks are shown on Table A.8.

Table A.8 Total quantities for tiebacks per row of the proposed wall

Activity	UNIT	Quantity
Tieback	LF	16,000
Testing	Ea	160

When scheduling the relationship between both activities, installation and testing, a finish to finish relation within a 7 natural day lapse is neededto ensure that the grout has properly cured prior to the testing. Both schedule are shown on Figures A.1 and A.2



ID	Task Name	Duration	Start	Finish	Resource Names	Predecessors
1	**Steel bar tendon 1 crew**	**32 days**	**Mon 3/31/14**	**Tue 5/13/14**		
2	Steel bar anchor installation	27 days	Mon 3/31/14	Tue 5/6/14	Bar Installation	
3	Testing steel bar anchor	6 days	Tue 5/6/14	Tue 5/13/14	Bar testing	2FF+7 edays
4	**Strand tendon 1 crew**	**23 days**	**Mon 3/31/14**	**Wed 4/30/14**		
5	Strand anchor installation	18 days	Mon 3/31/14	Wed 4/23/14	Strand installation	
6	Testing stand anchor	11 days	Wed 4/16/14	Wed 4/30/14	Strand testing	5FF+7 edays

Project: Bar VS Strand 1crew
Date: Sun 3/30/14

Task	▬	Inactive Summary	▬	Steel tiers	▬
Split	┈	Manual Task	▬	Trumpets	▬
Milestone	◆	Duration-only	▬	Drill shafts	▬
Summary	▬	Manual Summary Rollup	▬	Cap beam	▬
Project Summary	▬	Manual Summary	▬	Excavation	▬
External Tasks	▬	Start-only	[	Strand installation	▬
External Milestone	◆	Finish-only	]	Strand testing	▬
Inactive Task	▭	Deadline	⬇	Bar Installation	▬
Inactive Milestone	◇	Progress	▬	Bar testing	▬

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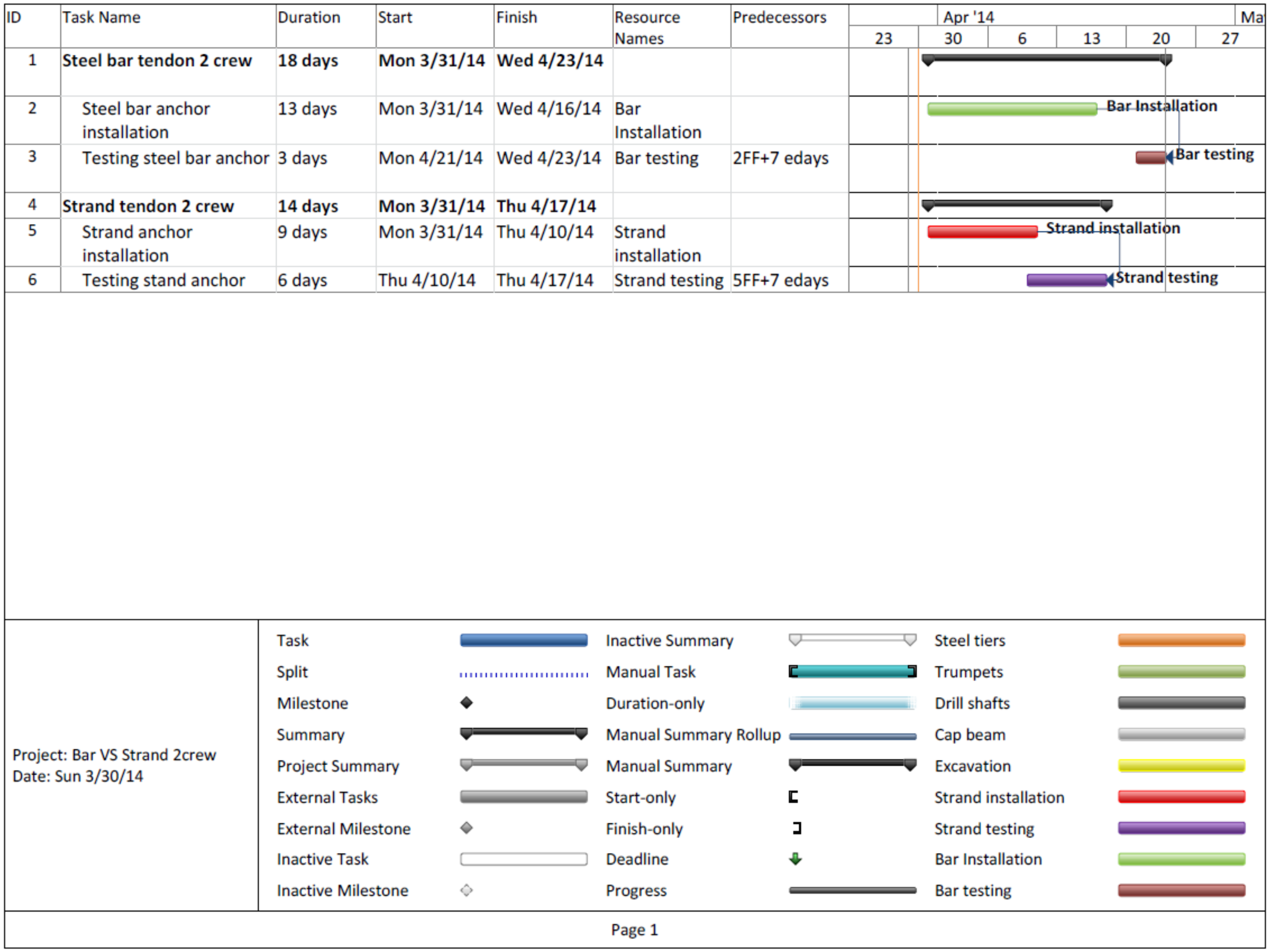
Figure A.1 Strand vs Steel bar schedule for 1 crew



ID	Task Name	Duration	Start	Finish	Resource Names	Predecessors
1	**Steel bar tendon 2 crew**	**18 days**	**Mon 3/31/14**	**Wed 4/23/14**		
2	Steel bar anchor installation	13 days	Mon 3/31/14	Wed 4/16/14	Bar Installation	
3	Testing steel bar anchor	3 days	Mon 4/21/14	Wed 4/23/14	Bar testing	2FF+7 edays
4	**Strand tendon 2 crew**	**14 days**	**Mon 3/31/14**	**Thu 4/17/14**		
5	Strand anchor installation	9 days	Mon 3/31/14	Thu 4/10/14	Strand installation	
6	Testing stand anchor	6 days	Thu 4/10/14	Thu 4/17/14	Strand testing	5FF+7 edays

Project: Bar VS Strand 2crew
Date: Sun 3/30/14

Task	Inactive Summary	Steel tiers
Split	Manual Task	Trumpets
Milestone	Duration-only	Drill shafts
Summary	Manual Summary Rollup	Cap beam
Project Summary	Manual Summary	Excavation
External Tasks	Start-only	Strand installation
External Milestone	Finish-only	Strand testing
Inactive Task	Deadline	Bar Installation
Inactive Milestone	Progress	Bar testing

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Figure A.2 Strand vs Steel bar schedule for 2 crews

A.3 Construction Costs for Different Types of Tendons

The construction cost analysis for each type of tendon installation will be presuming the same production rates for both types of tendons. As seen before, the production rates for steel bar installation are lower, which means an extra cost will have to be overcome in order to achieve the same production rates as the strand tendons.

The cost comparison was done by dividing it into two different sections, materials and installation. It is assumed that all the equipment to be used on this operation is fully dedicated to this operation and, therefore, it will be considered as a direct cost. No overhead cost will be included on this research and only direct costs will be analyzed.

The installation of one row of anchors of the proposed wall will be used as an example to validate and to compare all the information. Therefore the total quantity of tiebacks to be installed and tested will have to be taken into account. This information is provided on Table A.8.

The situation will be compared with the use of two crews. The size of the crews will differ because of the tendon selection. This crews will be evaluated according to the following subparts.

A.3.1 Materials

Not all materials are taken into consideration because some of them will not depend on tendon selection. For example, grout will be very similar for both types of anchor, and the only difference will be where the anchor is grouted. However, this difference will impact the weight of the anchor and, therefore, it will impact freight cost. The plates for the anchorage system will also not be evaluated because it is assumed that the cost is the same for strand tendons and for steel bar tendons.

Table A9 shows the cost per linear foot for each type of anchor. Note that only the two anchors used for comparison are the steel bar of 1 3/8" and the 4-strand anchor.

Table A.9 Cost of tendon by the linear foot

Tendon	UNIT	Cost
Strand	$/LF	$7.45
Steel Bar	$/LF	$8.75

Then the total cost of the anchors provided below in Table A.10.

Table A.10 Total cost of the anchor

Tendon	Unit Cost ($/LF)	Quantity (LF)	Total Cost ($)
Strand	$7.45	16,000	$119,200.00
Steel Bar	$8.75	16,000	$140,000.00

These costs do not include freight. The cost of the freight will be approximately $3,200 per truck load, and a truck load will carry 35 strand anchors or 50 steel bar anchors 100 feet long each. The difference is the space that the strand anchors take when they are transported due to being coiled. Therefore, taking into account that 160 anchors were needed for this row, the cost of the freight is shown on the next table.

Table A.11 Freight cost per tendon type

Tendon	Freight Cost ($/Load)	Number of loads	Total Cost ($)
Strand	$3,200.00	5	$16,000.00
Steel Bar	$3,200.00	4	$12,800.00

For the steel bar anchors an extra cost for the couplers will had to be figured. The price per coupler is $30 160 of them were needed. Therefore, the total cost of the couplers was $4,800. Each coupler had to be installed on site and it had to be protected against corrosion on site as well. This extra protection was not taken into consideration in the cost that is provided here.

The total cost of materials is shown on Table A.12.

Table A.12 Total material costs

Tendon	Material	Freight	Couplers	**Total Cost ($)**
Strand	$119,200.00	$16,000.00	$0.00	**$135,200.00**

Steel Bar	$140,000.00	$12,800.00	$4,800.00	**$157,600.00**

A.3.2 Installation

In order to compare the cost of installation of both types of tendons, a comparison was made for the crews that had equal production rates for both anchors. A two-drill crew was used for evaluation purposes, but the extra equipment and labor needed to ensure that the production rates were equal are shown in Table A.13.

Field observations and interviews with professionals in the sector allowed the author of this research to note the different crew sizes that ensured that the production would be equal for both anchor installations. Table A.13 notes the size of the crews along with the hourly rates for each piece of equipment and labor. The last column of the table reflects the differences between both on total hourly costs. The total cost difference per hour is noted on the bottom row of the table.

Table A.13. Crew costs for type of tendon installation

	TYPE OF TENDON						
	Strand			Steel bar			
Item	No per 2 crews	Hourly rate	Cost per hour	No per 2 crews	Hourly rate	Cost per hour	Difference (steel bar - strand) per hour
Excavator mounted drill	2	$110.00	$220.00	2	$110.00	$220.00	$0.00
Grout Pump	2	$50.00	$100.00	2	$50.00	$100.00	$0.00
Loader	1	$60.00	$60.00	1	$60.00	$60.00	$0.00
Excavator	1	$80.00	$80.00	2	$80.00	$160.00	$80.00
Drill operator	2	$17.50	$35.00	2	$17.50	$35.00	$0.00
Excavator operator	1	$15.00	$15.00	2	$15.00	$30.00	$15.00
Loader operator	1	$15.00	$15.00	1	$15.00	$15.00	$0.00
Spotter	2	$12.50	$25.00	2	$12.50	$25.00	$0.00
Laborer	4	$12.50	$50.00	8	$12.50	$100.00	$50.00
Foreman	1	$36.00	$36.00	1	$36.00	$36.00	$0.00
Pick-up truck	1	$15.00	$15.00	1	$15.00	$15.00	$0.00
			$651.00			**$796.00**	**$145.00**

It was assumed that one day has 8 work hours. Therefore, the cost difference per day was the one from Table A.13 multiplied by 8 hours. A extra cost of $1,160.00 per day was incurred when using steel bar tendons.

A.3.3 Testing

Testing will also have an impact on the cost of the anchor installation. According to the production rates shown in the previous part, the steel bar testing is almost twice as productive as the strand testing. Therefore, in order to maintain the production rates of the steel bar testing, a second crew will have to be allocated for this project.

A similar table to that showing costs of anchor installation is shown below. It evaluates the extra hourly cost of having a second crew for the strand testing.

Table A.14 Labor and equipment costs for type of tendon testing

	TYPE OF TENDON						
	Strand			Steel bar			
Item	Quantity	Hourly rate	Cost per day	Quantity	Hourly rate	Cost per hour	Difference (strand - steel bar) per hour
Mini excavator	2	$60.00	$120.00	1	$60.00	$60.00	$60.00
Testing equipment	2	$50.00	$100.00	1	$50.00	$50.00	$50.00
Testing labor	4	$14.00	$56.00	2	$14.00	$28.00	$28.00
Excavator operator	2	$15.00	$30.00	1	$15.00	$15.00	$15.00
			$306.00			$153.00	$153.00

The difference in hourly costs will be exactly the cost of one crew. Therefore, the difference in day cost will be $1,224.00 for a full day of work with more costs incurred as a result of strand testing rather than those costs incurred as a result of steel bar tendon testing.

A.3.4 Overall

The costs overall for the 1st row of tiebacks of the proposed retaining wall are shown in Table A.15. These extra costs were calculated for production rates with 3 different loss of productivity factors, one for each scenario. Note that this loss of production does not apply to the testing because it does not need much room to operate, thereby, other contractors in the area will not affect its production.

The production rates that are used will be the higher ones per tendon for either installation or testing. Therefore, it will be accounted that the maximum installation will be 900 linear feet of anchors per day per crew, and 25 anchors will be tested per day.

Table A.15 shows the amount of days needed to finish one row depending on the scenario chosen for two crews installing anchors and for 25 tests a day.

Table A.15 Days spent by operation by Scenario

		Factor of loss of production	Regular Production	Days
SCENARIO 1	Installation	1	1,800	9
	Testing	1	25	6
SCENARIO 2	Installation	0.8	1,800	11
	Testing	1	25	6
SCENARIO 3	Installation	0.6	1,800	15
	Testing	1	25	6

Table A.16 Costs of labor and equipment for Scenario 1 by type of tendon

			Strand		Steel bar	
		Days	Cost per day	Total cost	Cost per day	Total cost
SCENARIO 1	Installation	9	$5,208.00	$46,293.33	$6,368.00	$56,604.44
	Testing	6	$2,448.00	$15,667.20	$1,224.00	$7,833.60
TOTAL			$61,960.53		$64,438.04	

Table A.17 Costs of labor and equipment for Scenario 2 by type of tendon

			Strand		Steel bar	
		Days	Cost per day	Total cost	Cost per day	Total cost
SCENARIO 2	Installation	11	$5,208.00	$57,866.67	$6,368.00	$70,755.56
	Testing	6	$2,448.00	$15,667.20	$1,224.00	$7,833.60
TOTAL			$73,533.87		$78,589.16	

Table A.18 Costs of labor and equipment for Scenario 3 by type of tendon

			Strand		Steel bar	
		Days	Cost per day	Total cost	Cost per day	Total cost
SCENARIO 3	Installation	15	$5,208.00	$77,155.56	$6,368.00	$94,340.74
	Testing	6	$2,448.00	$15,667.20	$1,224.00	$7,833.60
TOTAL			$92,822.76		$102,174.34	

Table A.19 resumes all the tables above and shows the differences in pricing for each different scenario. Note that this table is done for the overall wall--not just for one row of anchors. Therefore, all the quantities are multiplied by 3 rows.

Table A.19 Labor and equipment total costs by Scenario

		Cost per row	Total wall cost
Scenario 1	Strand	$61,960.53	$185,881.60
	Steel bar	$64,438.04	$193,314.13
	DIFFERENCE	$2,477.51	$7,432.53
Scenario 2	Strand	$73,533.87	$220,601.60
	Steel bar	$78,589.16	$235,767.47
	DIFFERENCE	$5,055.29	$15,165.87
Scenario 3	Strand	$92,822.76	$278,468.27
	Steel bar	$102,174.34	$306,523.02
	DIFFERENCE	$9,351.59	$28,054.76

Note that for every scenario the steel bar tendon is more expensive than the strand tendon. Material costs shall be added to these values. Table A.20 shows the total costs including the material costs.

Table A.20 Overall costs for the retaining wall

		Material costs	Labor and equipment costs	TOTAL COST
Scenario 1	Strand	$405,600.00	$185,881.60	$591,481.60
	Steel bar	$472,800.00	$193,314.13	$666,114.13
	DIFFERENCE	$67,200.00	$7,432.53	**$74,632.53**
Scenario 2	Strand	$405,600.00	$220,601.60	$626,201.60
	Steel bar	$472,800.00	$235,767.47	$708,567.47
	DIFFERENCE	$67,200.00	$15,165.87	**$82,365.87**
Scenario 3	Strand	$405,600.00	$278,468.27	$684,068.27
	Steel bar	$472,800.00	$306,523.02	$779,323.02
	DIFFERENCE	$67,200.00	$28,054.76	**$95,254.76**

A.4 Availability of Space

Space constraints and availability of real estate are most important for the type of tendon selection and equipment that will be used. Clearance limitations for the equipment and space for storage, preparation and handling the anchors are critical.

As previously noted, the strand tendons are not rigid and are delivered to the construction site without grout. On the other hand, steel bar anchors are delivered grouted and are extremely rigid. These two characteristics make the steel bar tendons much harder to handle, store and prepare. Although the preparation of the anchor will take approximately the same room for both types of tendons, the space required to store and to handle them is larger.

A.4.1 Storage Room.

In order to provide a visual example of the storing problems that each type of tendon may cause. It was decided to create an example situation similar to the one of the proposed wall.

The example was created by evaluating the room needed to store all the anchors that are needed in one row. Therefore, this study focused on the room needed to store 160 strand anchors or 160 steel bar anchors. For this evaluation, the following characteristics of tendons were considered:

- A strand tendon can be store coiled.
- A total of 3 strand tendons can be stored on a pallet one on top of the other.
- A coiled strand tendon pallet occupies an area of 4 feet by 4 feet.
- Steel bar tendons are not store coupled
- Steel bar tendons can be stored one on top of the other when they are not bundled 2 tendons at a time.
- A total of 20 steel bar tendons will cover a width of 4 feet.
- The pallets of strand anchor can be stored side by side.
- 2 steel bar anchor stored longitudinally will not need to have any room between them.

- Steel bar anchors are delivered in 2 pieces, one—40 feet long and the other—60 feet long. Both pieces will be store one beside each other.

This calculation of space needed to store 160 steel bar anchors was done.

The proposed area measures 100 feet long which is enough feet to store both pieces of the anchor. The width can be calculated easily with the following formula.

$$Width(ft) = \frac{Total\ number\ of\ anchors\ to\ store}{2\ anchors\ on\ top\ of\ each\ other * 20\ \frac{anchors}{4\ ft\ wide}}$$

For a total number of anchors equal to 160 the width needed will be 16 feet.

Therefore, the area needed to store the steel bar anchors will be:

$$Area\ (ft^2) = Lenght\ (ft) * Width\ (ft)$$

The total area will be 1,600 ft^2 for the steel bar anchors.

The strand anchors are calculated differently. Per the assumptions it is known that the area that 3 strand anchors occupy is 16 ft^2. Using the formula below and rounding it to next whole number will give the total number of pallets of strand anchors needed.

$$Number\ of\ pallets\ of\ strand\ anchors = \frac{Total\ number\ of\ anchors}{3\ \frac{anchors}{pallet}}$$

The total number of pallets is 54 pallets (53 with 3 strands and 1 with just one).

Therefore, the total area to store 54 pallets of strands is $54\ pallets * 16\ \frac{ft^2}{pallet} = 864\ ft^2$

Table A.21 Space needs to store 160 anchors 100 feet long depending on the type of tendon

	Storage room (ft^2)
Strand anchors	864
Steel bar anchors	1,600

A.4.2 Handling Space

Although the room needed to handle the anchors is very difficult to quantify, it is obvious that the smaller the space is the more difficult the handling will be, thereby decreasing the production rates.

Moving the anchors from the storage area to the preparation area only requires one piece of equipment. In the case of the strand tendons a regular loader with forks will serve, while for the steel bar anchors the use of either excavator, two loaders, or two excavators will be needed.

Once the anchor is prepared for installation, it is common for the strand tendons to be coiled again so that they are moved close to the borehole. Once there, they are installed with the help of an excavator if available, if not the can be uncoiled by hand. On steel bar anchors, if the length is greater than 60 feet the use of two pieces of equipment is needed to ensure that the anchor does not drag on the ground while it is being moved. For anchors of 60 feet or less a single piece of equipment can be used. These considerations are made for the type of anchors that we are evaluating in this research, the 4 strand anchor and the steel bar of 1-3/8 inches.

For the anchor sizes considered in this research, field observations concluded that in order to maintain production rates an area at least twice larger was needed to handle the steel bar anchors compared to the space required to store strand anchors.

Figure A.3 Excavator handling a 60 feet long steel bar anchor

(Personal picture, March 26th, 2014)

A.4.3 Installation of the Anchor

For the installation of the anchor, there are two different aspects. First is the actual drilling, the equipment used for drilling the borehole has to have enough clearance and space to work productively. Second, the insertion of the anchor has to be feasible.

A.4.3.1 Drilling of the borehole

The evaluation of the needs for the drilling is done for the proposed retaining wall. The piece of equipment used will be 25 feet long with an excavator-mounted drill that will have to drill holes at a 30 degree angle.

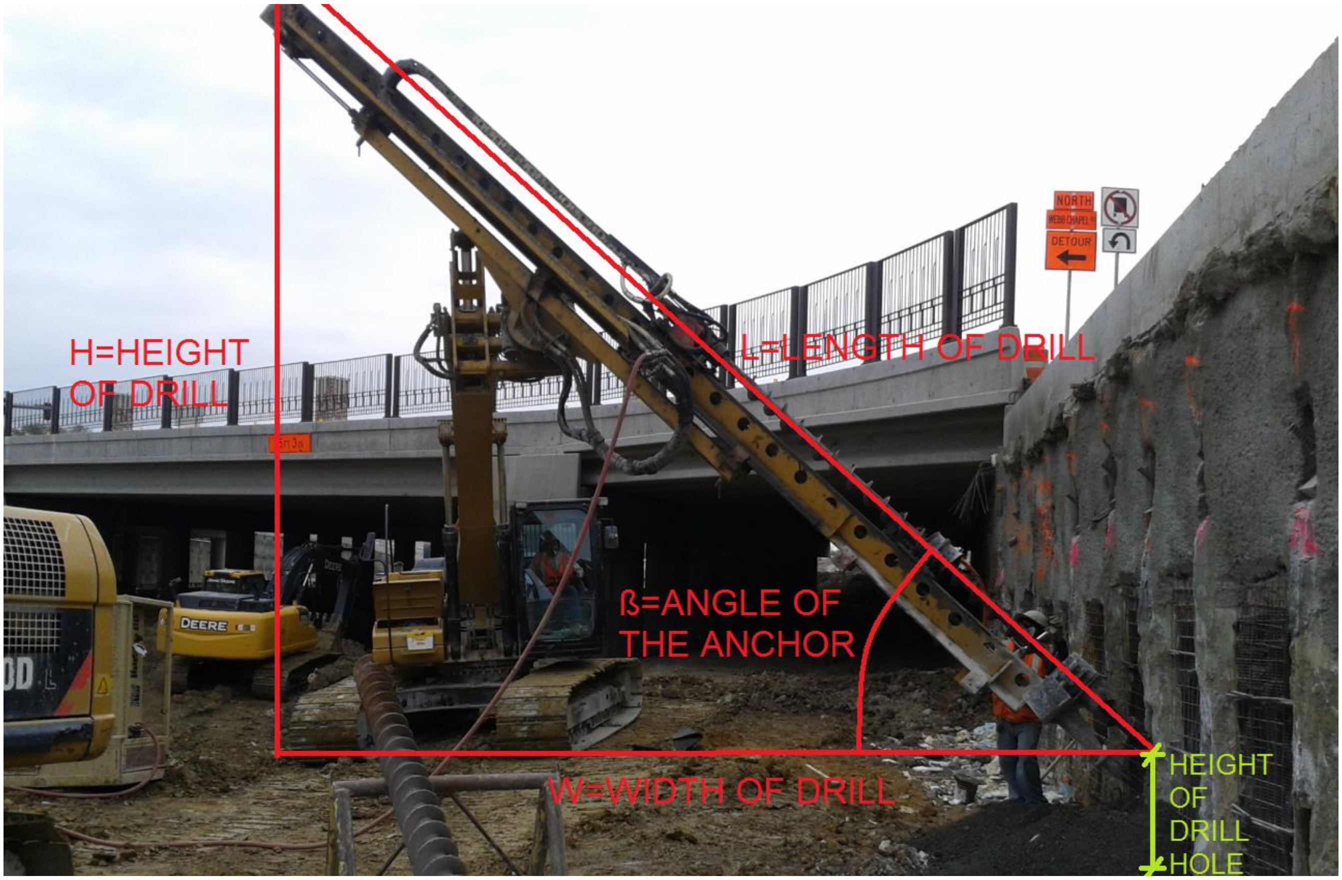


Figure A.4 Excavation mounted drill: Dimension of drill

(Personal file, March 5th, 2014).

As noted in the literature review the clearance needs to be able to drill with the piece of equipment selected, which is

$$Total\ height = Height\ of\ drill\ hole\ above\ the\ ground + Height\ of\ drill + 3\ feet\ to\ maneuver$$

where the height of the drill is

$$Height\ of\ the\ drill\ (ft) = Length\ of\ the\ drill\ (ft) * \sin(ß)$$

For the proposed wall ß is equal to 30 degrees and the length of the drill is 25 feet, and the height of drill hole above the ground is 2 feet.

Then,

$$Height\ of\ the\ drill\ (ft) = 25\ ft * \sin(30) = 12.5\ ft$$

and,

$$Total\ height = 2\ ft + 12.5\ ft + 3\ ft = 17.5\ ft$$

In order to maintain the production, a clearance of 17.5 feet is needed. If the clearance is between 14.5 feet and 17.5 feet the production rates will be reduced, and if it is lower than 14.5 feet a different piece of equipment will be needed.

The width of the platform will need to be

$$Platform\ width\ (ft) = Drill\ width(ft) + 3\ ft\ to\ maneuver$$

Where the drill width is

$$Width\ of\ the\ drill\ (ft) = Length\ of\ the\ drill\ (ft) * \cos(\text{ß})$$

where the length of the drill is 25 feet and the angle of the anchor is 30 degrees.

Then,

$$Width\ of\ the\ drill\ (ft) = 25\ ft * \cos(30) = 21.7\ ft$$

and,

$$Platform\ width\ (ft) = 21.7\ ft + 3\ ft\ to\ maneuver = 25\ ft$$

There are different pieces of equipment that have to be located behind the drill. For those, the calculation will be different, and the platform for the same length of drill will have to be wider. Examples of pictures showing this equipment follows.

Figure A.5 Excavator mounted drill

(HEM-40ED Soil Nailing Drill, TEI Rock Drills)

Figure A. 6 Comparison on the width of platform needed by both pieces of equipment

(Personal file, January 8th, 2014)

A.4.3.2 Anchor insertion

Depending on the type of tendon used on the anchor the insertion of it in the drill hole will be different. For a strand tendon, the insertion can be done almost manually. A piece of equipment is needed to move the strand close to the hole but once it is close to the drill hole the insertion can be done by laborers although it is faster with the help of a piece of equipment. Therefore, there are no clearance or space constraints for the strand anchors.

On the other hand, for steel bar anchors, the insertion is difficult and it requires, depending on the length of the anchor, larger clearances than the drilling operation.

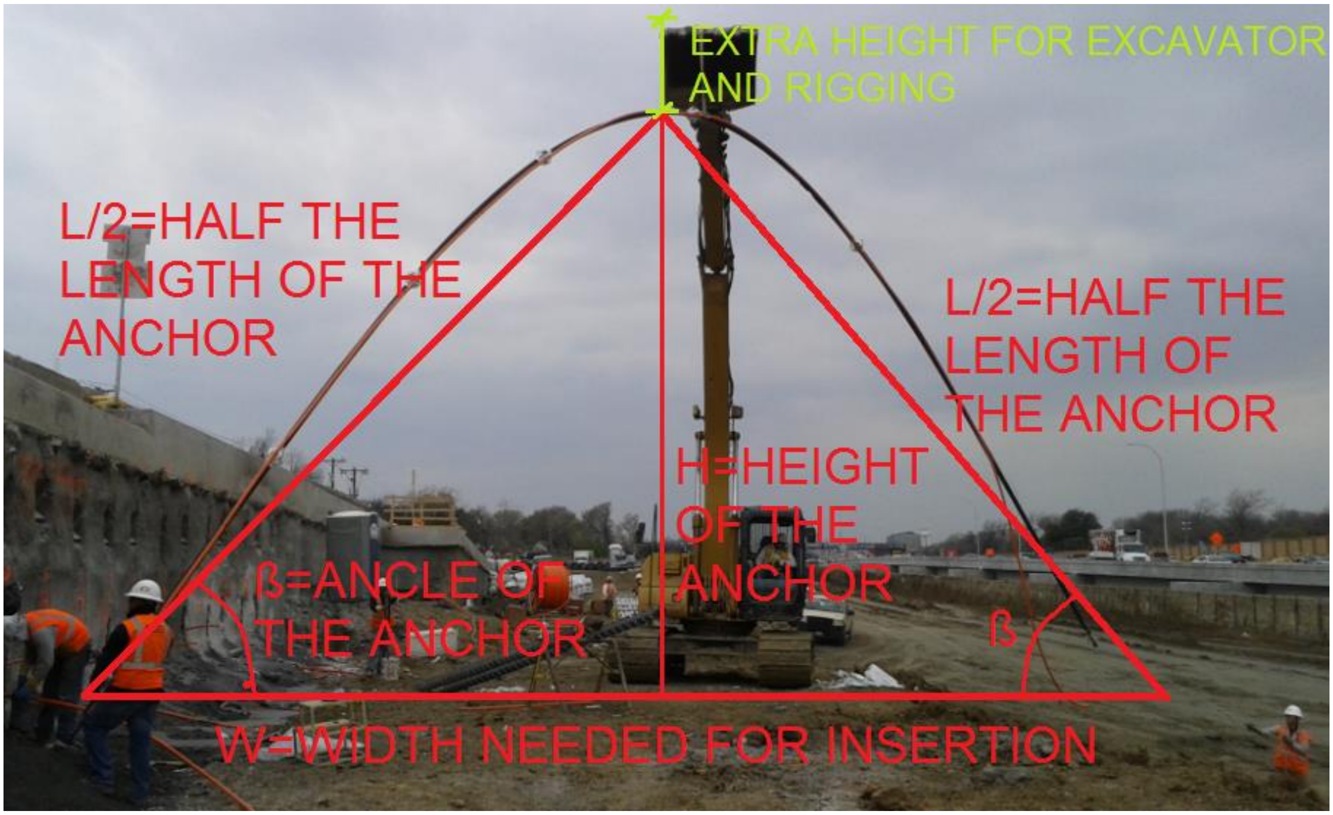


Figure A.7 Insertion of steel bar anchor. Dimensions

(Personal picture, March 26th, 2014)

The evaluation of the needs for the anchor insertion is done for the proposed retaining wall. The anchor length is 100 feet and two excavators are needed. The extra height for excavator and rigging is 5 feet and an extra 3 feet to maneuver was needed.

$$\mathit{Clearance}\ (ft) = H\ (ft) + \mathit{Extra\ height\ for\ excavator\ and\ rigging}\ (ft) + \mathit{Height\ of\ drill\ hole}$$

Where the height of the drill hole is 2 feet and

$$H(ft) = \frac{Anchor\ Length\ (ft)}{2} * \sin(ß)$$

Where, the anchor angle is 30 degrees.

$$H(ft) = \frac{100\ ft}{2} * \sin(30) = 25\ ft$$

Then,

$$Clearance\ (ft) = 25\ ft + 5\ ft\ + 2\ ft = 32\ ft$$

In order to maintain production rates an extra 3 feet for maneuvers will be needed. Therefore, the clearance that will maintain production rates will be 35 ft.

The platform width will be obtained with the following formula.

$$W(ft) = Anchor : Length\ (ft) * cos(ß)$$

where the anchor length is 100 feet and ß is 30 degrees.

Therefore,

$$W(ft) = 100\ ft * co\ s(30) = 86.6\ ft$$

In order to maintain the production rates, at least an extra 5 feet is needed. Then, the width that will maintain the production rates will be 92 feet.

If the platform is smaller than 87 feet wide the steel bar will have to be inserted in shorter pieces inside the borehole and coupling them inside it. This sequence will decrease the production rates.

In this case study, the platform is just 60 feet wide but for the purpose of this study and taking into account that the installation of steel bar anchors is already slower than that of the strands. It is assumed that no production loss is created due to the width of the platform.

A.5 Sequencing

The construction sequence of the anchored drilled shaft wall was scheduled for 3 different scenarios. On each scenario, a different schedule was done for the type of tendon that was selected. Therefore, a total of six cases were studied.

All the cases are based on the same total quantities for the retaining wall and on the same number of crews. The production rates of each crew depends on the scenario and on the type of anchor selected. Table A.22 comprehends the total quantities for the wall by unit.

Table A.22 Total quantities for the proposed retaining wall

Activity	Unit	Quantity
Drill Shafts	LF	9,600
Steel	lbs	1,280,000
Trumpets	EA	480
Cap Beam	LF	1,000
Excavation	CY	33,333
Tiebacks	LF	48,000
Testing	EA	480

The production rates per day and crew are shown on Tables A.23, A.24 and A.25. Theses tables also show the number of crews per activity and the factor of loss of production for each activity.

Table A.23 Production rates for Scenario 1

		SCENARIO 1				
ACTIVITY	**UNIT**	**Production per crew and day**	**Factor of loss of production**	**Total production per crew and day**	**# Crews**	**Total production per day**
Steel tying	lbs	50,000	1.00	50,000	3	150,000
Trumpets	Ea	30	1.00	30	2	60
Drill Shafts	LF	480	1.00	480	2	960
Cap Beam	LF	80	1.00	80	2	160
Excavation	CY	4,500	1.00	4,500	1	4,500
TB (strand)	LF	900	1.00	900	2	1,800
TB (bar)	LF	600	1.00	600	2	1,200
Testing (strand)	Ea	14	1.00	14	2	28
Testing (bar)	Ea	25	1.00	25	2	50

Table A.24 Production rates for Scenario 2

		SCENARIO 2				
ACTIVITY	**UNIT**	**Production per crew and day**	**Factor of loss of production**	**Total production per crew and day**	**# Crews**	**Total production per day**
Steel tying	lbs	50,000	0.75	37,500	3	112,500
Trumpets	Ea	30	0.75	23	2	45
Drill Shafts	LF	480	0.75	360	2	720
Cap Beam	LF	80	0.75	60	2	120
Excavation	CY	4,500	0.70	3,150	1	3,150
TB (strand)	LF	900	0.80	720	2	1,440
TB (bar)	LF	600	0.80	480	2	960
Testing (strand)	Ea	14	1.00	14	2	28
Testing (bar)	Ea	25	1.00	25	2	50

Table A.25 Production rates for Scenario 3

		SCENARIO 3				
ACTIVITY	**UNIT**	**Production per crew and day**	**Factor of loss of production**	**Total Production per crew and day**	**# Crews**	**Total production per day**
Steel tying	lbs	50,000	0.75	37,500	3	112,500
Trumpets	Ea	30	0.50	15	2	30
Drill Shafts	LF	480	0.50	240	2	480
Cap Beam	LF	80	0.50	40	2	80
Excavation	CY	4,500	0.35	1,575	1	1,575
TB (strand)	LF	900	0.60	540	2	1,080
TB (bar)	LF	600	0.60	360	2	720
Testing (strand)	Ea	14	1.00	14	2	28
Testing (bar)	Ea	25	1.00	25	2	50

A.5.1 Scenario 1

For this scenario the factors of loss of production are all equal to 1 because each activity is working on their own and they have all the space for themselves. All the activities will have the same duration for both cases, the strand tendon and the steel bar tendon, except for those of drilling and testing.

A.5.1.1 Strand Tendon

The duration for each activity is shown on the table below.

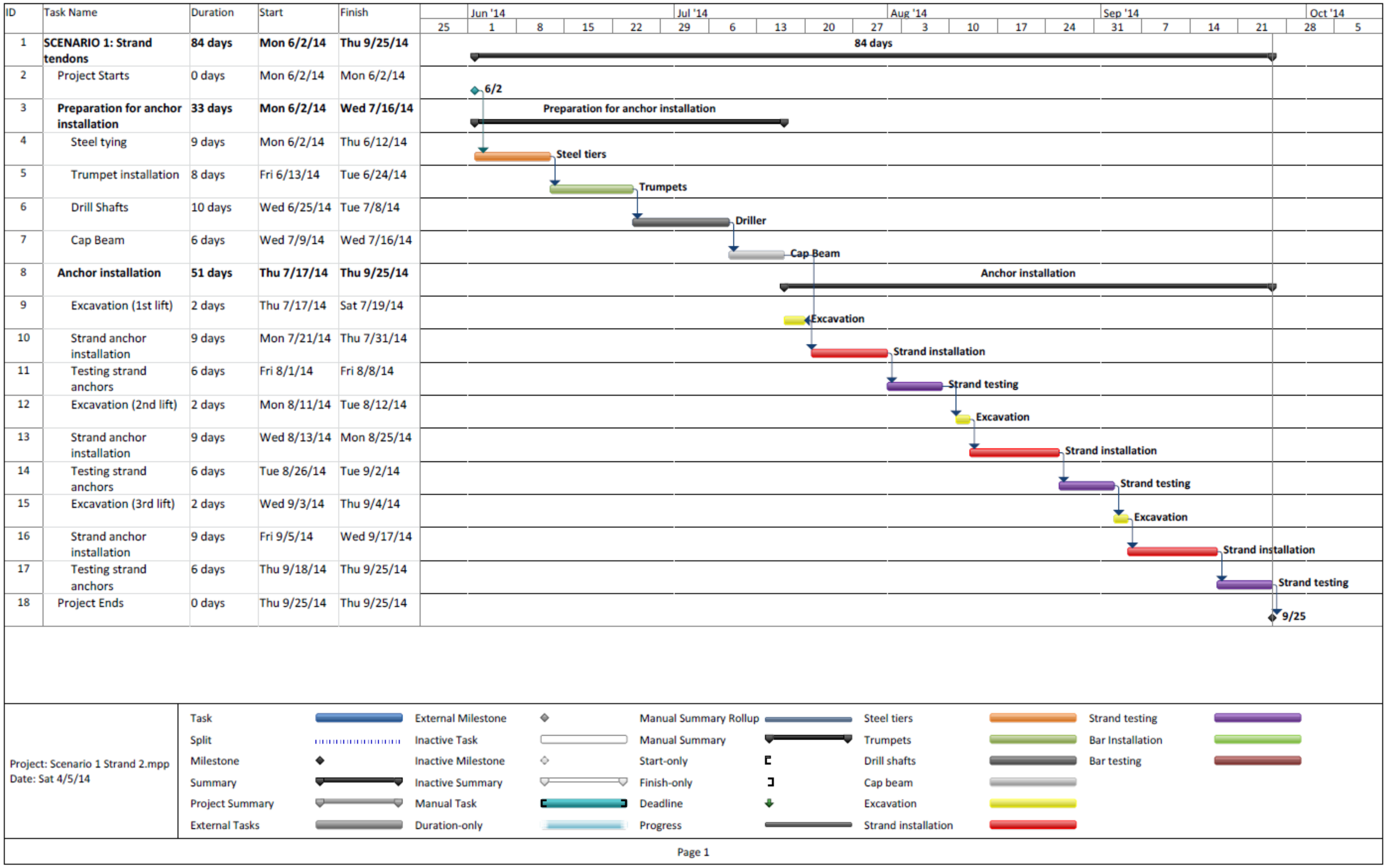
Table A.26 Days spent per activity for the strand installation for Scenario 1

ACTIVITY	UNIT	Total production per day	Days
Steel tying	lbs	150,000	9
Trumpets	Ea	60	8
Drill Shafts	LF	960	10
Cap Beam	LF	160	6
Excavation 1st lift	CY	4,500	2
TB (strand) 1st row	LF	1800	9
Testing (strand) 1st row	Ea	28	6
Excavation 2nd lift	CY	4,500	2
TB (strand) 2nd row	LF	1800	9
Testing (strand) 2nd row	Ea	28	6
Excavation 3rd lift	CY	4,500	2
TB (strand) 3rd row	LF	11800	9
Testing (strand) 3rdow	Ea	28	6

The conditions for the schedule are:

- Each activity starts once the predecessor finishes.
- The 1st lift of excavations has to finish at least 3 natural days after the cap beam to allow the curing period.
- The testing of the strand will have to finish at least 7 natural days after the drilling.

The total duration of this case is 84 days. The preparation of the anchor installation lasts for 33 days while the installation of the anchors has a duration of 51 days.



ID	Task Name	Duration	Start	Finish
1	**SCENARIO 1: Strand tendons**	**84 days**	**Mon 6/2/14**	**Thu 9/25/14**
2	Project Starts	0 days	Mon 6/2/14	Mon 6/2/14
3	**Preparation for anchor installation**	**33 days**	**Mon 6/2/14**	**Wed 7/16/14**
4	Steel tying	9 days	Mon 6/2/14	Thu 6/12/14
5	Trumpet installation	8 days	Fri 6/13/14	Tue 6/24/14
6	Drill Shafts	10 days	Wed 6/25/14	Tue 7/8/14
7	Cap Beam	6 days	Wed 7/9/14	Wed 7/16/14
8	**Anchor installation**	**51 days**	**Thu 7/17/14**	**Thu 9/25/14**
9	Excavation (1st lift)	2 days	Thu 7/17/14	Sat 7/19/14
10	Strand anchor installation	9 days	Mon 7/21/14	Thu 7/31/14
11	Testing strand anchors	6 days	Fri 8/1/14	Fri 8/8/14
12	Excavation (2nd lift)	2 days	Mon 8/11/14	Tue 8/12/14
13	Strand anchor installation	9 days	Wed 8/13/14	Mon 8/25/14
14	Testing strand anchors	6 days	Tue 8/26/14	Tue 9/2/14
15	Excavation (3rd lift)	2 days	Wed 9/3/14	Thu 9/4/14
16	Strand anchor installation	9 days	Fri 9/5/14	Wed 9/17/14
17	Testing strand anchors	6 days	Thu 9/18/14	Thu 9/25/14
18	Project Ends	0 days	Thu 9/25/14	Thu 9/25/14

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Figure A.8 Schedule for the strand anchor installation for Scenario 1

A.5.1.2 Steel Bar Tendon

The duration for each activity is shown on the table below.

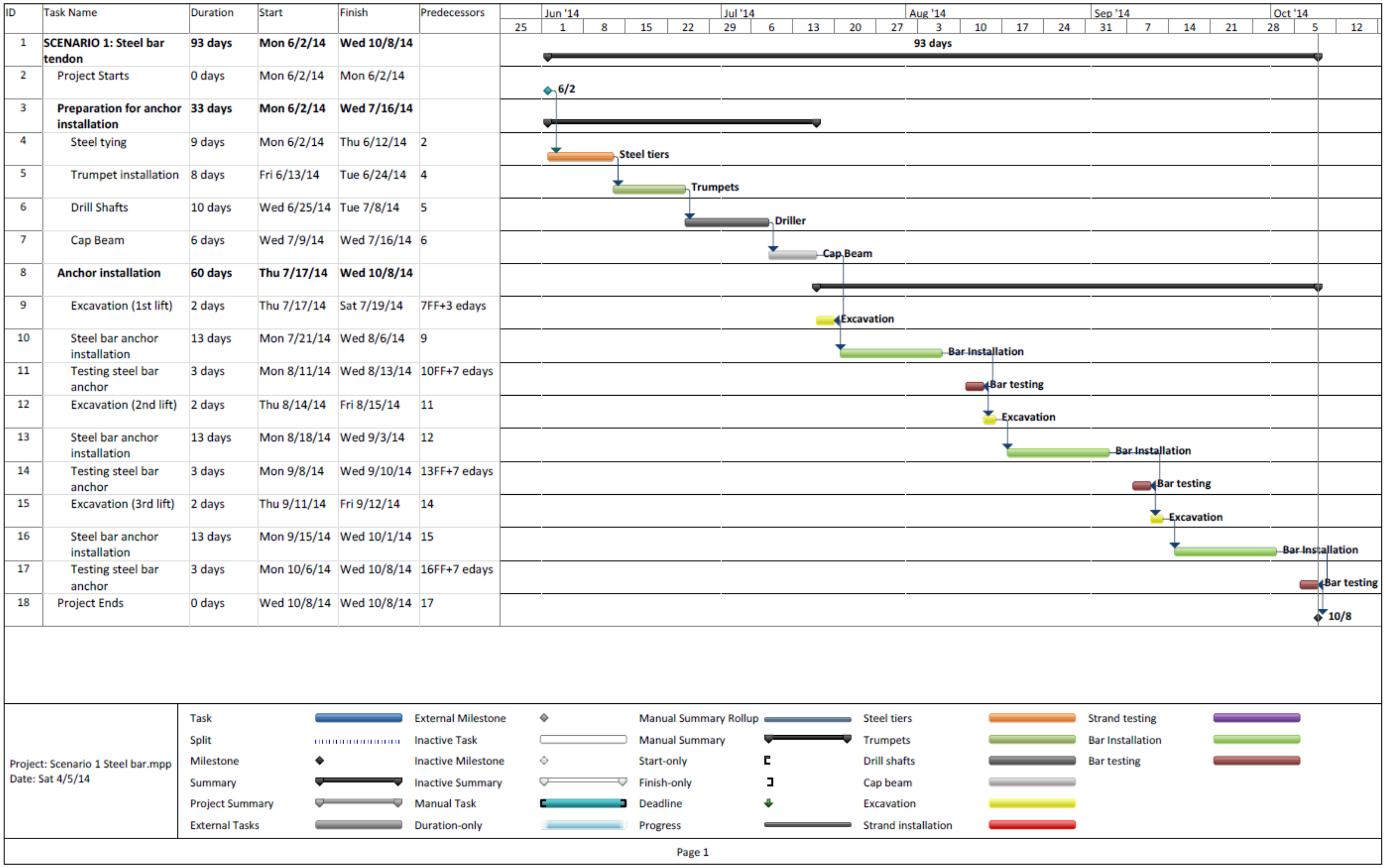
Table A.27 Days spent per activity for the steel bar anchor installation for Scenario 1

ACTIVITY	UNIT	Total production per day	Days
Steel tying	lbs	150,000	9
Trumpets	Ea	60	8
Drill Shafts	LF	960	10
Cap Beam	LF	160	6
Excavation 1st lift	CY	4,500	2
TB (bar) 1st row	LF	1200	13
Testing (bar) 1st row	Ea	50	3
Excavation 2nd lift	CY	4,500	2
TB (bar) 2nd row	LF	1200	13
Testing (bar) 2nd row	Ea	50	3
Excavation 3rd lift	CY	4,500	2
TB (bar) 3rd row	LF	1200	13
Testing (bar) 3rd row	Ea	50	3

The conditions for the schedule are:

- Each activity starts once the predecessor finishes.
- The 1st lift of excavations has to finish at least 3 natural days after the cap beam to allow the curing period.
- The testing of the strand will have to finish at least 7 natural days after the drilling.

The total duration of this case is 93 days. The preparation of the anchor installation lasts for 33 days while the installation of the anchors has a duration of 60 days.



ID	Task Name	Duration	Start	Finish	Predecessors
1	**SCENARIO 1: Steel bar tendon**	**93 days**	**Mon 6/2/14**	**Wed 10/8/14**	
2	Project Starts	0 days	Mon 6/2/14	Mon 6/2/14	
3	**Preparation for anchor installation**	**33 days**	**Mon 6/2/14**	**Wed 7/16/14**	
4	Steel tying	9 days	Mon 6/2/14	Thu 6/12/14	2
5	Trumpet installation	8 days	Fri 6/13/14	Tue 6/24/14	4
6	Drill Shafts	10 days	Wed 6/25/14	Tue 7/8/14	5
7	Cap Beam	6 days	Wed 7/9/14	Wed 7/16/14	6
8	**Anchor installation**	**60 days**	**Thu 7/17/14**	**Wed 10/8/14**	
9	Excavation (1st lift)	2 days	Thu 7/17/14	Sat 7/19/14	7FF+3 edays
10	Steel bar anchor installation	13 days	Mon 7/21/14	Wed 8/6/14	9
11	Testing steel bar anchor	3 days	Mon 8/11/14	Wed 8/13/14	10FF+7 edays
12	Excavation (2nd lift)	2 days	Thu 8/14/14	Fri 8/15/14	11
13	Steel bar anchor installation	13 days	Mon 8/18/14	Wed 9/3/14	12
14	Testing steel bar anchor	3 days	Mon 9/8/14	Wed 9/10/14	13FF+7 edays
15	Excavation (3rd lift)	2 days	Thu 9/11/14	Fri 9/12/14	14
16	Steel bar anchor installation	13 days	Mon 9/15/14	Wed 10/1/14	15
17	Testing steel bar anchor	3 days	Mon 10/6/14	Wed 10/8/14	16FF+7 edays
18	Project Ends	0 days	Wed 10/8/14	Wed 10/8/14	17

Project: Scenario 1 Steel bar.mpp
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Figure A.9 Schedule for the steel bar anchor installation for Scenario 1

A.5.2 Scenario 2

A.5.2.1 Strand Tendon

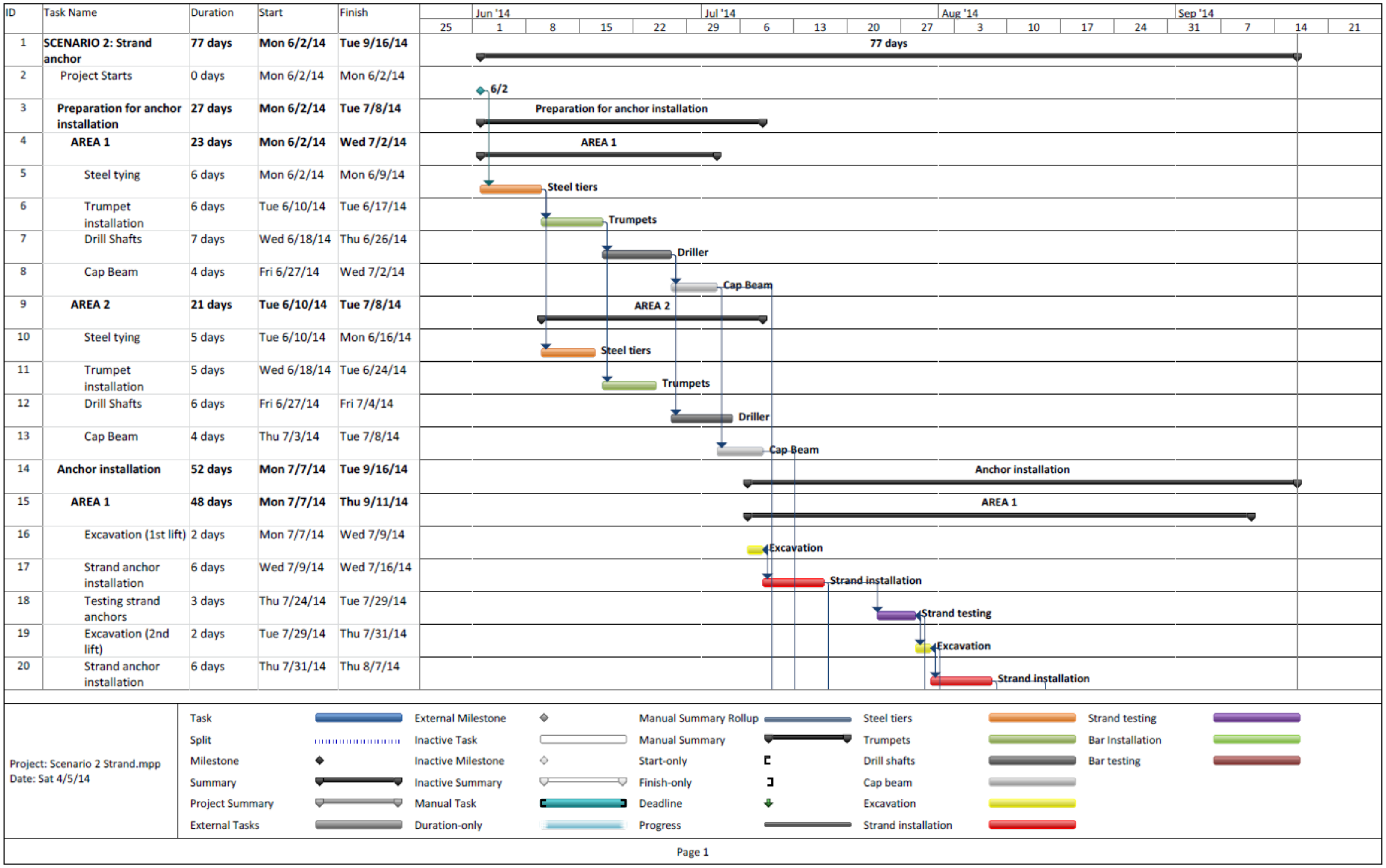
The following table shows the amount of days per activity

Table A.28 Days spent per activity for the strand anchor installation for Scenario 2

ACTIVITY	UNIT	Total production per day	Days
Steel tying	lbs	112,500	11
Trumpets	Ea	45	11
Drill Shafts	LF	720	13
Cap Beam	LF	120	8
Excavation 1st lift	CY	3,150	4
TB (strand) 1st row	LF	1,440	11
Testing (strand) 1st row	Ea	28	6
Excavation 2nd lift	CY	2,700	4
TB (strand) 2nd row	LF	1,440	11
Testing (strand) 2nd row	Ea	28	6
Excavation 3rd lift	CY	2,700	4
TB (strand) 3rd row	LF	1,440	11
Testing (strand) 3rdow	Ea	28	6

The conditions for the schedule are:

- Each activity starts once the predecessor finishes in Area 1 and once the starting activity is going to be able to finish without interruption. This second condition is achieved creating a Start to Finish minus 1 day relation between the activities of Area 1 and the activities of Area 2 and with a Finish to Finish plus 1 day relation between the activities in Area 2 and their predecessors.
- The 1^{st} lift of excavations for Area 2 has to finish at least 3 natural days after the cap beam of Area 2 to allow for the curing period.
- The testing of the strand will have to finish at least 7 natural days after the drilling.



ID	Task Name	Duration	Start	Finish
1	**SCENARIO 2: Strand anchor**	**77 days**	**Mon 6/2/14**	**Tue 9/16/14**
2	Project Starts	0 days	Mon 6/2/14	Mon 6/2/14
3	**Preparation for anchor installation**	**27 days**	**Mon 6/2/14**	**Tue 7/8/14**
4	**AREA 1**	**23 days**	**Mon 6/2/14**	**Wed 7/2/14**
5	Steel tying	6 days	Mon 6/2/14	Mon 6/9/14
6	Trumpet installation	6 days	Tue 6/10/14	Tue 6/17/14
7	Drill Shafts	7 days	Wed 6/18/14	Thu 6/26/14
8	Cap Beam	4 days	Fri 6/27/14	Wed 7/2/14
9	**AREA 2**	**21 days**	**Tue 6/10/14**	**Tue 7/8/14**
10	Steel tying	5 days	Tue 6/10/14	Mon 6/16/14
11	Trumpet installation	5 days	Wed 6/18/14	Tue 6/24/14
12	Drill Shafts	6 days	Fri 6/27/14	Fri 7/4/14
13	Cap Beam	4 days	Thu 7/3/14	Tue 7/8/14
14	**Anchor installation**	**52 days**	**Mon 7/7/14**	**Tue 9/16/14**
15	**AREA 1**	**48 days**	**Mon 7/7/14**	**Thu 9/11/14**
16	Excavation (1st lift)	2 days	Mon 7/7/14	Wed 7/9/14
17	Strand anchor installation	6 days	Wed 7/9/14	Wed 7/16/14
18	Testing strand anchors	3 days	Thu 7/24/14	Tue 7/29/14
19	Excavation (2nd lift)	2 days	Tue 7/29/14	Thu 7/31/14
20	Strand anchor installation	6 days	Thu 7/31/14	Thu 8/7/14

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Task	▬	External Milestone	◆	Manual Summary Rollup	▬	Steel tiers	▬	Strand testing	▬
Split	┈	Inactive Task	▭	Manual Summary	▬	Trumpets	▬	Bar Installation	▬
Milestone	◆	Inactive Milestone	◇	Start-only	[	Drill shafts	▬	Bar testing	▬
Summary	▬	Inactive Summary	▭	Finish-only	]	Cap beam	▬		
Project Summary	▬	Manual Task	▬	Deadline	⬇	Excavation	▬		
External Tasks	▬	Duration-only	▬	Progress	▬	Strand installation	▬		

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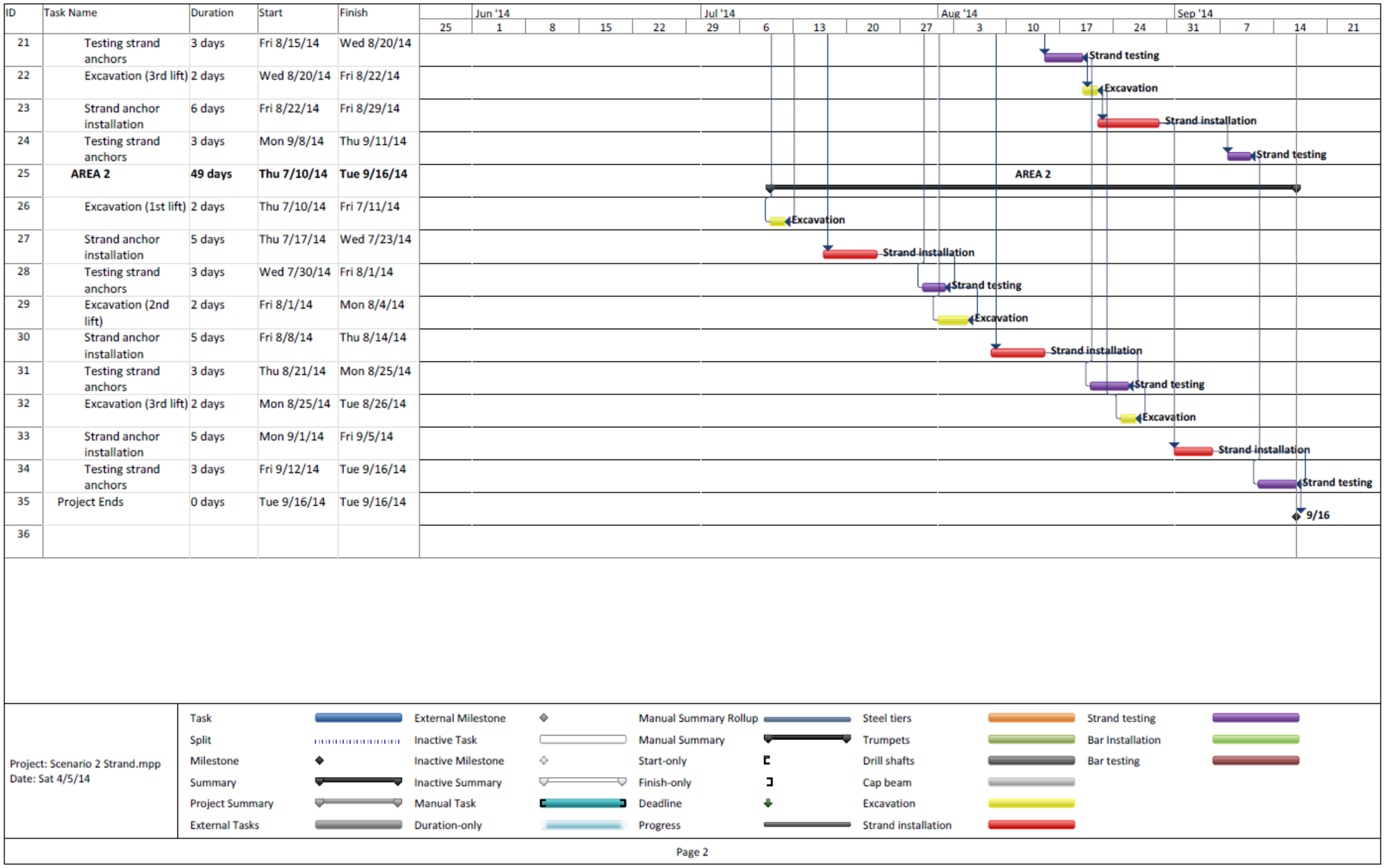
Figure A.10 Schedule for the strand anchor installation for Scenario 2, page 1



ID	Task Name	Duration	Start	Finish
21	Testing strand anchors	3 days	Fri 8/15/14	Wed 8/20/14
22	Excavation (3rd lift)	2 days	Wed 8/20/14	Fri 8/22/14
23	Strand anchor installation	6 days	Fri 8/22/14	Fri 8/29/14
24	Testing strand anchors	3 days	Mon 9/8/14	Thu 9/11/14
25	**AREA 2**	**49 days**	**Thu 7/10/14**	**Tue 9/16/14**
26	Excavation (1st lift)	2 days	Thu 7/10/14	Fri 7/11/14
27	Strand anchor installation	5 days	Thu 7/17/14	Wed 7/23/14
28	Testing strand anchors	3 days	Wed 7/30/14	Fri 8/1/14
29	Excavation (2nd lift)	2 days	Fri 8/1/14	Mon 8/4/14
30	Strand anchor installation	5 days	Fri 8/8/14	Thu 8/14/14
31	Testing strand anchors	3 days	Thu 8/21/14	Mon 8/25/14
32	Excavation (3rd lift)	2 days	Mon 8/25/14	Tue 8/26/14
33	Strand anchor installation	5 days	Mon 9/1/14	Fri 9/5/14
34	Testing strand anchors	3 days	Fri 9/12/14	Tue 9/16/14
35	Project Ends	0 days	Tue 9/16/14	Tue 9/16/14
36				

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Figure A.11 Schedule for the strand anchor installation for Scenario 2, page 2

The total duration of this case is 77 days. The preparation of the anchor installation lasts for 27 days while the installation of the anchors has a duration of 52 days.

A.5.2.2 Steel Bar Tendon

Table A.29 shows the amount of days needed per activity

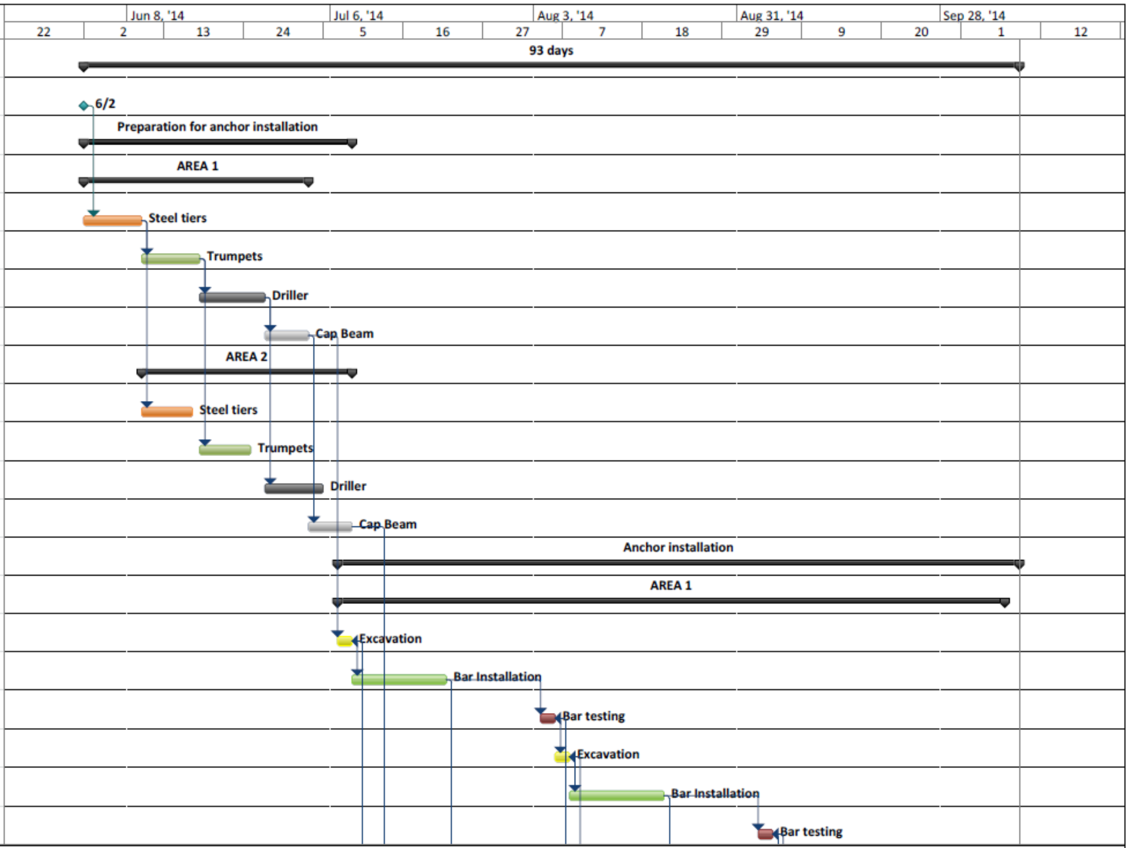
Table A.29 Days spent per activity for the steel bar anchor installation for Scenario 2

ACTIVITY	UNIT	Total production per day	Days
Steel tying	lbs	112,500	11
Trumpets	Ea	45	11
Drill Shafts	LF	720	13
Cap Beam	LF	120	8
Excavation 1st lift	CY	3,150	4
TB (bar) 1st row	LF	960	17
Testing (bar) 1st row	Ea	50	3
Excavation 2nd lift	CY	2,700	4
TB (bar) 2nd row	LF	960	17
Testing (bar) 2nd row	Ea	50	3
Excavation 3rd lift	CY	2,700	4
TB (bar) 3rd row	LF	960	17
Testing (bar) 3rd row	Ea	50	3

The conditions for the schedule are:

- Each activity starts once the predecessor finishes Area 1 and once the starting activity can finish without interruption. This second condition is to achieve creating a Start to Finish minus 1 day relation between the activities of Area 1 and the activities of Area 2 and with a Finish to Finish plus 1 day relation between the activities on Area 2 and their predecessors.
- The 1st lift of excavations for Area 2 has to finish at least 3 natural days after the cap beam of Area 2 to allow the curing period.
- The testing of the strand will have to finish at least 7 natural days after the drilling.

ID	Task Name	Duration	Start	Finish
1	**SCENARIO 2: Steel bar anchor**	**93 days**	**Mon 6/2/14**	**Wed 10/8/14**
2	Project Starts	0 days	Mon 6/2/14	Mon 6/2/14
3	**Preparation for anchor installation**	**27 days**	**Mon 6/2/14**	**Tue 7/8/14**
4	**AREA 1**	**23 days**	**Mon 6/2/14**	**Wed 7/2/14**
5	Steel tying	6 days	Mon 6/2/14	Mon 6/9/14
6	Trumpet installation	6 days	Tue 6/10/14	Tue 6/17/14
7	Drill Shafts	7 days	Wed 6/18/14	Thu 6/26/14
8	Cap Beam	4 days	Fri 6/27/14	Wed 7/2/14
9	**AREA 2**	**21 days**	**Tue 6/10/14**	**Tue 7/8/14**
10	Steel tying	5 days	Tue 6/10/14	Mon 6/16/14
11	Trumpet installation	5 days	Wed 6/18/14	Tue 6/24/14
12	Drill Shafts	6 days	Fri 6/27/14	Fri 7/4/14
13	Cap Beam	4 days	Thu 7/3/14	Tue 7/8/14
14	**Anchor installation**	**68 days**	**Mon 7/7/14**	**Wed 10/8/14**
15	**AREA 1**	**66 days**	**Mon 7/7/14**	**Tue 10/7/14**
16	Excavation (1st lift)	2 days	Mon 7/7/14	Wed 7/9/14
17	Steel bar anchor installation	9 days	Wed 7/9/14	Mon 7/21/14
18	Testing steel bar anchors	2 days	Mon 8/4/14	Wed 8/6/14
19	Excavation (2nd lift)	2 days	Wed 8/6/14	Thu 8/7/14
20	Steel bar anchor installation	9 days	Fri 8/8/14	Wed 8/20/14
21	Testing steel bar anchors	2 days	Wed 9/3/14	Fri 9/5/14



Project: Scenario 2 Steel bar
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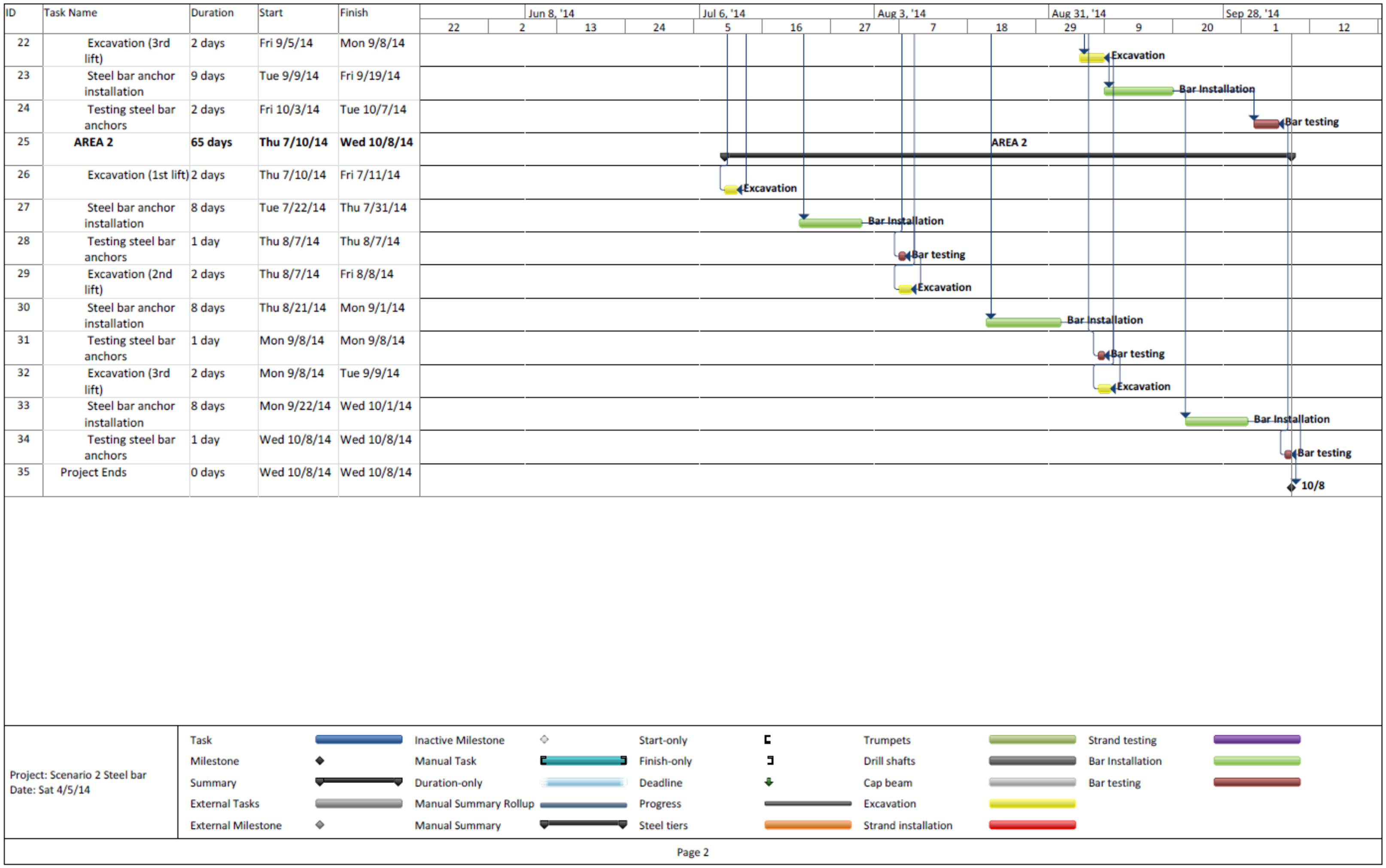
Task	▬	Inactive Milestone	◇	Start-only	[	Trumpets	🟩	Strand testing	🟪
Milestone	◆	Manual Task	▬	Finish-only	]	Drill shafts	▬	Bar Installation	🟩
Summary	▬	Duration-only	▬	Deadline	⬇	Cap beam	▬	Bar testing	🟥
External Tasks	▬	Manual Summary Rollup	▬	Progress	▬	Excavation	🟨		
External Milestone	◆	Manual Summary	▬	Steel tiers	🟧	Strand installation	🟥		

Figure A.12 Schedule for the steel bar anchor installation for Scenario 2, page 1



ID	Task Name	Duration	Start	Finish
22	Excavation (3rd lift)	2 days	Fri 9/5/14	Mon 9/8/14
23	Steel bar anchor installation	9 days	Tue 9/9/14	Fri 9/19/14
24	Testing steel bar anchors	2 days	Fri 10/3/14	Tue 10/7/14
25	**AREA 2**	**65 days**	**Thu 7/10/14**	**Wed 10/8/14**
26	Excavation (1st lift)	2 days	Thu 7/10/14	Fri 7/11/14
27	Steel bar anchor installation	8 days	Tue 7/22/14	Thu 7/31/14
28	Testing steel bar anchors	1 day	Thu 8/7/14	Thu 8/7/14
29	Excavation (2nd lift)	2 days	Thu 8/7/14	Fri 8/8/14
30	Steel bar anchor installation	8 days	Thu 8/21/14	Mon 9/1/14
31	Testing steel bar anchors	1 day	Mon 9/8/14	Mon 9/8/14
32	Excavation (3rd lift)	2 days	Mon 9/8/14	Tue 9/9/14
33	Steel bar anchor installation	8 days	Mon 9/22/14	Wed 10/1/14
34	Testing steel bar anchors	1 day	Wed 10/8/14	Wed 10/8/14
35	Project Ends	0 days	Wed 10/8/14	Wed 10/8/14

Project: Scenario 2 Steel bar
Date: Sat 4/5/14

Task	▬	Inactive Milestone	◇	Start-only	[	Trumpets	▬	Strand testing	▬
Milestone	◆	Manual Task	▬	Finish-only	]	Drill shafts	▬	Bar Installation	▬
Summary	▬	Duration-only	▬	Deadline	⇩	Cap beam	▬	Bar testing	▬
External Tasks	▬	Manual Summary Rollup	▬	Progress	▬	Excavation	▬		
External Milestone	◆	Manual Summary	▬	Steel tiers	▬	Strand installation	▬		

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Figure A.13 Schedule for the steel bar anchor installation for Scenario 2, page 2

The total duration of this case is 93 days. The preparation of the anchor installation lasts for 27 days while the installation of the anchors has a duration of 68 days.

A.5.3 Scenario 3

A.5.3.1 Strand Tendon

Table A.30 shows the amount of days needed per activity.

Table A.30 Days spent per activity for the strand anchor installation for Scenario 3

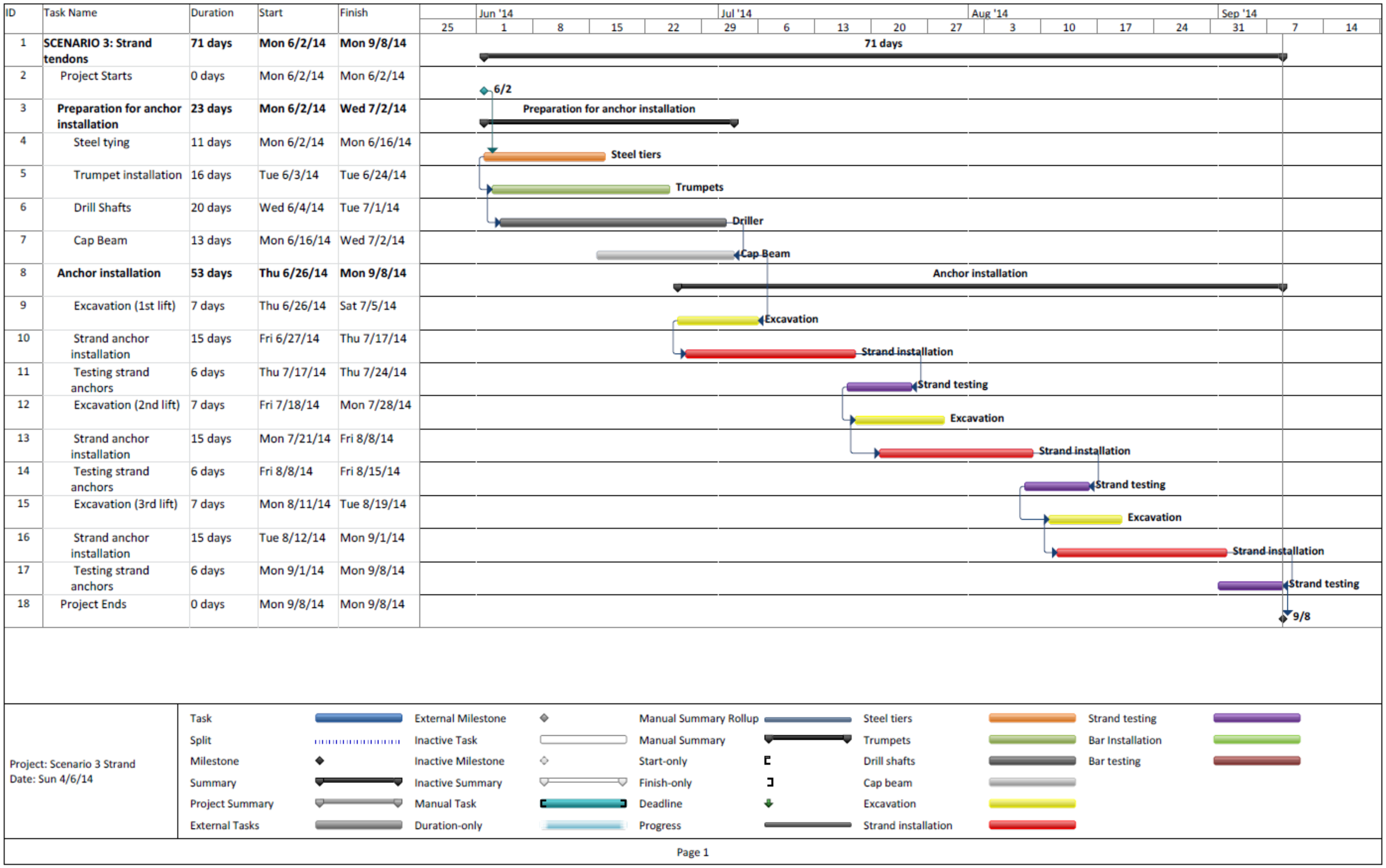
ACTIVITY	UNIT	Total production per day	Days
Steel tying	lbs	112,500	11
Trumpets	Ea	30	16
Drill Shafts	LF	480	20
Cap Beam	LF	80	13
Excavation 1st lift	CY	1,575	7
TB (strand) 1st row	LF	1,080	15
Testing (strand) 1st row	Ea	28	6
Excavation 2nd lift	CY	1,575	7
TB (strand) 2nd row	LF	1,080	15
Testing (strand) 2nd row	Ea	28	6
Excavation 3rd lift	CY	1,575	7
TB (strand) 3rd row	LF	1,080	15
Testing (strand) 3rdow	Ea	28	6

The conditions for the schedule are:

- Each activity starts once it is going to be able to finish without interruption. This condition is achieve creating, depending on the duration of the starting activity and its predecessor. If the starting activity has a greater duration than its predecessor the relation between them is a Start to Start plus 1 day, so that the second activity starts just one day after its predecessor. If the predecessor activity is longer than the starting one, the relation will be a Finish to Finish plus one day, so that the starting activity will finish one day after its predecessor.

- The 1st lift of excavations 2 has to finish at least 3 natural days after the cap beam to allow the curing period.
- The testing of the strand will have to finish at least 7 natural days after the drilling and grouting to allow the grout to cure.

The duration of this case is 71 days. The preparation for the anchor installation lasts for 23 days, and the anchor installation lasts for 53 days.



ID	Task Name	Duration	Start	Finish
1	**SCENARIO 3: Strand tendons**	**71 days**	**Mon 6/2/14**	**Mon 9/8/14**
2	Project Starts	0 days	Mon 6/2/14	Mon 6/2/14
3	**Preparation for anchor installation**	**23 days**	**Mon 6/2/14**	**Wed 7/2/14**
4	Steel tying	11 days	Mon 6/2/14	Mon 6/16/14
5	Trumpet installation	16 days	Tue 6/3/14	Tue 6/24/14
6	Drill Shafts	20 days	Wed 6/4/14	Tue 7/1/14
7	Cap Beam	13 days	Mon 6/16/14	Wed 7/2/14
8	**Anchor installation**	**53 days**	**Thu 6/26/14**	**Mon 9/8/14**
9	Excavation (1st lift)	7 days	Thu 6/26/14	Sat 7/5/14
10	Strand anchor installation	15 days	Fri 6/27/14	Thu 7/17/14
11	Testing strand anchors	6 days	Thu 7/17/14	Thu 7/24/14
12	Excavation (2nd lift)	7 days	Fri 7/18/14	Mon 7/28/14
13	Strand anchor installation	15 days	Mon 7/21/14	Fri 8/8/14
14	Testing strand anchors	6 days	Fri 8/8/14	Fri 8/15/14
15	Excavation (3rd lift)	7 days	Mon 8/11/14	Tue 8/19/14
16	Strand anchor installation	15 days	Tue 8/12/14	Mon 9/1/14
17	Testing strand anchors	6 days	Mon 9/1/14	Mon 9/8/14
18	Project Ends	0 days	Mon 9/8/14	Mon 9/8/14

Project: Scenario 3 Strand
Date: Sun 4/6/14

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Figure A.14 Schedule for the strand anchor installation for Scenario 3

A.5.3.2 Steel Bar Tendon

The days spent per activity are shown on Table A.31.

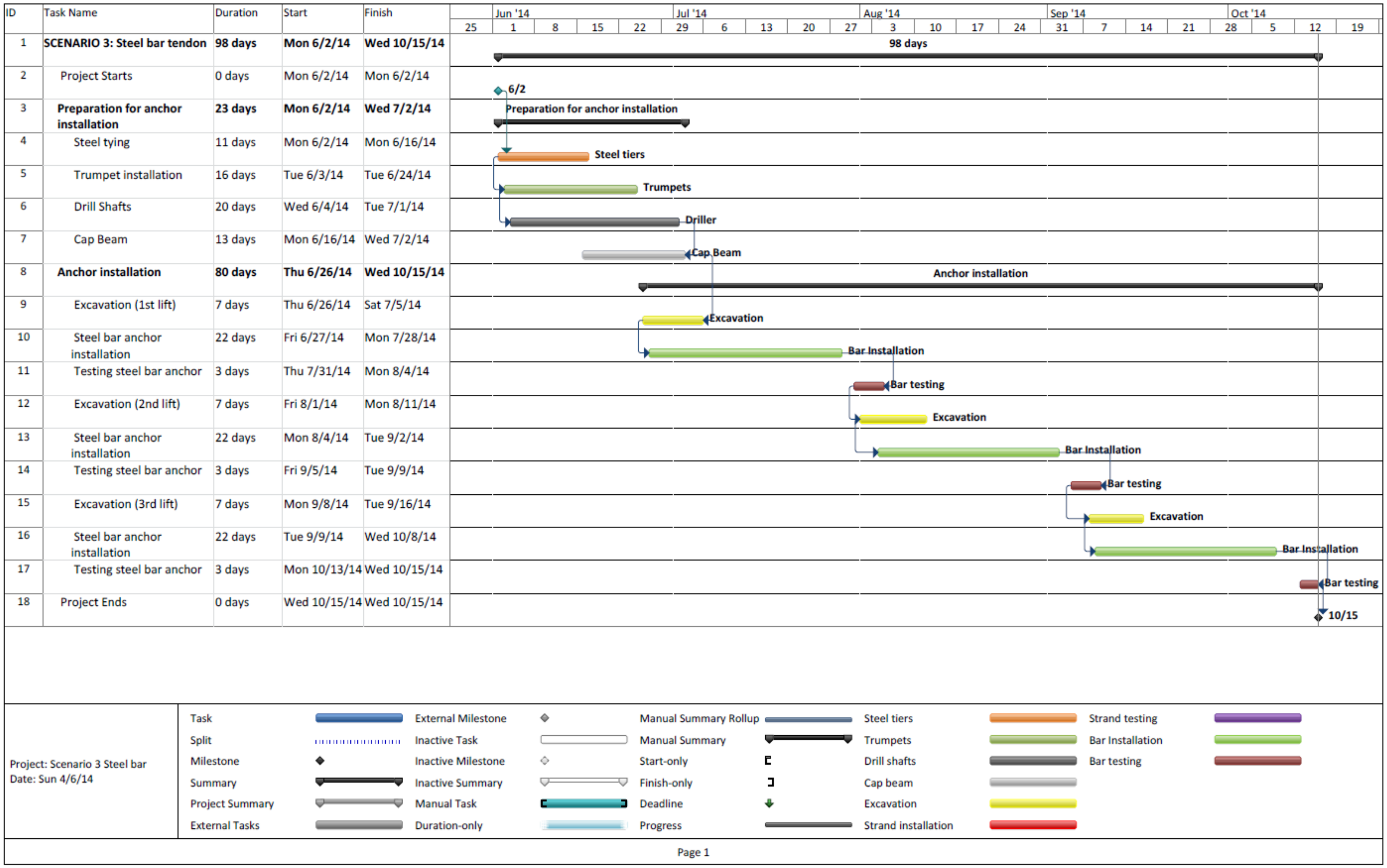
Table A.31 Days spent per activity for the steel bar anchor installation for Scenario 3

ACTIVITY	UNIT	Total production per day	Days
Steel tying	lbs	112,500	11
Trumpets	Ea	30	16
Drill Shafts	LF	480	20
Cap Beam	LF	80	13
Excavation 1st lift	CY	1,575	7
TB (bar) 1st row	LF	720	22
Testing (bar) 1st row	Ea	50	3
Excavation 2nd lift	CY	1,575	7
TB (bar) 2nd row	LF	720	22
Testing (bar) 2nd row	Ea	50	3
Excavation 3rd lift	CY	1,575	7
TB (bar) 3rd row	LF	720	22
Testing (bar) 3rd row	Ea	50	3

The conditions for the schedule are:

- Each activity starts once it is going to be able to finish without interruption. This condition is achieved creating, depending on the duration of the starting activity and its predecessor, a relation between both activities. If the starting activity has a greater duration than its predecessor the relation between them is a Start to Start plus 1 day, so that the second activity starts just one day after its predecessor. If the predecessor activity is longer than the starting one, the relation will be a Finish to Finish plus one day, so that the starting activity will finish one day after its predecessor.
- The 1st lift of excavations has to finish at least 3 natural days after the cap beam to allow the curing period.
- The testing of the strand will have to finish at least 7 natural days after the drilling and grouting to allow the grout to cure.

The duration of this case is 98 days. The preparation for the anchor installation lasts for 23 days and the anchor installation lasts for 80 days.



ID	Task Name	Duration	Start	Finish
1	**SCENARIO 3: Steel bar tendon**	**98 days**	**Mon 6/2/14**	**Wed 10/15/14**
2	Project Starts	0 days	Mon 6/2/14	Mon 6/2/14
3	**Preparation for anchor installation**	**23 days**	**Mon 6/2/14**	**Wed 7/2/14**
4	Steel tying	11 days	Mon 6/2/14	Mon 6/16/14
5	Trumpet installation	16 days	Tue 6/3/14	Tue 6/24/14
6	Drill Shafts	20 days	Wed 6/4/14	Tue 7/1/14
7	Cap Beam	13 days	Mon 6/16/14	Wed 7/2/14
8	**Anchor installation**	**80 days**	**Thu 6/26/14**	**Wed 10/15/14**
9	Excavation (1st lift)	7 days	Thu 6/26/14	Sat 7/5/14
10	Steel bar anchor installation	22 days	Fri 6/27/14	Mon 7/28/14
11	Testing steel bar anchor	3 days	Thu 7/31/14	Mon 8/4/14
12	Excavation (2nd lift)	7 days	Fri 8/1/14	Mon 8/11/14
13	Steel bar anchor installation	22 days	Mon 8/4/14	Tue 9/2/14
14	Testing steel bar anchor	3 days	Fri 9/5/14	Tue 9/9/14
15	Excavation (3rd lift)	7 days	Mon 9/8/14	Tue 9/16/14
16	Steel bar anchor installation	22 days	Tue 9/9/14	Wed 10/8/14
17	Testing steel bar anchor	3 days	Mon 10/13/14	Wed 10/15/14
18	Project Ends	0 days	Wed 10/15/14	Wed 10/15/14

Project: Scenario 3 Steel bar
Date: Sun 4/6/14

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Figure A.15 Schedule for the steel bar anchor installation for Scenario 3

A.6 Preparation for Anchor Installation Cost Analysis

This cost analysis is performed to give an overall cost of the activities previous to the first lift of excavation. A deeper study of the costs for the anchor installation depending the tendon selection has already been done.

The cost analysis is done from the perspective of a general contractor that subcontracts all the operations. It only accounts for the direct cost (subcontractor costs), and the pricing has been surveyed among professionals of each independent field. The total quantities for the wall are known. Therefore, a simple calculation will provide the total direct cost of each operation. Every subcontractor was prompted for pricing including all the materials, equipment and labor.

On the table below the cost analysis of the costs for the steel tying, trumpet installation, pier drilling cap beam construction is shown.

Table A.32 Cost of preparation for anchor installation by activity

Activity	Unit	Total Quantity	Unit Rate	Cost
Steel Tying	Lbs	1,280,000	$0.50	$640,000.00
Trumpet Installation	Ea	480	$485.00	$232,800.00
Drilled Shafts	LF	9,600	$70.00	$672,000.00
Cap Beam	LF	1,000	$140.00	$140,000.00

The total cost for all the previous activities for the anchor installation except the excavation will be the sum of all the costs from Table A.32.

Table A.33 Total costs of the retaining wall activities prior to excavation

Total Cost	**$1,684,800.00**

The excavation costs are not included because in many occasions those costs are not budgeted along with the retaining wall but by itself.

A.7 Testing Results

The results of the testing for a retaining wall of the "*IH-635 Managed Lanes Project"* was used to evaluate the reliability of each type of anchor. The total number of results that were used for this evaluation is 1,007 tests. Of those, 692 were done for strand anchors and 315 were done for steel bar anchors.

The results of these tests are resumed on the following table.

Table A.34 Test summary

	Passed	Failed	Total Tests	% of failures
Bar	312	3	315	1%
Strand	659	33	692	5%

The percentage of failures is calculated with this formula

$$\%\ of\ failures = \frac{Failed\ Tests}{Total\ Tests} * 100$$

The reliability of the anchors equals to

$$Reliability\ (\%) = 100 - \%\ of\ failures$$

Then, the reliability for these anchors is

Table A.35 Reliability by the type of anchor

	Reliability
Bar	99%
Strand	95%

A.8 Instrumentation

In order to compare the performance of the two different type of anchors. The author used the monitoring information of one of the retaining walls of the *"IH-635 Managed Lanes Project"*. The readings of two different inclinometers are presented below.

Both inclinometers are located on the same wall. Location 1 is on the area of a retaining wall that has 6 steel bar anchors with a wall height of 38 feet. Location 2 has 5 strand anchors and a wall height of 35 feet.

Five different dates are shown on the diagram:

- May 3rd, 2013 represents zero. It is the measurement that is taken after the installation of the inclinometer casing.
- May 22nd, 2013 after the installation of the 1st row of anchors.
- July 19th, 2013 after the installation of the 3rd row of anchors.
- November 7th, 2013 the wall is completed.
- March 25th, 2014 the final most relevant measurement is taken.

Figure A.16 Location 1 above bridge abutment

(Personal file, September 23rd, 2013)

Figure A.17 Location 2

(Personal file, June 20th, 2013)

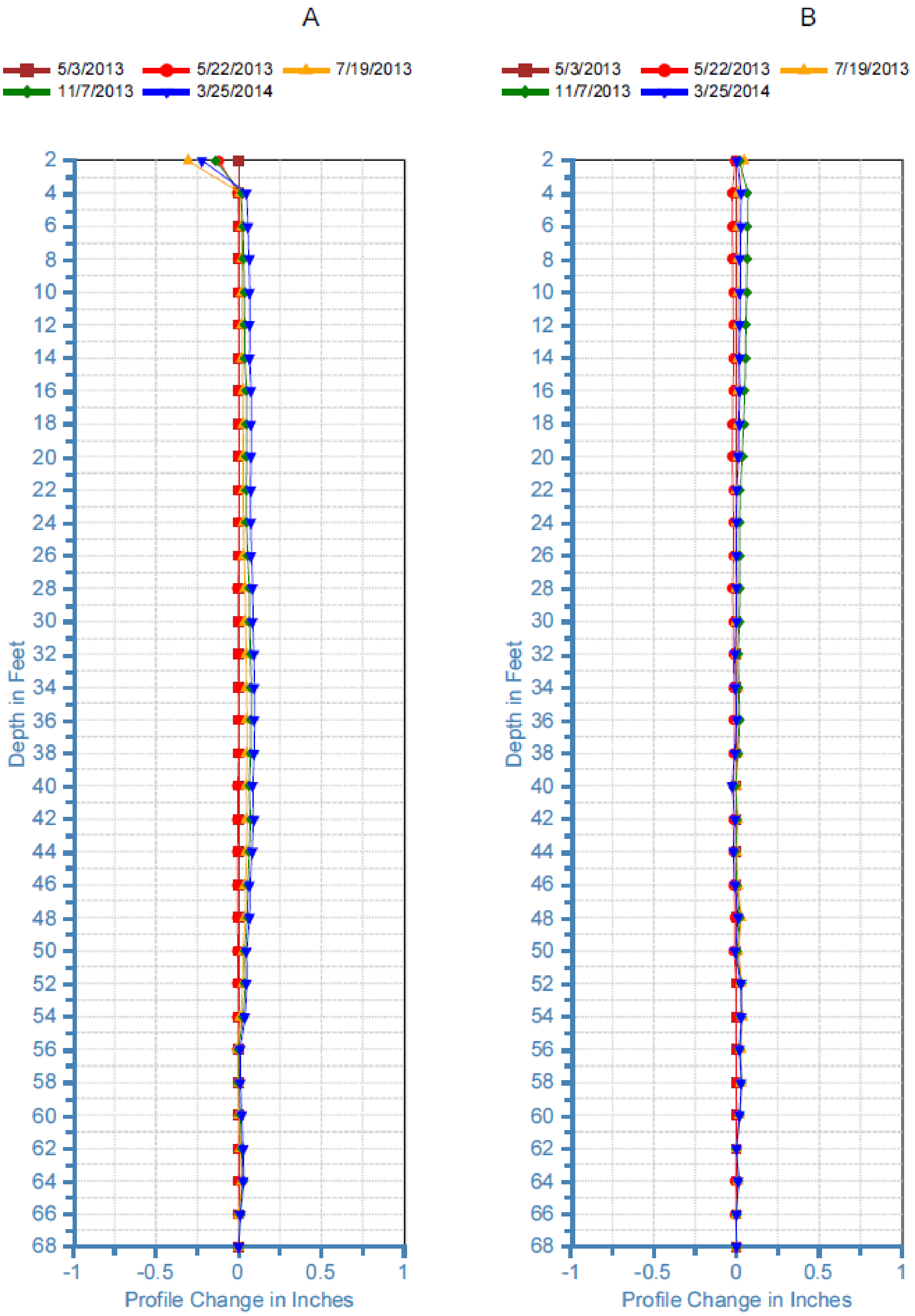

Figure A.18 Inclinometer readings for Location 1

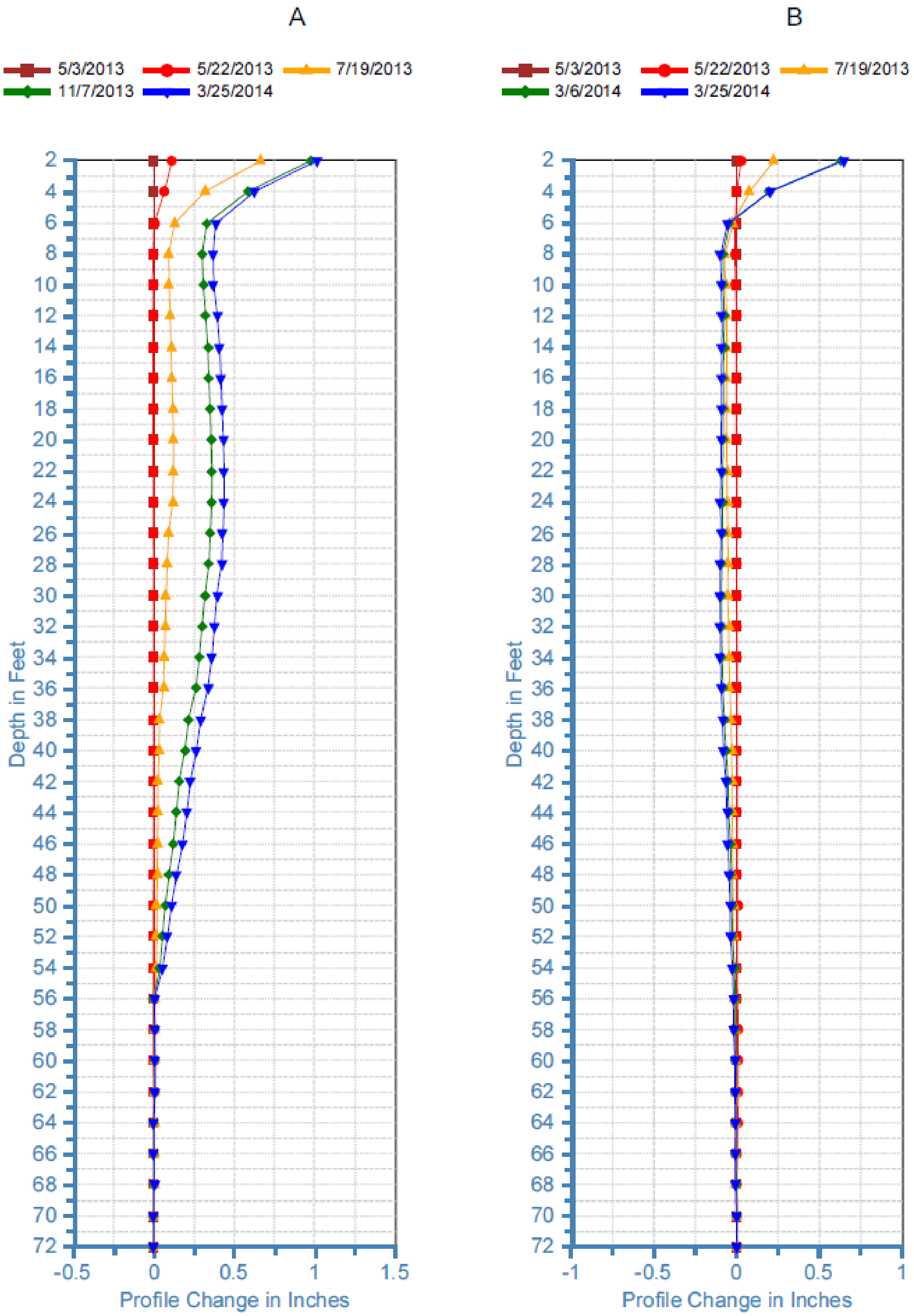

Figure A.19 Inclinometer readings for Location 2

Appendix B:

Interviews

A series of interviews were done to provide sufficient backup to this study research. People with different profiles were interviewed so that the global vision of the topic was more complete. Professionals from the design area, construction management, and actual onsite construction supervisors were prompted about the different topics explained in this research. A partial transcript of the interviews is written below, only the information that was used on the research is included. In order to maintain anonymity the professionals are named by their initials.

B.1 Geotechnical Designer

JIL was interviewed on January 24th 2014 at his office.

The author: Good morning JIL.

JIL: Good morning.

The author: JIL I came here today to ask you some question regarding anchored drilled shaft walls. I am trying to get enough information from many type of backgrounds so that I can complete my Master's theses with all the information needed. But, first of all, I would like you to tell me a little bit about yourself and about what you do for living.

JIL: I am a geotechnical professional engineer. I work as a designer on a construction company. I have been working, calculating, reviewing designs, and even inspection retaining walls for over 20 years. Right now, I work for a multinational company but I am strongly focused on a single project. However, this is a major project for my company and I am involved in every aspect of it. I review the drawings from our consulting designers, I propose changes to the drawings, I verify that the construction team is performing their duty on the field and that they are inspecting what is supposed to be inspected. My main focus right now are the anchored drilled shaft walls and I hope I can clarify the questions that you may have.

The author: OK, I do not want to go over the construction sequence in this interview. However, there are a couple questions that I would like to have feedback from a design engineer. What is the most critical part of an anchored drilled shaft wall?

JIL: In my opinion, everything is important in construction and no detail shall be oversee. From the steel tying to the stressing every operation is critical and it should be design, constructed and inspected as if it was the most important part of the project.

The author: You mention that an activity should not be oversee. What do you mean? Is it your experience that some activities get overseen?

JIL: What I mean is that an activity does not have the same rate of inspections or supervision as other activities. In my experience, the installation of the trumpets is commonly overseen. Only the location along the drilled shaft is inspected but no their inclination against the horizontal and the vertical. These three factors will determine the anchor location and inclination, aspects that are defined on the design, thereby critical, and in many occasions are overseen, as I said before.

The author: What is the importance of the cap beam? It seems as a minor component of the wall. Is it?

JIL: The cap beam or capping beam is very important from a designing perspective. The cap beam is the piece of the puzzle, that makes the wall resist as a single element. The cap beam will transfer and distribute the extra loads in the case that an anchor or a drilled shaft fails. In some wall design, anchors are located within the cap beam, on those walls the cap beam becomes even more important.

The author: The drilling of the anchor and excavation of the wall sequencing, has to be approved by the designer? Is it always the same?

JIL: No, the sequencing between the installation of the anchors and the excavation can vary depending on the designer, the geotechnical conditions or the means and methods of construction. For example, right now I am working on a soil nail wall that has to be excavated staggered because it is located on an area with a sandy clay and in the presence of water. But usually it is common practice to excavate in lifts of 5 feet deep as long as the face of the wall gets shore within 24 hours for soils or 48 hours for rock.

The author: Comparing the two typical types of tendons the strand tendon and the steel bar tendon, from a design stand point what are the differences between them? Does it matter what you choose on the design phase?

JIL: On the design phase of an anchor wall the type of tendon is not an important feature to take into account, because while designing it is basically an arrow with a number. However, there are some differences between them. First, the quality of the steel is better on the strand tendons having greater strength. Second, I have the feeling that on site grouting for the strands creates a variable that is less control than off site grouting for the steel bars. Nevertheless, the main difference is the anchoring system, while on the strand tendon a wedge system is used, on the steel bar a simple nut is what anchors the anchor. The system is more efficient for the steel bar that does not need to be above any load to be able to work. Also the wedges have greater seating loads than the steel bar anchorage system. Lift off testing reveals that the losses for the different type of anchors are greater when dealing with strand tendons (8%) than on steel bar tendons (around 4%).

The truth is that the design is not really affected by this choice, but I believe that the retaining wall and its construction is determine by this election.

The author: Thanks you very much for your time.

JIL: It has been a pleasure.

B.2 Construction Manager

O.O. was interviewed in his office on February 3, 2014.

The author: Mr. O, How are you?

O.O.: Very well, thanks.

The author: Before we start could you please introduce yourself?

O.O.: Yes, of course. I am project manager for one of the most important ground anchor company in the country. I have been working with them for almost 10 years now. We built temporary shoring, permanent rock nails, permanent tiebacks on drilled shafts, almost anything.

The author: Fair enough. Please tell me if you find in your profession any differences between installing strands or bars?

O.O.: Buff! There are thousands. For me is much better the cable (strand). It is cheaper, easier to move, to install, to work with, and it is more productive. First, cables are flexible while bars aren't, making everything much harder. Bars need much more room to work, you need to have excavators moving them, sometimes 2 excavators at the same time, clearances are very important for bars while for cables the only clearance important is the one of the drill. When you are working with equipment space is always critical, less space less production, and you need to think of space as a 3-D because clearances are very important. But when working with bars space is even more important.

The author: Is there any advantage to the bar?

O.O.: Well, yes. For example, grouting is more complicated on cables because they are not delivered pre-grouted like bars are. Therefore, there is extra time spent on the grouting operation. Not because of the amount of grout but because of the connection that has to be made between the grout pump and the conduit. On the cables, you need to connect twice, while on the bars you just need to fill the external conduit.

The author: How about the testing?

O.O.: That is the other thing I was going to tell you. Testing is much faster on bars than on cables. Cleaning and installing the plate takes much longer on the cables. But the worst part is that when you are starting the testing you need to hold the jack with a mini (excavator) until the cables reach the necessary stress. On the bar you don't need anything you set the jack and the bar holds it. The third advantage that I was thinking is that when the soil is not very good and for a geotechnical reason the tieback has to be longer, the cable is no useful anymore while with the bar you can just set a coupler and install it.

The author: On a different topic. Is your company also the one that installs the trumpets for the drilled shafts?

O.O.: Yes, although I subcontract steel tiers as labor, the supervision is ours. There is too much responsibility on that process and it affects us greatly, so we can't leave it to somebody else. At the end the trumpet act as a blockout for the tieback where you install the trumpets is where the tieback is going to go.

The author: Thank you very much

O.O.: You are very welcome.

B.3 Superintendent

P.G. was interviewed on February 5, 2014 at the jobsite.

The author: Good afternoon

P.G.: Hello

The author: Before we begin, I would like you to tell me a little bit of your background.

P.G.: OK. I am a superintendent for a ground anchor company. I have been a superintendent for 12 years and I have in this company 17. I started working here as a labor, then operator, then foreman and now superintendent. I have worked on tiebacks, soil nails, rock nails all my life. I love my job and I think I am good at it.

The author: Good. Let's start. In your opinion what type of tendon is easier to work with strand or bar?

P.G.: Easy question, easy answer. The cable is much easier but I bet you already knew.

The author: OK, you are right. I am going to ask you some questions about clearances and platform widths. How much room would you say that you need to be able to drill with the 25 feet drill under a bridge?

P.G.: Let's see. It will depend on the angle of the tiebacks.

The author: Good point. How about 30 degrees?

P.G.: For 30 degrees you will need around 15 feet just to work. But in order to work productively you will need at least 18 feet.

The author: Can you please explain the process to me?

P.G.: Yes, first usually the drill holes are 2 feet above the ground to prevent water and debris from getting in them. Then 13 feet for the drill at a 30 degree, that's 15 that is the minimum and another 3 for clearance.

The author: How about to move and install a bar anchor?

P.G.: Now, that is harder. First, if the tieback is longer than 60 feet you need two hoes to move it. Then, the way the anchor is picked up from the center with a sling that is another 8 feet at least. But when using two anchors because the sling is not on the center of the tieback it will be around 5 feet. So, to do your math, you have the height of the hole 2 feet plus 8 feet to allow for the sling and excavator if the anchor is picked up on the center, or 5 feet if it is picked up with two excavators and then you need to add the height of the tieback that for a 60 feet tieback it will be close to 15 feet. Then the total will be 15 plus 2 plus 8 25 feet clearance just to be able to do it. Remember you need to add some room to be productive.

The author: How about platform widths?

P.G.: That is easier you bigger the platform the better.

The author: I know that. How wide does it need to be to work productively?

P.G.: The width of your drill plus, I would asked for 5 feet, but with 3 feet you should be able to maneuver.

The author: Thank you very much

P.G.: See you later.

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Appendix C

Surveys

Two different survey forms were created. A specific survey form was sent just to the anchoring contractors, while the second one was more general and was sent to the rest of the contractors.

Table C.1 General survey form

ANCHORED DRILLED SHAFT WALL SURVEY	
Name:	Years of experience:
Position:	Date:
Area of expertise:	Location:
Please describe your business	
Please note the typical production rates that you will account for on Scenario 1 where you work by yourself	
Tie reinforcing steel	Construct Cap beam
Drill 42" shafts	Excavate
Please note the typical production rates for Scenario 2 where you will share the work area with another contractor	
Tie reinforcing steel	Construct Cap beam
Drill 42" shafts	Excavate
Please note the typical production rates for Scenario 3 where you will share the work area with multiple other contractors	
Tie reinforcing steel	Construct Cap beam
Drill 42" shafts	Excavate
Please provide typical unit costs for a preliminary study?	
Tie reinforcing steel	Construct Cap beam
Drill 42" shafts	Excavate

Table C.2 Specific form for ground anchor contractors

ANCHORED DRILLED SHAFT WALL SURVEY	
Name:	Years of experience:
Position:	Date:
Area of expertise:	Location:
Please describe your business	
Please note the typical production rates that you will account for on Scenario 1 where you work by yourself	
Installation of Trumpets	Installing steel bar anchors
Installing strand anchors	Testing steel bar anchors
Testing strand anchors	
Please note the typical production rates for Scenario 2 where you will share the work area with another contractor	
Installation of Trumpets	Installing steel bar anchors
Installing strand anchors	Testing steel bar anchors
Testing strand anchors	
Please note the typical production rates for Scenario 3 where you will share the work area with multiple other contractors	
Installation of Trumpets	Installing steel bar anchors
Installing strand anchors	Testing steel bar anchors
Testing strand anchors	
Please provide typical unit or hourly costs for a preliminary study?	
Steel bar tendon	Excavator
Excavator mounted drill 25 ft	Grout Pump
Trumpet Installation	Loader
Mini excavator	Testing Jack and equipment
Operator	Foreman
Laborer	Testing technician

Most of the contractors provided production rates and pricing, but a minority did not. The information obtained with this surveys was used along with the field observations to calculate the unit costs and production rates that are used on this research.

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Biographical Information

Inigo Azofra Arrizabalaga received his degree of Civil Engineer from the "Universidad Politecnica de Madrid" in Madrid, Spain in the spring of 2010. He started working for Trinity Infrastructure LLC in October of that same year as a construction engineer. He was admitted to the graduate program of Construction Management at the University of Texas in Arlington in the fall of 2012. He completed his Masters of Science in Civil Engineering in the spring of 2014