EVALUATION OF BEST PRACTICES FOR IMPLEMENTATION OF SLOPE REPAIR METHODS IN TEXAS

by

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Abstract

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Embankment slope failures occur frequently in areas with extreme weather (frequent wetting and drying periods) and unstable soil conditions (high swelling potential clay) such as state of Texas. Despite all progresses in the geotechnical knowledge and the advancement of slope repair methods, still, many repaired slopes fail again after a period of time.

The primary objectives of this study are to (1) Review and evaluate existing repair methods for shallow slope failures from the construction perspective, and (2) Recommend appropriate implementation procedures for successful implementation of slope repair methods. The research approach which has been followed to achieve the project objectives includes review of the literature, survey, and interview of subject matter experts.

Results of this study showed that the risk of recurring slope failures would decrease by using combination of different slope repair methods. In this study, the current state of knowledge and practice are captured and integrated to present slope repair practices that offer long-term performance of embankment slopes along roads and highways especially for the regions with extreme weather and unstable soil conditions.

Table of Contents

List of Illustrations

List of Tables

Chapter 1

Research Background

1.1 Introduction

Slope instability is one of the main reasons which cause damage to roadway infrastructures. Embankment slope failures lead to substantial cost and casualty losses in the United States (White et al. 2005). Based on the U.S. Geological Survey (Spiker and Gori 2000), the U.S. is experiencing more than $1 billion in damages and about 50 deaths every year due to slope failures. In some cases, the annual cost of slope remediation and maintenance exceeds state and county transportation budgets (White et al. 2005). The following sections provide an introduction to slope failure, literature reviews, problem statement, gaps in knowledge, and research objectives.

1.2 Slope Failure

Climatic and geological conditions, topography, and vegetation or combination of these features can consequence to instability of the slopes (Basile et al. 2003; Ost et al. 2003). Slope failures happen when the soil mass above the slip surface moves downward. This incident can occur gradually or suddenly when the shear strength of the soil cannot resist the driving forces pushing the soil mass down the slope.

Hossain et al. (2017) stated instability in soil mass which cause slope failure, can be result of any changes in soil condition. These changes disturb the balance between driving and resisting forces. For example, fluctuation in moisture content of expansive soils, which are common in Texas with unstable soil and climate condition, cause soil swelling and shrinkage (Puppala et al. 2013). Soil shrinkage in dry season makes cracks in the surface of the soil and water infiltration from the cracks leads to loss of soil strength. Furthermore, external condition such as surcharge load from structures or excavation can cause slope failure (Niroumand et al. 2012).

Depth of failure is impacted by four factors: soil type, soil stratification, the geometry of slope, and soil water content (Titi and Helway 2007). Generally, Slope failures are categorized into two group based on depth of the failure: (1) deep-seated failure and (2) shallow failure. There are also other types of slope failure classifications based on the shape of failure.

Depth of shallow slope failure is usually less than four feet and it is also recognized as infinite slope failure (Day and Axten 1989). Infinite slope failure is the movement of the soil mass approximately parallel to the slope face (Das 2010). Although shallow slope failure is not a threat to human life and does not cause major damages, they still can lead to some damages to infrastructure systems, such as bridges, culverts, guardrails, shoulders, pavements, drainage facilities, and landscape. They also interrupt the flow of traffic where the debris of failed area flows onto the roadways. Therefore, it is necessary to identify and evaluate slope repair methods to select the most appropriate one based on different failure type.

1.3 Problem Statement

While result of repairing slopes using common repair methods are satisfactory in many cases, some repaired slopes fail again after a period of time. Recurring slope failures take place more frequently in areas with extreme weather and soil conditions such as state of Texas. The Texas Department of Transportation (TxDOT) annually spends millions of dollars to repair embankment slope failures and the damaged structures due to slope failure.

Synthesis and evaluation of existing slope repair methods is essential to recommend suitable implementation procedures to prevent recurring failure. Reduction in recurring slope failures could considerably decrease construction operations and maintenance costs. Other benefits of reduction number of recurring slope failures are Improving safety, infrastructure service life, environmental sustainability, and transportation system reliability.

1.4 Literature Review

A lot of researches have been conducted regarding the subject of embankment slope failures (Abrams and Wright 1972; Day 1996; Titi and Helwany 2007; Hossain et al. 2017). These studies can be classified into a few categories.

First groups of these studies are those which assessed different slope repair methods or tried to introduce new techniques (Barker 1997; Shao and Kouadio 2002; Prikryl et al. 2005; Zhang et al. 2005; Arellano 2011; Esmaeili et al. 2012; Duncan et al. 2014; Wu et al. 2017; Hossain et al. 2017). Nevertheless, these studies did not evaluate slope repair methods from construction point of view.

The second group are the studies which have been done by various transportation agencies. For example, Utah DOT (UDOT 2017), Indiana DOT (INDOT 2018), and New York State DOT (NYSDOT 2014) provided manuals which offers methodologies to analyze slope failures and recommend design guidelines. However, these studies did not suggest implementation procedures or recommendations for successful application of slope repair methods.

The third group of studies provided slope management systems for maintaining embankment slopes such as studies which have been done by Collin et al. (2008) and Liang and Pensomboon (2010). These studies are extremely valuable for administration processes, but they would not be effective if appropriate implementation procedures are not followed.

The main focus of this research is the state of Texas, but there are only a few studies on the topic of slope failures in Texas. Abrams and Wright (1972) studied the slope repair methods that were used at the time. Although this study is not update and only covers a few conventional slope repair methods, it provides valuable insight into the fundamental issue of slope failure in Texas. Additionally, Stauffer and wright (1984) also studied a few slope failures occurred in Texas from geotechnical aspect. They have done geotechnical soil tests on the failed slope soil and compared the results with the data which has been used for design of the slope. They emphasized the data achieved from old laboratory soil tests were not sufficient for appropriate embankment slope design. So, it is essential to evaluate existing slope repair methods from construction perspective to identify barriers to successful implementation of slope repair methods in Texas. It is also important to recognize best practices to avoid, or at least reduce recurring failures. This reduction in recurring slope failures could significantly reduce construction operation and maintenance costs.

1.5 Gaps in Knowledge

Despite all progresses in the geotechnical knowledge and the advancement of slope repair methods, still, many repaired slopes fail again after a period of time all around the state. Review of literature shows that related studies;

- Did not assess reasons for recurring slope failures from construction point of view.
- Did not synthesize practical recommendations to overcome the issue of recurring failures and address the common barriers against successful implementation of slope repair methods.

Consequently, assessing slope repair methods especially from the construction point of view is essential to identify practical procedures for successful implementation of slope repair methods. It is necessary to recognize best practices to reduce recurring slope failures along Texas roads.

1.6 Research Objectives

The primary objectives of this research are to (1) review and evaluate existing repair methods for shallow slope failures from the construction perspective, and (2) recommend appropriate implementation procedures for each method to avoid recurring failures. In this study, the current state of knowledge and practice are captured and integrated to present slope repair practices that offer long-term performance of embankment slopes along roads and highways especially for the regions with extreme weather and unstable soil conditions.

Chapter 2

Research Approach

2.1. Introduction

The research approach which has been followed to achieve the project objectives includes review of the literature, survey, and interview of subject matter experts. Figure 2-1 shows the framework of the research approach.

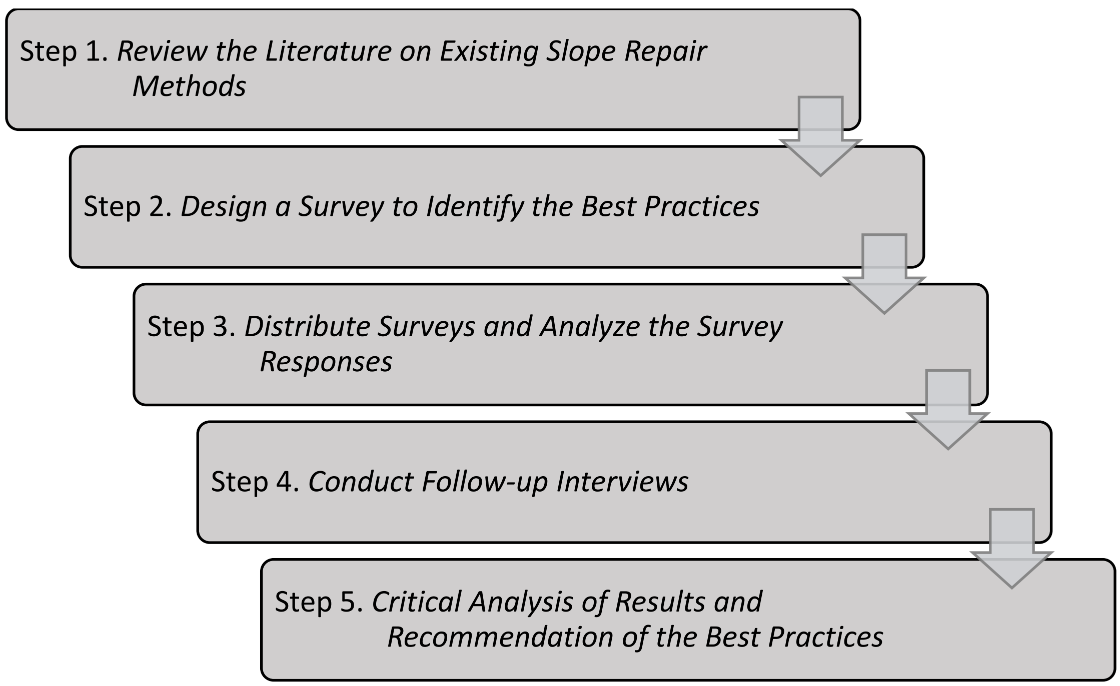


Figure 2-1. Framework of the research approach

An extensive review of the literature has been done to recognize and examine the related research on slope repair methods. The results of literature analysis are presented in Chapter 3. The findings of the literature review were used to develop a survey questionnaire to capture the current state of practice in repairing embankment slope failures. The survey was distributed among professionals in the field of embankment slope repairs from all districts of TxDOT to gather information on the present slope repair practices being used. The analysis of survey responses is presented in Chapter 4. Based on the survey responses, individuals with the most successful experience in implementation of slope repair projects have been selected for performing follow-up interviews. Follow-up interviews have been done to recognize their best practices and lessons learned from real projects. The data collected from literature, survey questionnaire, and interviews were analyzed and synthesized in Chapter 5. This chapter presents the recommendations for successful implementations of slope repair methods in form of tables. Finally, Chapter 6 summarizes the conducted research and presents its contribution to the body of knowledge. it also offers the recommendations for future research related to this topic.

2.2. Review the literature on repair methods for shallow slope failures

This step focused on evaluating the existing repair methods for shallow slope failure from construction perspective. An extensive research has been done in books, articles, and reports related to this topic. Also, the state DOT websites were searched for any resource related to this topic, such as a formal approach for selecting a slope repair method.

Afterward, the slope repair methods were classified based on construction techniques. This classification expedited the process of slope repair methods examination. Furthermore, it simplified the identification of best practices to reduce recurring slope failures.

2.3. Survey

Conducting surveys is one of the methods for determining value of research in a variety of influenced areas (Ashuri et al. 2013; Shahandashti et al. 2015; Shahandashti et al. 2017). The information collected from survey responses enabled us to quantify value of avoiding recurring slope failures. Additionally, the survey has been done to capture the current state of practice in repairing slopes. Survey questions were designed based on Findings of the literature review. The following areas were main subjects of interest:

- The most common embankment slope repair methods used based on the climate and ground conditions;
- The long-term performance of the existing methods;
- The ease of implementation of the existing methods;
- The impact of the existing methods on traffic and roadway conditions;
- The sustainability of the existing methods;
- Special equipment requirements for the existing methods.

2.3.1. Survey questionnaire structure

The survey was a combination of multiple choice and text questions with additional space for comments of respondents. It began with a short explanation of the project and an instruction on how to complete the survey. Respondents contact information have been gathered in section 1 of the survey. Section 2 was designed to collect information about rate of recurring slope failures and the conditions that maintenance divisions adopt a formal analysis to select a repair method. In section 3, we requested respondents to select methods which they had used for repairing slopes. In this way, they were able to skip questions about methods that they had no experience of using.

For each selected repair method, respondents were asked to answer questions about the following topics:

- performance of the method
- reasons for selecting the method
- performing entity
- soil characteristics of repaired slope
- the degree of slope.

2.3.2. Survey distribution

The survey was distributed among subject matter experts with different positions from all TxDOT districts. An invitation email with the online link to the survey was sent to survey respondents for survey distribution. This email included a brief introduction followed by a brief instruction on how to answer survey questions. “SurveyMonkey.com” has been used as an online platform to perform the survey for this study. Conducting survey online enabled respondents to take the survey in their desired time. Moreover, a PDF version of the survey was sent to the respondents upon their request.

2.4. Interview

Findings from reviewing and examining the literature on slope repair methods and analyzing survey responses were used to develop the interview questionnaire. Interviewing expert practitioners provided the opportunity to capture the state of practice in the successful implementation of embankment slope repairs.

Following items has been considered for selection of potential interview respondents:

- Selecting individuals with the most successful experience on embankment slope repairs.
- Covering the most regions of Texas.
- Covering the most slope repair methods.

Finally, ten interviewees were selected from TxDOT districts and maintenance division. The interviewees hold different positions, such as district bridge engineer, district maintenance engineer, director of construction, and district area engineer. The selected interviewees were contacted, and one or more face-to-face or over-the-phone interview sessions were scheduled at their convenient time and place.

Chapter 3

Slope Repair Methods

3.1. Introduction

Several repair methods have been identified for stabilizing embankment slope failures. Figure 3-1 shows the classification of slope repair methods based on construction techniques. Figure 3-1 also lists slope repair methods under each category. The following sections describe each slope repair category and corresponding repair methods.

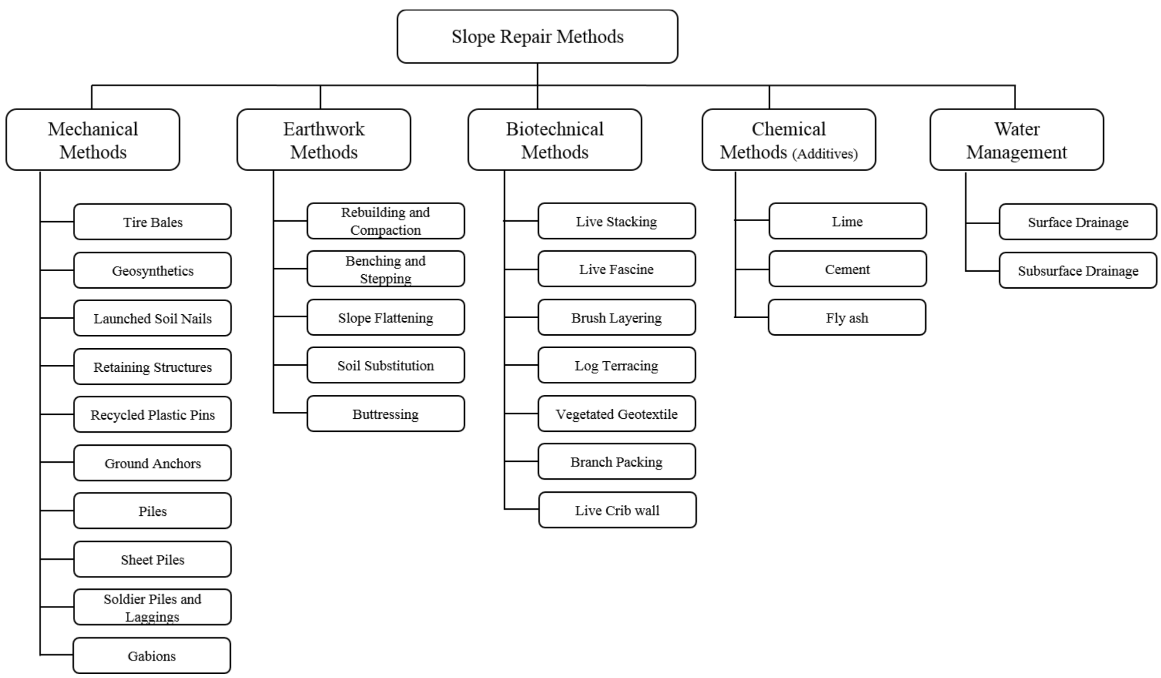


Figure 3-1. Classification of slope repair methods (Shahandashti et al. 2019)

3.2. Mechanical slope repair methods

Mechanical slope repair methods stabilize slopes, either by altering the physical composition of the soil or placing a barrier in or on the soil to obtain the desired effect. Mechanical slope repair methods include, but are not limited to retaining walls, launched soil nails, recycle plastic pins, geosynthetics, and gabions. The following sections provide a detailed review of these mechanical slope repair methods.

3.2.1. Tire bale

Tire bales involve a relatively low-cost manufacturing process, which makes them a cost-effective substitute for imported granular fill materials, especially in terms of long-term stability benefits (Zornberg and LaRocque 2006; Prikryl et al. 2005). Tire bales are blocks of compressed scrap tires tied by galvanized or steel tie-wires. The average weight of a standard tire bale block is reported 2000 lbs (1 ton) and contains about 100 scrap tires (Freilich and Zornberg 2009). The dimension of such blocks are approximately 60 inches long, 50 inches wide, and 30 inches tall (Zornberg et al. 2005; LaRocque 2005; Winter et al. 2006). Nevertheless, the block dimension can be customized due to project requirements. Use of the tire bale technique not only provides durable and long-lasting embankments but it disposes of scrap tires in an environmentally and legally sound manner (Prikryl et al. 2005; Bandini et al. 2008).

From the constructability point of view, implementation of tire bales is not complicated. Zornberg et al. (2005) reported that the construction operations for repairing slopes do not require special equipment since they can be moved and placed even by conventional forklifts. The researchers recommended that tire bales be stacked in a brick-like fashion for the better performance. According to this report (Zornberg et al. 2005), manufacturing and use of tire bales does not require highly skilled labor or quality control.

3.2.2. Geosynthetics

Geosynthetics are tensile reinforcing elements that significantly increase the strength of the soil (Nelson et al. 2017). The economics and successful performance of geosynthetic reinforced slopes have resulted in a significant growing use of this method (Christopher and Stulgis. 2005). Usually, geosynthetics are used to create reinforced soil slopes (RSS) (Berg et al. 2009). The RSSs are embankment slopes with face inclinations of less than 70 degrees, constructed using appropriate fill materials placed in layers with geosynthetic reinforcement in between.

A significant advantage of geosynthetics is their flexibility and long-term performance (Reddy et al. 2003). The geosynthetic material allows projects to meet environmental and aesthetic requirements. Geosynthetics are often used due to their ease of installation and work well in combination with other stabilization methods (Nelson et al. 2017).

Nevertheless, the long-term behavior of geosynthetic materials depends on exposure to various types of possible degradation mechanisms (Hsuan et al. 2008). This includes both chemical and mechanical behavior, and sometimes even their interactions with one another. Damage during construction could also affect the performance and durability of geosynthetics. Since several possible applications and types of geosynthetics are available to choose from, different design methodologies are always an option (Koerner 2012). The following sections describe three frequently used types of geosynthetics in more detail—geotextiles, geogrids, and geofoams, which have been largely used in slope repair projects.

- Geotextiles

Geotextiles are a planar, permeable, polymeric textile material, which may be nonwoven, knitted or woven (Müller and Saathoff 2015). The term “geotextile” describes a permeable fabric (Nelson et al. 2017); for that reason, geotextiles are sometimes called “filter fabrics” (Koerner 2012). Permeability (across their manufactured plane and also within their thickness) is the most important specification of geotextiles for slope repair applications (Koerner 2012).

- Geogrids

Geogrids are fabricated from high-density polyethylene (HDPE) or polypropylene (PP) resins and are used for reinforcing the soil by placing them inside the slopes (Koerner 2012). Repair of a failed slope using geogrids requires removal of the failed soil mass and benching of the section below the slip surface. Next steps include the installation of a drainage system by spreading geogrids, followed by covering with compacted granular material (Day 1996). Geogrid application in slope reinforcement has increased significantly because of its reasonable cost. In addition, the construction cost could decrease more if lower quality fill materials are used along with geogrid reinforcement (Niroumand et al. 2012).

This method requires a detailed design considering several factors such as soil properties, depth of failure, type of geogrids, and soil infiltration characteristics. Cautious implementation is one of the other limitations of geogrids. For instance, geogrids are often used in combination with geotextiles, especially in the case of soft soils with inadequate support to provide stability to the embankment soil (WSDOT 2017). However, this combination should be performed carefully because sometimes, placing a geotextile drain in conjunction with geogrid reinforcement can result in a reduction in strength as the presence of a drainage layer can lubricate the surface of the reinforcement (Heshmati 1993).

- Geofoams

Geofoam is a product created by polymeric expansion processes resulting in a material with a texture of numerous, closed, gas-filled cells (Horvath 1995). The unit weight of EPS-block geofoams is substantially less than traditional earth fills (approximately 99% less). Considering the cost and characteristics of EPS-blocks, they are a perfect substitute to traditional earth fills in highway embankment construction, especially where small unit weight and high bearing capacity is needed (Arellano et al. 2011; Stark et al. 2012; Ruttanaporamakul et al. 2016). However, they are not a suitable substitute for all earth-fill applications such as places where high unit weight (toe berms) or limited permeability (levees) are required.

EPS geofoams are environmentally friendly and safe during manufacturing, construction, and after they have been put in the ground (Riad et al. 2003). Also, the unique strength and flexibility of EPS geofoams make them resilient under seismic conditions (Trandafir and Ertugrul 2011).

In this method, the failed mass must be excavated and reconstructed by geofoam. In many cases, this process requires a temporary soil retaining system that increases the cost of the project (Hossain et al. 2017). EPS geofoams are susceptible to certain hydrocarbon chemical (liquid petroleum products). Therefore, it is essential to use separation material such as a geomembrane or geotextile to protect the geofoam against potential hydrocarbon spills.

3.2.3. Launched Soil Nails

Launched soil nails reinforce the soil mass by transferring the tensile and shear resistance of nails to the sliding soil (USDA Forest Service 1994). Launched soil nails, use compressed air to accelerate a steel nail or rod into the face of the slope at a speed of over 350 km/hr (Smith et al. 2009). This technique can be used to repair failures up to 15 ft (4.5 m) from the surface, in which case 20-ft-long (6 m) nails with a diameter of 1.5 in. (3.8 cm) would be used (USDA Forest Service 1994). Shorter nails are used in shallower cases, or the extra segment of the nail is cut off at the ground surface. Conventionally, soil nails are made of steel bars, but nowadays hollow galvanized steel or fiberglass tubes are much more common, since they provide more resistance to corrosion (Barrett and Devin 2011).

Type of ground, site accessibility, length and thickness of nails, the construction procedure, and availability of skilled workforce are the factors that affect the cost of this repair method. This method is suitable for most types of soil, such as sand, gravel, silt, clay, and soil with only a few cobbles and boulders. However, the depth of penetration would decrease in slopes with excessive cobbles or boulders (USDA Forest Service 1994).

Another advantage of the LSN method is their rapid installation process (approximately 80 linear ft. (25 m) of road per day for a two-row installation) (New York DOT 2015a). The major cost of this method is in the case of wall facing. In most cases, a temporary vertical soil nail wall is constructed to retain the cut section to provide uninterrupted traffic flow (Hossain et al. 2017). This method best fits excavation applications to ground with vertical cuts and often requires a small right of way (single lane closure for mobilization) (New York DOT 2015a).

3.2.4. Retaining structures

Retaining structures are used to stabilize slopes by increasing the resisting forces (shear stress) from sliding mass (Collin et al. 2008; Fey et al. 2012). Low-height retaining structures at the toe of a slope make it possible to grade the slope back to a more stable angle that can be successfully revegetated without loss of land at the crest (USDA 1992). However, it could be less effective, when applied in fine-grained soil, because of less sliding resistance (Hossain et al. 2017). These structures may also be used at the top portion of the slope to provide an extra space for expanding roadside width (Fey et al. 2012). Along with the direct function of holding back earth, they can also improve the aesthetic quality of the transportation systems (Indiana DOT 2013).

Different types of retaining structures are used in highway slope repair projects such as precast concrete panel walls, cast in place concrete gravity and cantilever walls, crib walls, gabion walls, MSE walls, tieback walls, rock walls, and “H-pile” and laggings. Since these structures include different materials, they vary in application, cost, features, and implementation procedures. For instance, gabion and rock retaining walls are more permeable than other types of retaining structures. This feature makes them more suitable for high water table and no filtration conditions. Mechanically stabilized earth (MSE) walls are constructed like reinforced soil slopes (RSS) with reinforced facing (usually reinforced concrete blocks). MSE walls are cost-effective soil-retaining structures that can tolerate much larger settlements than reinforced concrete walls (Elias et al. 1997). Berg et al. (2009) established a step-by-step design approach for MSE walls that have been verified through extensive experimental evaluation by FHWA. Mechanically stabilized earth (MSE) walls are more cost-effective and popular than other types of retaining structures when the height of the wall exceeds 10 feet (Berg et al. 2009).

One of the limitations of retaining structures is the requirement for a proper engineering design. A retaining structure may be inadequate to retain the driving forces (active soil pressure from the retained soil mass) if it is not designed accordingly (Collin et al. 2008).

3.2.5. Recycled Plastic Pins

Recycled Plastic Pins (RPPs) are fabricated from recycled plastics and waste materials (polymers, sawdust, and fly ash) (Chen et al. 2007). This method has been recognized as a cost-effective solution for slope stabilization, in comparison with the available in situ slope stabilization methods, such as retaining structures (Loehr and Bowders 2007; Khan et al. 2017). RPPs increase the factor of safety by providing an additional resistance along the slope failure plane (Hossain et al. 2017).

RPPs are lightweight and less susceptible to chemical and biological degradation than other reinforcement materials (Khan et al. 2017). RPPs are commercially available in different lengths, sizes, and shapes. In addition, RPPs are different in composition since they are manufactured by recycled plastics obtained from different sources (Loehr et al. 2000). To use RPPs for repairing slope failures, an engineering design is required (the design could be conducted using simple charts). Based on the design and calculations, proper RPPs are installed using a crawler-type drilling rig, having a mast-mounted vibrator hammer (Bowders et al. 2003). Since RPPs are commercially available and can be installed within a few days, they are an attractive option for emergency slope failure management (Khan et al. 2017).

3.2.6. Ground Anchors

Ground anchors are structural elements designed to transfer the load applied to them to a more stable stratum. Grouted ground anchors (typical ground anchors) and helical ground anchors are two common types of ground anchors used for repairing slope failures Figure 3-2 shows different components of a grouted ground anchor. Ground anchor systems (components) vary in shape, length, material, and implementation procedure, which makes them different in application.

In many cases, anchors provide extra stability for retaining structures such as MSE walls, soldier piles and lagging systems, as well as sheet pile walls.

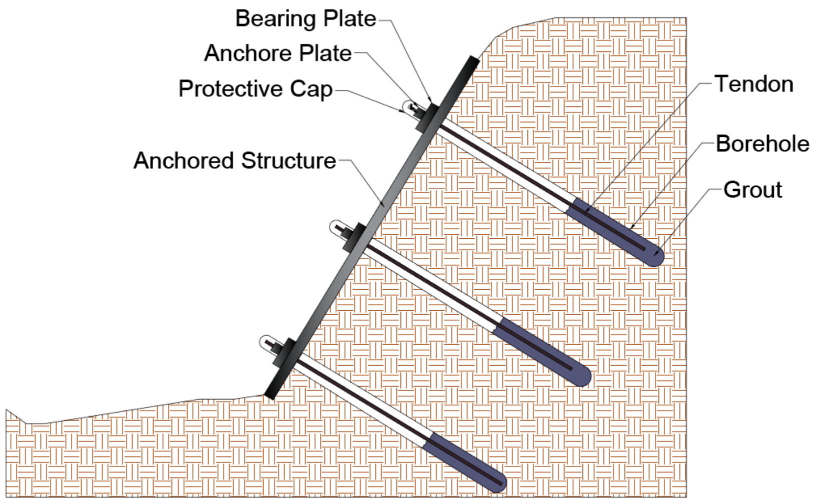


Figure 3-2. Components of a general ground anchor system (Shahandashti et al. 2019)

Grouted earth anchors installation is similar to soil nails and foundation piles. These anchors are installed and grouted in predrilled holes. The helical type anchors that consist of one or several rows of helical plates or helices can be simply screwed into soil for placement (Saftner et al. 2017). Titi and Helwany (2007) reported the frequent use of a ground anchors used by different state departments of transportation including the North Carolina DOT, CalTran, and Hawaii DOT. In this method, first the failed slope is re-profiled with the original soil or appropriate fill material. Next, appropriate facing material such as geotextiles and geogrids are installed. Further, a drainage system such as petit drains are installed. The final step includes the installation of ground anchors and landscaping. The installation of ground anchors is carried out by pushing them into ground below the failure surface. Then the wire tendon of the anchor is pulled and tightened to the end-plate to move the anchor to its full working position (Titi and Helwany 2007).

Improvements in design methods, construction techniques, anchor component materials, and on-site acceptance testing has made the ground anchors and anchored systems more popular and cost-effective with a long service life of 75 to 100 years (Sabatini et al. 1999). Despite all the advantages, there are a few limitations regarding this stabilization system. Ground anchors commonly need preproduction load testing to ensure their designed and long-term performance. In addition, their performance evaluation is strongly influenced not only by the methods and materials used, but also by the experience of the contractor (Iowa DOT 2011).

3.2.7. Piles

Piles stabilize slopes by providing passive resistance against soil lateral force (Wei and Cheng, 2009). Piling requires minimal or even no excavations (Fay et al. 2012). Plate piles and micro-piles are the two most common used pile systems for slope repair.

Shallow slope repair (less than 3 feet failure depth) using plate piles is a relatively new technique compared to other types of piles (Fay et al. 2012). They are often made of 6-foot long steel piles with a rectangular steel plate at the end (Short et al. 2006). In this method, plate piles are inserted in rows parallel to the slope crest with a certain spacing and pattern. Figure 3-3 illustrates an installation pattern of plate piles and their resisting mechanism. The plate section resists against the sliding of upslope loose soil mass by transferring the forces to the lower stable layers.

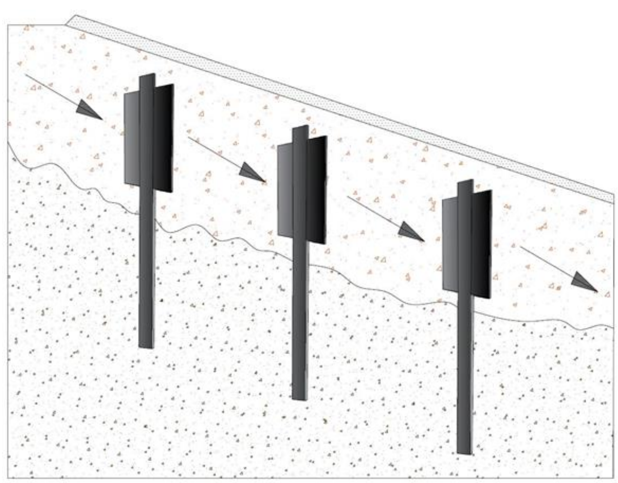


Figure 3-3. Plate piles installation pattern and resisting mechanism (Shahandashti et al. 2019)

Plate piles can reduce the construction cost six to ten times in comparison with other conventional methods, such as soil replacement and retaining walls (Hossain et al. 2017). Plate piles are used to stabilize shallow slope failures in regions with frequent wetting and drying cycles, such as California and Texas (Short et al. 2006).

Micro-piles are small-diameter, high-capacity drilled or grouted piles (Richards and Rothbauer 2004). Micro-piles are ideal for foundations stabilization (Pearlman 2000; Richards and Rothbauer 2004). However, they have been proven as an effective solution for repairing slope failures (Wei and Cheng 2009; Fay et al. 2012). Micro-piles can be installed at different angles to stabilize loose soil mass on slopes. Micro-piles have been successfully utilized by different states for repairing and stabilizing shallow slopes, such as Idaho and Montana (Fay et al. 2012).

3.2.8. Sheet Piles

Sheet piles are structural sections with interlocking edges that are pressed into the ground to resist horizontal water or soil pressures (King 1995; Škrabl 2006). Sheet piles are appropriate solution for stabilizing slopes where the water table is high and near ground surface (Niroumand et al. 2012). Water-tightness of sheet piles provides seepage control characteristics (Korenaga et al. 1998). Sheet piles stabilize the slope by transferring the driving force of the soil above the slip surface to the lower soil layers, which are more stable (Ashour and Ardalan 2012).

Sheet piles are in two types of (1) cantilever sheet piles and (2) anchored sheet piles. Anchor sheet piles are more cost-effective than cantilever types when deep cantilever sheet piling is required (Tsinker 1983).

Sheet piles are made from different materials, including wood, reinforced concrete, vinyl (synthetic resin or plastic), and steel (Shao and Kouadio 2002). The most important factor and the driving criterion for choosing the type of sheet pile is the soil type (Niroumand et al. 2012). For instance, steel sheet piles are preferred for stiff soils, where a larger driving force is needed to drive the sheet pile into the soil. Moreover, sheet piles are also available in different shapes such as U shape, Z shape, and straight web shape.

Slope stabilization using sheet piles provides several advantages. Sheet piles are relatively lightweight, and the construction operation is rapid (Niroumand et al. 2012). They are reusable and have a long service life (Niroumand et al. 2012). Other advantages of using sheet piles are their strength and availability in various section shapes. Moreover, their length can be easily extended by welding or bolting (King 1995).

3.2.9. Soldier Piles and Lagging

Soldier piles and lagging is an excavation support technique that retains soil using vertical steel piles and a horizontal lagging system. Soldier piles are usually in the form of steel pipe piles, I-beams, or H-piles. The lagging system could be made of horizontal timber beams, precast reinforced concrete segments, or cast-in-place reinforced concrete. This system provides resistance alongside the failed slope. Soldier piles and lagging could also be implemented in multiple levels buried in the slope from the top to the toe of the slope. This method starts by the disposal of the failed soil mass from the site. Then, the sublayer is formed in benches to provide a base for pipes and lagging installation. Steel H-piles are either driven in place or installed in pre-bored holes at regular distances (New York DOT 2015b). Lagging beams or panels are inserted behind the piles' front flanges, and selected materials are used as filler and compacted in layers. In most cases, a drainage system must be implemented behind these structures (Day 1996).

Soldier piles are driven to a depth lower than the failed plane (competent layer) to provide adequate resistance against the pressure of the upper soil layer (failed layer). As a general approximation, the length of pile embedded within competent soil or rock is typically greater than 1/3 the total length of the pile (Deschamps and Lange 1999). Furthermore, additional lateral support can be provided to soldier piles and lagging systems by anchors or bracings.

This method of repair is fast to construct, and lagging can be installed quickly. Shallow slope repairs using this method do not require advanced construction techniques in comparison with other systems. On the other hand, this method is limited to temporary construction and is not recommended for locations with a high-water table (Hong 2002). The major reason behind the failure of this method is the bending of piles due to the lateral soil pressure that transfers from wood lagging to piles (Titi and Helwany 2007).

3.2.10. Gabions

Gabions are welded wire baskets filled with materials such as stone, concrete, sand, or soil. The main goal of using gabion baskets is to utilize smaller and cheaper stones that are not stable by themselves to build retaining walls (Greenway et al. 2012). They have numerous applications, such as bed protection, bank stabilization, and retaining walls (Freeman and Fischenich 2000).

Generally, gabions are implemented in two ways. They can be placed along the slope to create gabion revetments (gabion mattress) (Figure 3-4-b) or be stacked vertically on top of each other to form gabion walls (Figure 3-4-a). This method is also appropriate for protecting river embankments from washouts and preventing landslides (Tamrakar 2015).

Vertical gabions are vulnerable to structural failure, while gabion revetments are more stable (Greenway et al. 2012). Gabion wall height is recommended to be less than twice its width (WSDOT 2013). Diaphragms of the same gabion mesh must be added to the structure, where the length of the gabion exceeds 1.5 times its horizontal width (KYTC 2009). Figure 3-5 shows the use of diaphragms in gabions.

Gabions can be combined with other materials and slope repair methods to provide better performance. For instance, geogrid reinforcement can be used to improve the stability of gabion walls (Brand 1992). Geogrids can be placed between the gabion baskets and extended to the backfill soil to support the gabion wall. However, failure can happen if geogrids are not appropriately implemented. Therefore, the combination of these two methods requires a detailed design and careful implementation.

The stability of gabions will increase over time by vegetation and silt collected inside the gabions. These materials can also be added to the regular gabions in the construction phase. This process forms a new structure called vegetated rock gabions (USDA 1992). Proper vegetation can stabilize gabions via their rooting system and bind the gabion wiring and contents into the soil mass. However, vegetation can also provide adverse effects on the structural stability of gabions. Large vegetation can break gabion wires and destabilize the whole retaining system (Kandaris 1999; Greenway et al. 2012).

Slope stabilization with gabions offers several advantages. Gabions are easy to construct and do not require highly skilled workforces and heavy equipment (Kandaris 1999; Chen and Tang 2011). The maintenance cost of gabions is not significant, since they only require minimal repair of broken wires (Greenway et al. 2012). Gabions improve the drainage and filtration characteristics of repaired slopes (Fay et al. 2012).

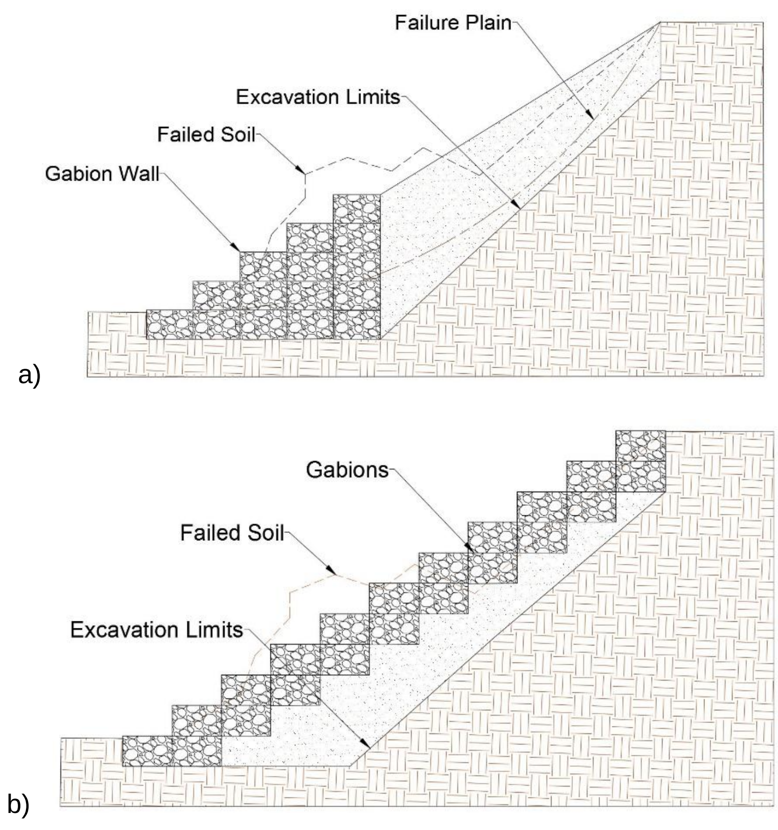


Figure 3-4. a) Gabion retaining wall and (b) gabion mattress (Shahandashti et al. 2019)

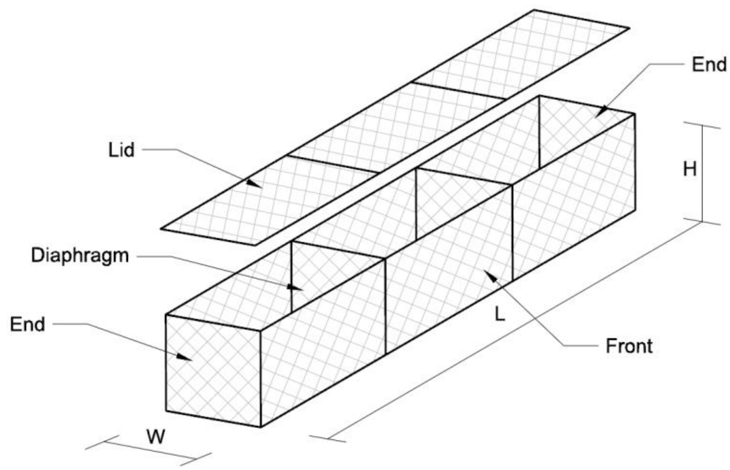


Figure 3-5. Supporting long gabions using diaphragms (Shahandashti et al. 2019)

Gabions are considered as more of a short-term solution for many slope failures. No specific service-life has been formally introduced for gabions (Racin and Hoover 2001). The reason is that gabions are built with different materials (different wire coatings), used for different purposes, and in different environments. For instance, gabions that are used to protect river or coastal banks have relatively lower service-life in comparison with gabions used to protect slopes in dry regions. Typically, gabions do not improve the aesthetic quality of repaired slopes (Racin and Hoover 2001). Gabions have a limited aesthetic application in comparison with biotechnical stabilization methods.

3.3. Earthwork slope repair methods

Earthwork slope repair methods stabilize slopes by physical movement of the failed area. Typically, these methods are one of the least expensive (Hossain et al. 2017) and most utilized methods for repairing shallow embankment failures (Zhang et al. 2003; Collin et al. 2008). Earthwork slope repair methods are usually conducted by agency maintenance workforces using typical equipment such as rollers, compactors, and backhoes. Nevertheless, these methods usually require space beyond the immediate zone of the failed slope (Bromhead et al. 2012). Although these methods are intended to provide more stability and strength to the failed slope, they have the potential to create instability to undisturbed adjacent soil and structures (Collin et al. 2008). These instabilities may be due to several reasons such as inadequate subsoil bearing and shear strength, utilization of improper equipment, and low-quality workmanship. The following sections discuss five common earthwork slope repair methods.

3.3.1. Rebuilding and Compaction

Rebuilding the slope is the action of replacing the failed soil mass and reshaping the slope as before the failure. Compaction is the action of decreasing the volume of a soil mass by reducing the soil pore space. Based on the size of failure, slope rebuilding can be done using hand tools or equipment such as dozers and backhoes.

Slope rebuilding and compaction method starts by removing and air-drying the failed soil mass, installing the required drainage systems, rebuilding the failed slope and finally compacting the slope (Titi and Helwany 2007). Compaction decreases the permeability and infiltration characteristics of the slope; thus, revegetation of the repaired slope usually takes a long time (Shillito and Fenstermaker 2014; Titi and Helwany 2007). For that reason, it is recommended to use erosion control fabrics after repairing slopes with this method.

This method is considered as one of the most economical methods of repair and is performed as routine maintenance work on failed slopes (Zhang et al. 2003; Collin et al. 2008). However, this method will vary in effectiveness depending on the type of soil. For instance, although the physical properties of cohesionless soils are generally improved by compaction to the maximum dry unit density (Abramson et al. 2002), the physical properties of cohesive soils (e.g., clay) are not necessarily improved by compaction to a maximum unit density. Although this method is the most common method used by maintenance workforces, reoccurrence of failure is often reported in slopes repaired using this method (Stauffer and Wright 1984; Deschamps and Lange 1999; Zhang et al. 2003; Collin et al. 2008; Titi and Helwany 2012). Best performance of this method requires workers with special skills in engineering applications and design. Compaction equipment must be selected based on the type of soil to be compacted (Collin et al 2008).

3.3.2. Benching and Stepping

Benching stabilize the slopes by converting a steep slope to several lower ones by excavating horizontal cutouts periodically along the slope (Nelson et al. 2017). Benches are 4 to 10 ft (1.2 to 3 m) wide, built horizontally or with a slight reverse angle towards the slope, while steps are 1 to 4 ft (0.3 to 1.2 m) wide, and usually horizontal (TIRRS 2001). The height of each bench usually depends on the soil characteristics and slope geometry. Slopes are more stable as they are nearer to their natural angle of repose (Shakoor and Admassu 2016).

Benching starts by excavating a flat bench until a designed vertical height and width (about 5-6 feet) is achieved. Next, the exposed face is cut back to an angle (usually about 1:1), and then another bench is constructed. In many cases, benching should be conducted before placing new fill at a failed slope (Lohnes et al. 2001). In order to provide long-term stability of benches, a drainage system should be installed for each bench to convey runoff to a suitable discharge outlet (Nelson et al. 2017; Abramson et al. 2002).

This method is recommended for slope failure on slopes steeper than 4H:1V, as well as new construction (Lohnes et al. 2001; Ohio DOT 2017). Benching dimension guidelines are usually available in local building and safety codes, such as OSHA (2015).

One of the advantages of benching is to control runoff and minimize erosion by converting the steep slope to several steps that lowers the velocity of water running off the slope (TIRRS 2001). Using water management systems in combination with stepping would provide appropriate runoff control system. This method has also been used to establish vegetation on slopes (Abramson et al. 2002). Benching is an appropriate slope stabilization method for steep slopes in weathered rock where flattening is challenging (Collin et al. 2008). Although, benching results in a higher overall slope and greater excavation, it reduces subsequent maintenance costs and thereby offsets increased construction costs (Abramson et al. 2002). Benching is not recommended for slopes with sandy, non-cohesive or highly erodible soils (ITD 2011). Appropriate drainage systems should be established in case of slopes with excessive seepage or surface runoff (ITD 2011).

3.3.3. Slope Flattening

Slope flattening can be accomplished either by excavation or addition of soil. The flattening of a slope by excavation stabilizes the slope by reducing the driving forces, while adding and compacting soil, principally in the toe region, increase the resisting forces against the slope failure (Abrams and Wright 1972). When flattening the slope by adding material, placing additional material should be accomplished in a controlled fashion and be compacted, if needed. Additional material should be selected to have better or at least the same strength properties as that found in the existing slope, preferably with proper drainage characteristics (Collin et al. 2008).

It is important to ensure that flattening of the slope will not interrupt important drainage features; otherwise, it is essential to maintain or include new drainage systems for the flattened slope (Collin et al. 2008). Other limitations and challenges regarding slope flattening projects are disposal of extra material, procurement of fill material, and acquisition of additional right-of-way (Fay et al. 2012; Abramson et al. 2002; Duncan et al. 2014).

3.3.4. Soil Substitution

Soil substitution is the replacement of the failed soil mass with a more suitable material, such as silt or clay of low plasticity and cohesionless sands and gravels (Duncan et al. 2014). This method is effective especially for shallow slope failures (Collin et al. 2008). Replacement of failed soil mass with suitable material increases the stability of the slope by improving slope shear strength, drainage characteristics, and passive resistance forces (by weight) (Abrams and Wright 1972). This method also reduces the driving forces when using lightweight fill materials (Abramson et al. 2002). A proper implementation of this technique will be achieved by excavating the original slope beyond the existing sliding surface (Collin et al. 2008). This method involves procurement of proper substitute material, which makes it cost-effective where a convenient source of fill material is located near the site (Nelson et al. 2017).

3.3.5. Buttressing

Building a buttress (buttressing) increase stabilizing forces and decrease overall slope height by loading the toe of the slope with heavy material (Lohnes et al. 2001; Nelson et al. 2017; Saftner et al. 2017). This method is best used to stabilize slope failures occurring at the toe of the slope (Nelson et al. 2017). Buttressing can be implemented with rock fills, earth fills (counter berms), or pneusol (scrap tires and soil) (Abramson et al. 2002; Lohnes et al. 2001).

Slope repair using a buttress can also be used in combination with shear keys and mechanical stabilized embankments (MSEs). Shear key is a deep trench that is excavated at the toe of a slope and below the sliding surface (Cornforth 2005). The trench is excavated along the slope and filled with granular material having greater internal shear strength than the native soils (Abramson et al. 2002).

Rock buttressing is an appropriate option for shallow slope failures where a little additional stability is needed, but there are right of way (ROW) limitations (Lohnes et al. 2001). This method is a suitable option to increase slope stability especially where adequate rock fills are locally available. Likewise, this method is recommended to be used on small- to medium-size slope failures, which are the most common size and often occur along forest service roads (Hall et al. 1994).

Although, this method may improve the stability of the slope above the buttress, it may decrease the stability of the slope below the buttress (Collin et al. 2008). Therefore, further geotechnical analysis of the downslope should be carried out to ensure the stability of the entire slope after using this method (Lohnes et al. 2001). Slope repair and stabilization using a buttress requires careful engineering considerations, such as external and internal stability of the buttress, surface and subsurface drainage, changes in ground water behind the buttress, and foundation bearing capacity (Hall et al. 1994). In many cases, buttressing methods are not a cost-effective method to repair shallow slope failures, compared to alternative methods such as flattening the slope angle or using a lightweight fill material that would reduce the weight load on a slope (Hall et al. 1994). More specifically, these methods are not cost-effective when an embankment failure is too far from the toe of the slope and, thus, will require a huge amount of buttress material. Buttressing is also not feasible in areas where no native rock is available near the failed slope.

3.4. Biotechnical slope repair methods

Biotechnical slope stabilization methods use a combination of live plants and structural components to protect slopes, embankments, and streambanks from surficial failure and erosion (Gray and Sotir 1992; Donat 1995; Adair et al. 2002). Biotechnical methods such as live crib walls, log tracing, and joint plantings (live staking) can be used to repair and stabilize slopes in the form of porous structures (Norris et al. 2008; Bella et al. 2017). These structures provide slopes with resistance to sliding, erosion, and washout. Biotechnical slope repair methods provide reinforcement in the soil profile in two stages (Gray and Sotir 1992). The primary stabilization occurs after installment of live cut stems and branches; the secondary reinforcement happens when adventitious roots are developed along the length of the buried stems.

Biotechnical slope methods offer several advantages in comparison with the other methods. They are more cost-effective in comparison with other conventional methods, such as retaining walls, soldier piles and laggings (Gray et al. 1980). This advantage is mainly attributed to availability of material and resources. Typically, materials used in these methods are natural and locally available, such as soil, rock, timber, and vegetation, which are environmentally friendly and more compatible with the landscape than the concrete and steel provided by mechanical methods (Adair et al. 2002; Schuster 1992).

Plant rooting systems in many biotechnical methods provide better reinforcement and drainage characteristics than the earthwork associated with mechanical methods such as slope repair, retaining walls, and sheet piles. The biotechnical approach also reduces construction and maintenance costs (Donat 1995; Highland and Bobrowsky 2008). In some cases, they are also used in combination with other stabilization methods to improve the visual aesthetics of retaining structures.

Although biotechnical slope repair methods offer several advantages, they have limited applications for the following conditions: steep slopes, adverse soil texture (excessive amount of fine and course material), poor nutrient status, adverse soil chemistry, low soil temperature, low soil moisture, and the hostile weather condition (Polster 1997; Withers 1999). Therefore, it is critical to understand and evaluate the project site conditions prior to adopting biotechnical slope repair methods.

3.5. Chemical slope repair methods (additives)

Slope repair by additives is used to alter the soil gradation, change the strength and durability, or act as a binder to cement the soil (U.S. Army Corps of Engineers 1984).

The selection of an additive and determination of the percentage to be added to the soil is usually based on two factors: (1) the soil classification and properties, and (2) the desired degree of improvement in soil quality (U.S. Army Corps of Engineers 1984; Al-Rawas et al. 2002; Abramson et al. 2002; Collins et al. 2008; Seco et al. 2011).

Although, chemical slope stabilization has several advantages, such as increasing soil shear strength, slope durability, and decreasing consolidation and settlement, there are several challenges attributed to this method. One of the main challenges affecting the performance of this method is the quality of mixing additives to the soil. If the process of mixing additive with soil is not performed properly, un-cemented zones will be susceptible to erosion, which leads to recurring slope failures (Day 1996). Other important challenges are poor compaction of stabilized mixture, an inadequate or excessive amount of additives, and an inadequate depth of treatment (Abrams and Wright 1972; Druss 2003). The following sections provide a detailed review of the most common slope repair methods using additives.

3.5.1. Lime

Lime can be used to stabilize and prevent embankment slope failures especially in the regions affected by heavy rains. Adding lime to a soil mass enhances the physical properties of the soil by: (1) drying the soil mass, (2) decreasing the hydraulic conductivity of the soil, which limits the depth of water infiltration into the soil, and (3) increasing the shear strength of the soil (Daneshmand 2009). This method is applicable for slopes with plastic clays, silts, and dirty sands (Bell 1996; National Lime Association 2004). Adding lime is effective for soils with a plasticity index greater than or equal to 10% (Collin et al. 2008). Lime stabilization can be used for failed slope masses as well as inferior borrow materials during construction (Carpenter et al. 1995). This method is more appropriate for shallow slope failures with depth less than 4 feet, while it has also been used for deeper failures (Abrams and Wright 1972). For the shallow failures, lime is added and mixed with soil directly whereas for deep stabilizations it is placed (injected) in drilled holes (Deschamps 1999).

Mixing the lime with embankment soil can be accomplished either at the location of the slope failure or in a separate mixing area. After mixture, the treated soil mass is placed back on the slope and recompacted (National Lime Association 2004).

Stabilization using lime should be avoided under the sun and should never be applied to a frozen soil mass (National Lime Association 2004). This method should be implemented in 40-degree Fahrenheit temperature or higher. Also, the water content should be 1 to 3 percent more than the optimum to make sure the clay reaction is complete (Bell 1996; National Lime Association 2004).

The permeability behavior of the soil-lime mixture is sometimes uncertain compared with the original soil. Thus, lime stabilization requires adequate laboratory studies prior to design (Abramson et al. 2002). Another limitation of this method could be the need for a workspace to properly mix the soil mass and lime. Carbonation, a sulfate attack and environmental impacts could also limit the effectiveness of using lime in slope stabilization (Jawad et al. 2014).

Although stabilization of embankments using lime has been one of the successful methods, there has been some cases of recurring failure using this technique. The most probable factors contributing to such recurrences were identified by Abrams and Wright (1972) as:

- Poor mixing of the lime and the soil,

- Poor compaction of the stabilized mixture,
- Inadequate depth of treatment, particularly for deeper slides,
- Improper consideration of failure causes.

3.5.2. Cement

Soil stabilization by adding cement is a method that has been successfully used for different purposes, such as providing an appropriate base-layer for pavements and shallow foundations, repair and stabilization of slopes, and protecting earth dams. Adding cement to embankment soil mass increases the stability of the embankment by two means (Schweizer and Wright 1974):

- Fills void spaces and as a result keeping water out of the embankment section,
- Adds strength to the soil mass as the cement cures.

Cement stabilization can be used for cohesive and granular soils (Parsons and Milburn, 2003). However, this method is mainly used for granular soils. Soils with less than 35% passing the number 200 sieve and a plasticity index less than 20% are suitable for cement stabilization (Collin et al. 2008).

Slope stabilization by adding cement is implemented using two main types of soil and cement mixtures: Soil-Cement and Cement-modified soil. Soil-Cement contains an adequate amount of cement mixed and mechanically compacted with soil and water to pass specified durability tests (Carpenter et al. 1992). This type of stabilization is also called cement-treated base, Cement-stabilized soil, and cement-stabilized aggregate (Portland Cement Association 1995). Cement-modified soil is improving the chemical and physical properties of soil by adding smaller quantities (compared to the soil-cement type) of Portland cement and water. It reduces the plasticity index and increases the shearing strength of the soil (Portland Cement Association 1995).

In most cases, cement is added directly to the soil. Other techniques, such as jet grouting for soil improvement and construction of lime or cement-stabilized soil columns for deeper slope stabilization have also been used (Haralambos 2009). The repair procedure of shallow slope failures using soil-cement consists of the complete removal of the failed soil mass, benching the sublayer, placing the soil-cement mixture, and compaction to at least 90% of the Modified Proctor maximum unit weight (Day 1997).

Cement can be added to almost any soil type, except those with an organic content greater than 2% or to soil with a pH lower than 5.3 (ACI 1990). One of the limitations of using this method is associated with complexity in assessment of strength, homogeneity, and other properties of the soil mass after treatment (Druss 2003).

3.5.3. Fly ash

Fly ash is a pozzolan that reacts with calcium constituents to produce cementitious products, resulting in a substantial strength increase (Carpenter et al. 1992). Fly ash is a byproduct of coal combustion process. The reactions prompted by fly ash occur more slowly than cement but more rapidly than lime (Xu and Sarkar 1993).

Proper handling, placement, and compaction of fly ash fills is required to achieve the desired strength and compressibility characteristics assumed for design. Fly ash is transported to project sites in bulk tanker trucks or packed in super sacks or smaller bags for specialty applications (American Coal Ash Association 2003). Fly ash is usually conditioned with water at the power plant and hauled to the job site or may be transported to the job site in a dry condition and mixed with water when ready for placement (FHWA 2016).

Fly ash should be placed in uniform layers no thicker than 12 inches, when loose (TxDOT 1998). Compaction must be completed within six hours of placement (TxDOT 2014). Experience has shown that steel-wheel vibratory compactors or pneumatic tired rollers have provided the best performance (FHWA 2016). If a vibratory compactor is used, the first pass should be made with the roller in the static mode (without any vibration), followed by two passes with the roller in the vibratory mode and traveling relatively fast. Additional passes should be in the vibratory mode at slow speed (ASTM 1997).

Soil stabilization using self-cementing fly ash can be a much faster and more economical method compared to removing and replacing these low-quality onsite soils (TxDOT 1998). Silts are generally considered the most suitable fine-grained soil type for treatment with lime-fly ash or cement-fly ash mixtures (Carpenter et al. 1992).

Fly ash with a sulfate content greater than 10 percent may cause soils to expand more than desired (American Coal Ash Association 2003). In many cases, leaching tests may be required by local and state agencies (Weithe et al. 2006). Certain fly ash sources may be corrosive to metal pipes placed within an embankment (FHWA 2016). Thus, the corrosive potential of fly ash should be evaluated beforehand.

3.6. Water Management slope repair methods

Water is known as the most common and most important cause of slope failures and landslides (Abrams and wright 1972; Deschamps and Lange 1999; Lohnes et al. 2001; Abramson et al. 2002; Collin et al. 2012; Fay et al 2012). The presence of water in slopes, either as groundwater or surface runoff, increases the hydrostatic (pore water) pressure and reduces the available shearing resistance of the soil. Water management techniques should be adopted to control the water from entering the slope initially and to drain any water which does enter the slope. Typically, these methods are used in combination with other slope repair methods to ensure the durability of the repairs and prevent recurring failures due to drainage issues. Effective water drainage decreases driving forces and increases soil shear strength (Lohnes et al. 2001). Furthermore, the effective and long-term performance of water management methods requires proper monitoring and maintenance after implementation (Collin et al. 2012).

There are several water management methods to drain the extra water from slopes. These methods can be classified into two categories: the surface and sub-surface drainage methods. A successful stabilization of slopes using water management methods almost always incorporate more than one type of drainage method (Deschamps and Lange 1999). Subsurface drainage systems must be used to control groundwater and surface drainage must be applied to reduce infiltration. The following sections describe recommended surface and subsurface drainage methods that can be used to improve drainage conditions in areas prone to slope failures.

3.6.1. Surface Water Management

Surface water management is important in the stability of any slope and is critical in case of repaired slopes (Cedergren 1997). Generally, surface water management is provided by proper grading of the road and slope surface, sealing joints, cracks and fissure, and the use of structures to drain surface water (Copstead et al. 1989; Collin et al. 2008). Surface drainage systems act indirectly to reduce groundwater levels, by reducing infiltration or by channeling the overland flow away from the slope (Deschamps and Lange 1999). The most commonly used surface water management methods are building surface ditches, sealing joints, cracks and fissure, re-grading the slope to eliminate ponding, and using vegetation (Collin et al. 2008).

Surface ditches, also called interceptor ditches, are constructed at the top, toe, and on the face of slopes to convey the drained water away from the slope. Figure 3-6 illustrates different applications of surface ditches. Surface ditches constructed at the top of the slope are able to channel the surface water and divert it away from the slope face (Lohnes et al. 2001). Surface ditches built at the toe of slopes are usually for discharging drained water from the slope to a place away from the slope (Deschamps and Lange 1999). In case of slopes with a long slope face and a water table near the surface, interceptor ditches are constructed on the face of the slope to collect and discharge the water from horizontal subsurface drainage systems. Roadside ditches are usually lined with reinforced concrete, riprap, and vegetation (Keller and Sherar, 2003).

Existence of tensile cracks at the top of some slopes, often provide a natural path for entrance of runoff into the slope and the subsequent development of high-pore water pressure (Collin et al. 2008). Therefore, it is essential to seal these cracks immediately and prevent the entrance of surface water into the slope area. Sealing cracks is usually accomplished with asphalt by the maintenance crew.

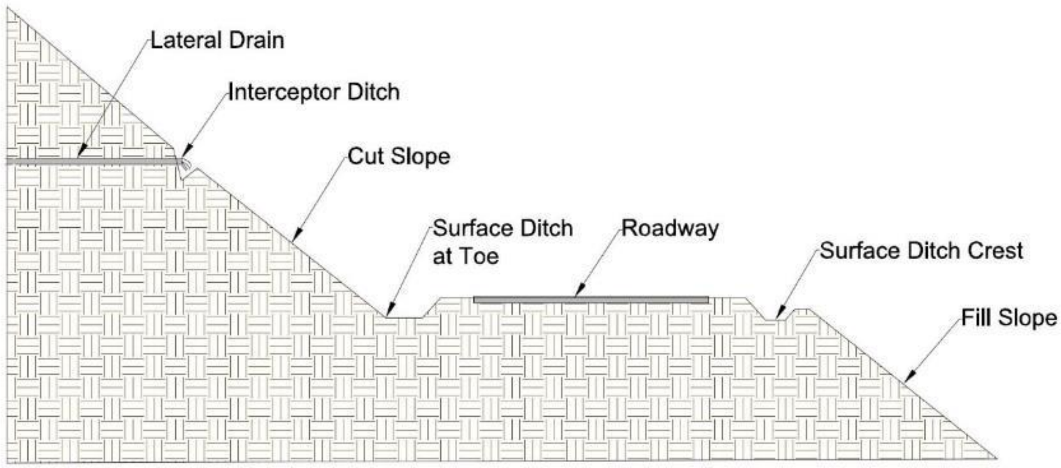


Figure 3-6. Different surface ditches (Shahandashti et al. 2019)

Regrading and using vegetation are other activities that controls surface water runoff and prevents excessive infiltration of surface water into the slope. Vegetation not only protects the slope surface from being eroded by water runoff, but their rooting system also provides reinforcement to the soil top layer (Collin et al. 2008). Vegetation is not a suitable method in terms of steep slopes (Fay et al. 2012). In this case, other surface protection techniques such as geosynthetics or permeable aprons are appropriate alternatives. Permeable aprons are placed on the slope surface providing a porous layer that conveys surface water flow down the slope. This method reduces the infiltration of the water into the slope and surface erosion (Lohnes et al. 2001).

3.6.2. Subsurface Water Management

Subsurface water management systems often control or reduce groundwater levels, directly (Deschamps and Lange 1999). Subsurface water management methods include drainage systems with different sizes and alignments (vertically or horizontally). The most commonly used methods for slope stabilization purposes are conventional horizontal drains, drain blankets, wick drains, vertical wells, drainage tunnels, and subsurface ditches.

Horizontal drains are made of small diameter (typically 1.5 to 2.0 inches) slotted PVC or perforated metal pipes (Deschamps and Lange 1999). These pipes are typically placed in holes drilled into the face of the slope. Horizontal drains are usually installed with a 3–20% grade to allow gravity drainage (Collin et al. 2008). Horizontal drains should be installed at least in two rows (Abramson et al. 2002), positioned in the lower portion of the slope and below the toe of the slope in natural ground (Collin et al. 2008). Horizontal drains are highly cost-effective with low maintenance requirements; however, they require proper construction and filter design to assure long term operation (Deschamps and Lange 1999).

Drain blankets are used to collect and convey groundwater away from the slope. The blanket consists of porous drainage material that acts like a filter to control and divert subsurface water to collector ditches and outlet channels. One of the issues regarding this method is the entrance of fine soil particles into the blanket, which can clog the drain. An alternative to the conventional drainage blanket is a geosynthetic drainage composite consisting of a geotextile filter sandwiching the plastic drainage core (Collin et al. 2008). The drainage blanket should be wrapped with a geotextile filter.

Subsurface water management methods are more cost-efficient to implement into initial design and construction of the slopes than to use them as remedial methods after slope failure (Abramson et al. 2002). Application of filter protection such as a geotextile or properly sized sand or gravel is very important in implementation of subsurface water management systems. A proper filtration prevents the migration of fine soil particles into drains causing blockage (Fey et al. 2012).

Chapter 4

Survey Response Analysis

4.1. Introduction

Totally, we received 33 responses from the surveys distributed among subject matter experts. The survey respondents were from 17 different TxDOT districts which are Amarillo, Lubbock, Abilene, Wichita Falls, Paris, Dallas, Atlanta, Tyler, Waco, San Angelo, Austin, Lufkin, Beaumont, San Antonio, Houston, Corpus Christi, and Pharr. As Figure 4-1 shows most of our respondents were area engineers who have the most interaction with slope repair projects.

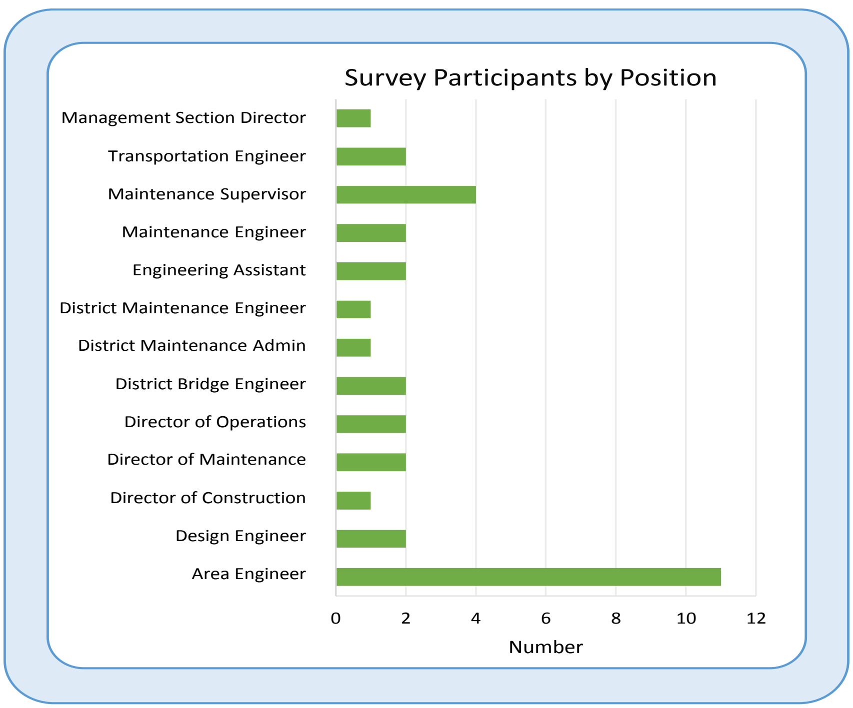


Figure 4-1. Summary of survey responses to Section 1 of the survey (Shahandashti et al. 2019)

Figure 4-2 illustrates information achieved on rate of recurring slope failure, the most popular slope repair methods in Texas, and the reasons which maintenance division adopt a formal analysis for selecting slope repair methods. Based on survey responds about 55% of slope repairs annually are on the slopes which have been failed before. Figure 4-2 also shows Rebuilding and compaction, retaining structures, and using geosynthetics are the most popular methods used in Texas for repairing slopes. Additionally, the results indicated that TxDOT maintenance workforces adopt a formal analysis to select a slope repair method when:

- a slope has failed more than once.
- The paved roadway surface is impacted on a fil section.
- A structure such as bridge is involved.

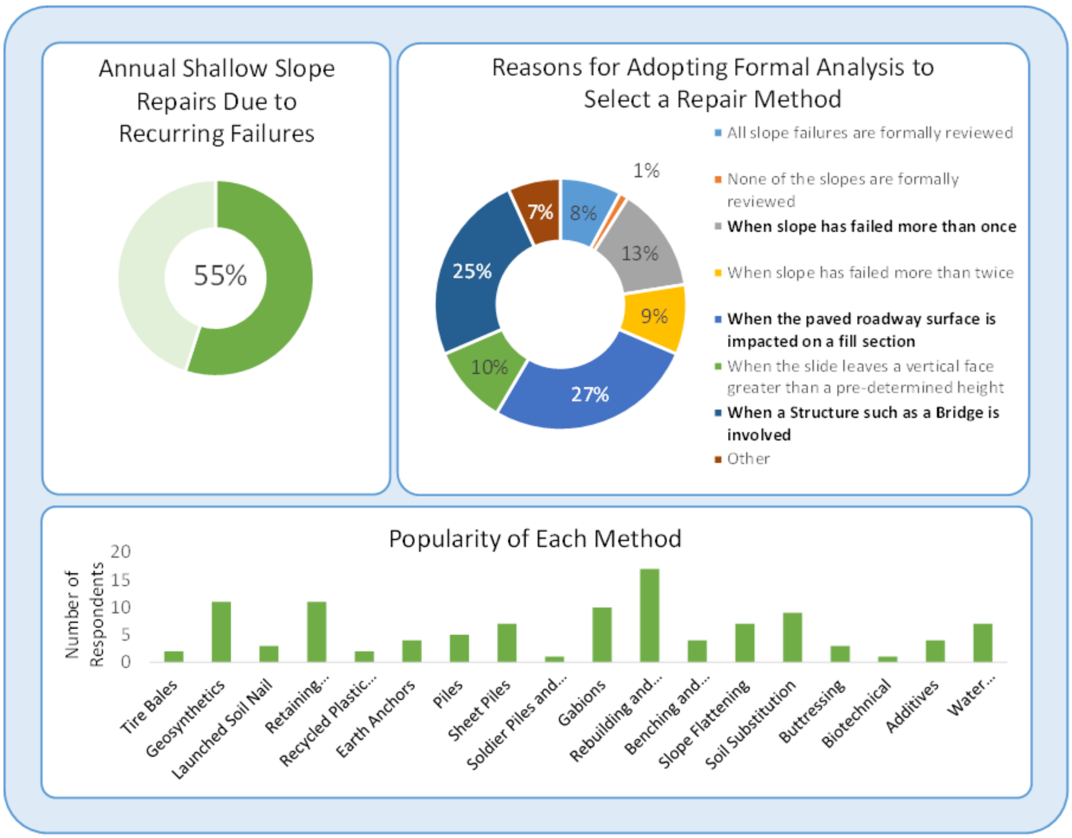


Figure 4-2. Summary of survey responses to Section 2 of the survey (Shahandashti et al. 2019)

The following sections summarize the survey results on the evaluation of various slope repair methods.

4.2. Tire Bales

Figure 4-3 illustrates the information achieved from survey responses for tire bale method. This method is not very popular in Texas and only had been used by two respondents. One of these respondents had failure experience for a slope repaired using this method. These are the main reasons for adopting this method by respondents:

- It does not need any special equipment.
- It is a rapid slope repair method.
- It is a low-cost repair method.

They used this method in slopes with clayey soil, good drainage condition and where the slope angle is less than 3:1 (H:V). Repair of slopes using tire bale method has been done both by in house maintenance crews and contractors.

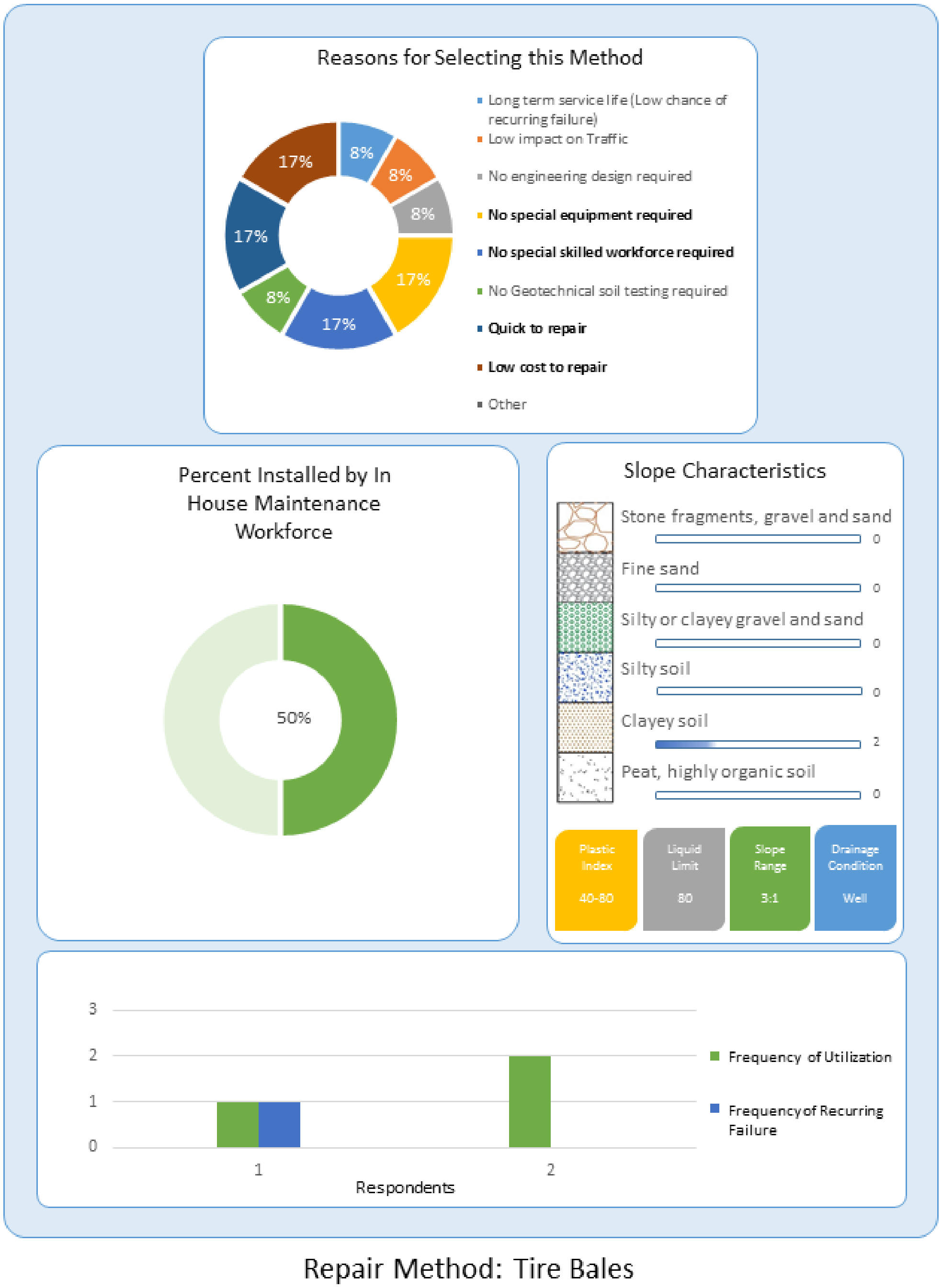
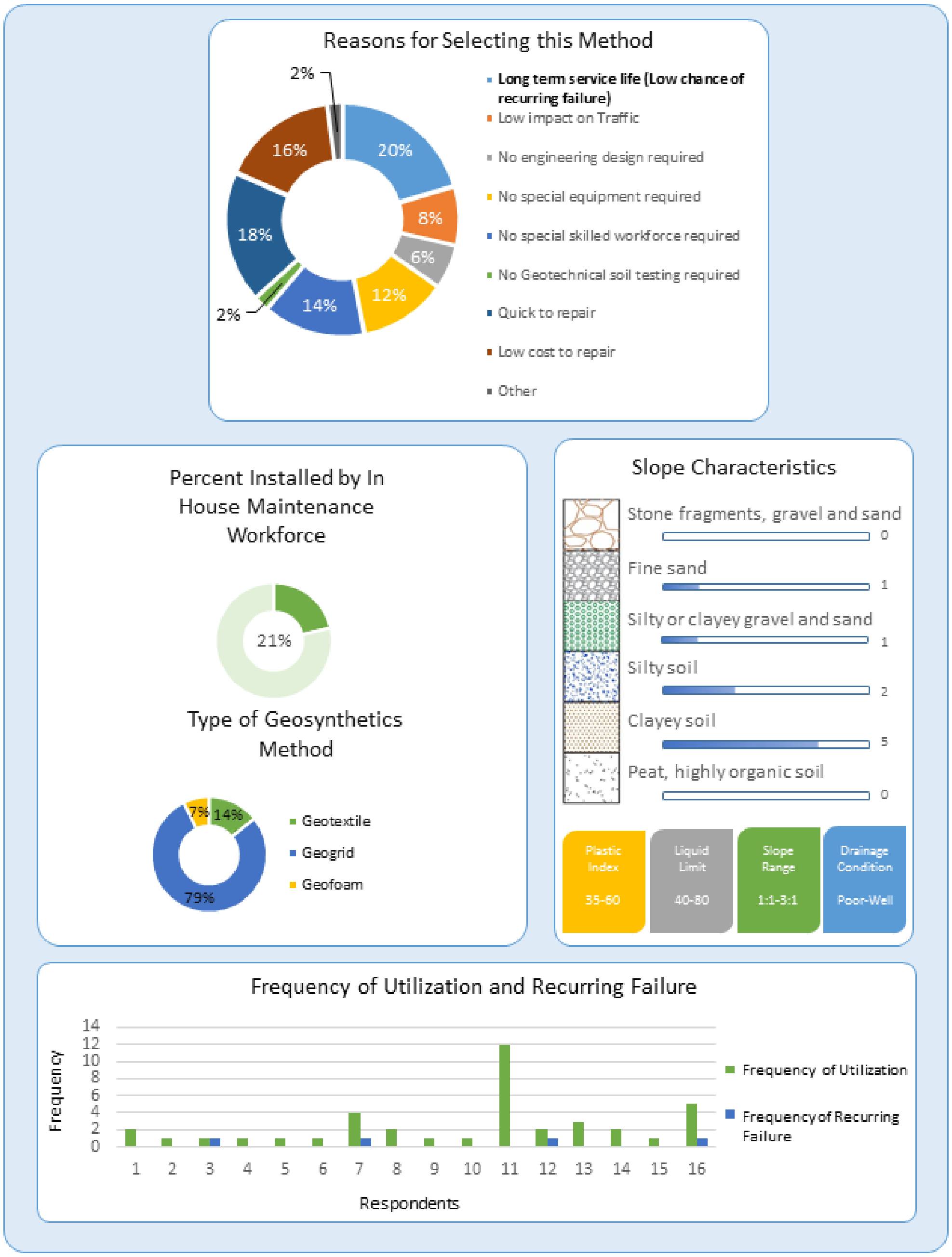


Figure 4-3. Summary of survey results for tire bale method (Shahandashti et al. 2019)

4.3. Geosynthetics

Figure 4-4 illustrates the information achieved from survey responses for geosynthetics method. This method has been used by Sixteen respondents from different parts of Texas. Although the main reason for selecting this method is its long-term service life, a few slopes repaired by geosynthetics have failed. Stabilizing slopes using geogrids are more popular than using geotextiles and geofoam. Respondents also selected this method because it is rapid, cost-effective, and does not need any special equipment and skilled workforce.

They used this method in slopes with clayey soil, good drainage condition and where the slope angle is less than 3:1 (H:V). Repair of slopes using tire bale method has been done both by house maintenance crews and contractors. Respondent used this method in various slope grade, drainage conditions, and soil types such as clayey soil, silty soil, silty or clayey gravel and sand, and fine sand. This method mostly has been implemented by professional contractors.



Repair Method: Geosynthetics

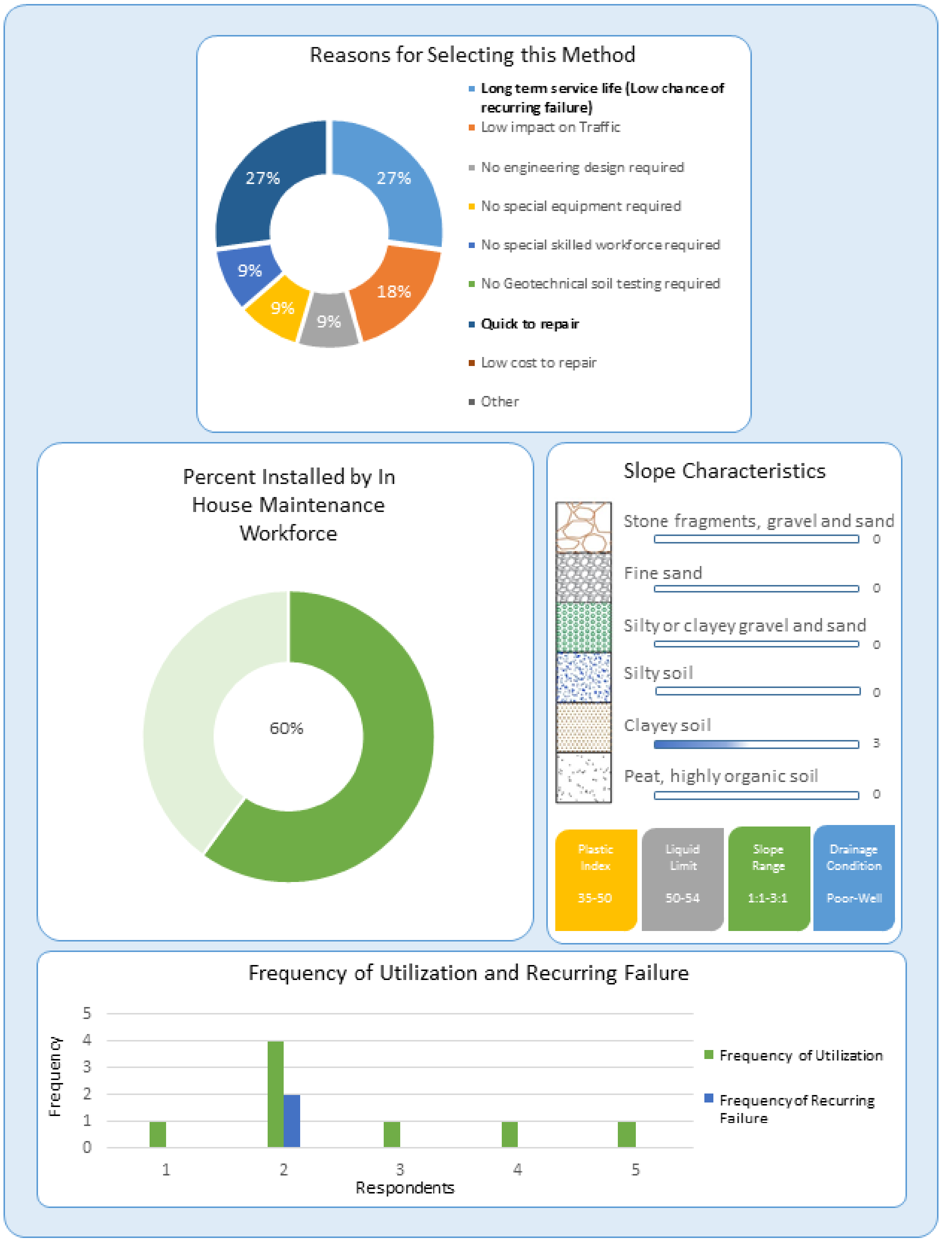
Figure 4-4. Summary of survey results for geosynthetic method (Shahandashti et al. 2019)

4.4. Launched Soil Nails

Figure 4-5 illustrates the information achieved from survey responses for launched soil nails method. This method has been used by five of our respondents and only one of them has recurring failure experience for a slope repaired using this method. These are the main reasons for adopting this method by respondents:

- It has long-term service life.
- It is a rapid slope repair method.

Respondents used this method in slopes with clayey soil, different drainage condition and where the slope angle is less than 1:1 (H:V). Repair of slopes using launched soil nails method has been done both by in house maintenance crews and contractors.



Repair Method: Launched Soil Nail

Figure 4-5. Summary of survey results for launched soil nail method (Shahandashti et al. 2019)

4.5. Retaining Structures

Figure 4-6 illustrates the information achieved from survey responses for retaining structures method. This method is one of the most popular slope repair methods in Texas. Nineteen respondents used this method for repair of slopes. Results illustrate that five respondents have experience of recurring failure for slopes repaired by retaining structure. Nevertheless, long-term service life is the main reason for the selection of this method by professionals. One of the limitations of slope repairs using retaining structures is the requirement for a proper engineering design. Respondents used this method in slopes with different drainage condition and where the slope angle is less than 1:1 (H:V). Retaining structures has been used for slopes with clayey soil, highly organic soil, and silty or clayey gravel and sand. This method mostly has been implemented by professional contractors.

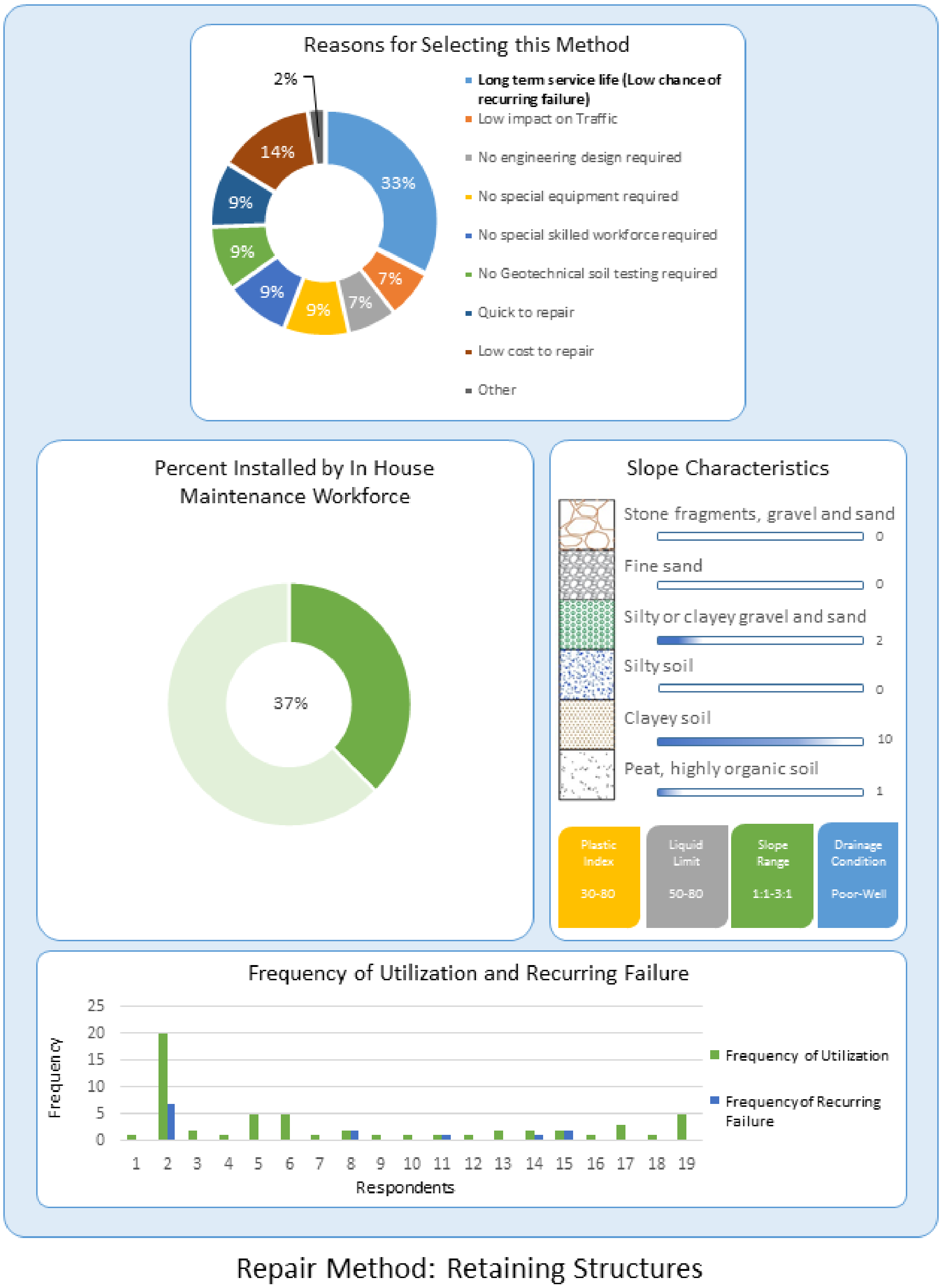


Figure 4-6. Summary of survey results for retaining structure method (Shahandashti et al. 2019)

4.6. Recycled Plastic Pins

Figure 4-7 illustrates the information achieved from survey responses for recycled plastic pins method. One of the three respondents, which have used this method for repairing slopes in Texas, has experience of recurring failure. The key reason for selecting this method is rapidity. Respondents also selected this method because it is cost- effective, have Long-term performance, and does not interrupt traffic a lot. To use RPPs for repairing slope failures, an engineering design is required. Respondents used this method in slopes with poor drainage condition and where the slope angle is less than 2:1 (H:V). Recycled plastic pins has been used for repairing slopes with various soil types including clayey soils and silty soils. This method mostly has been implemented by professional contractors and requires specialty equipment.

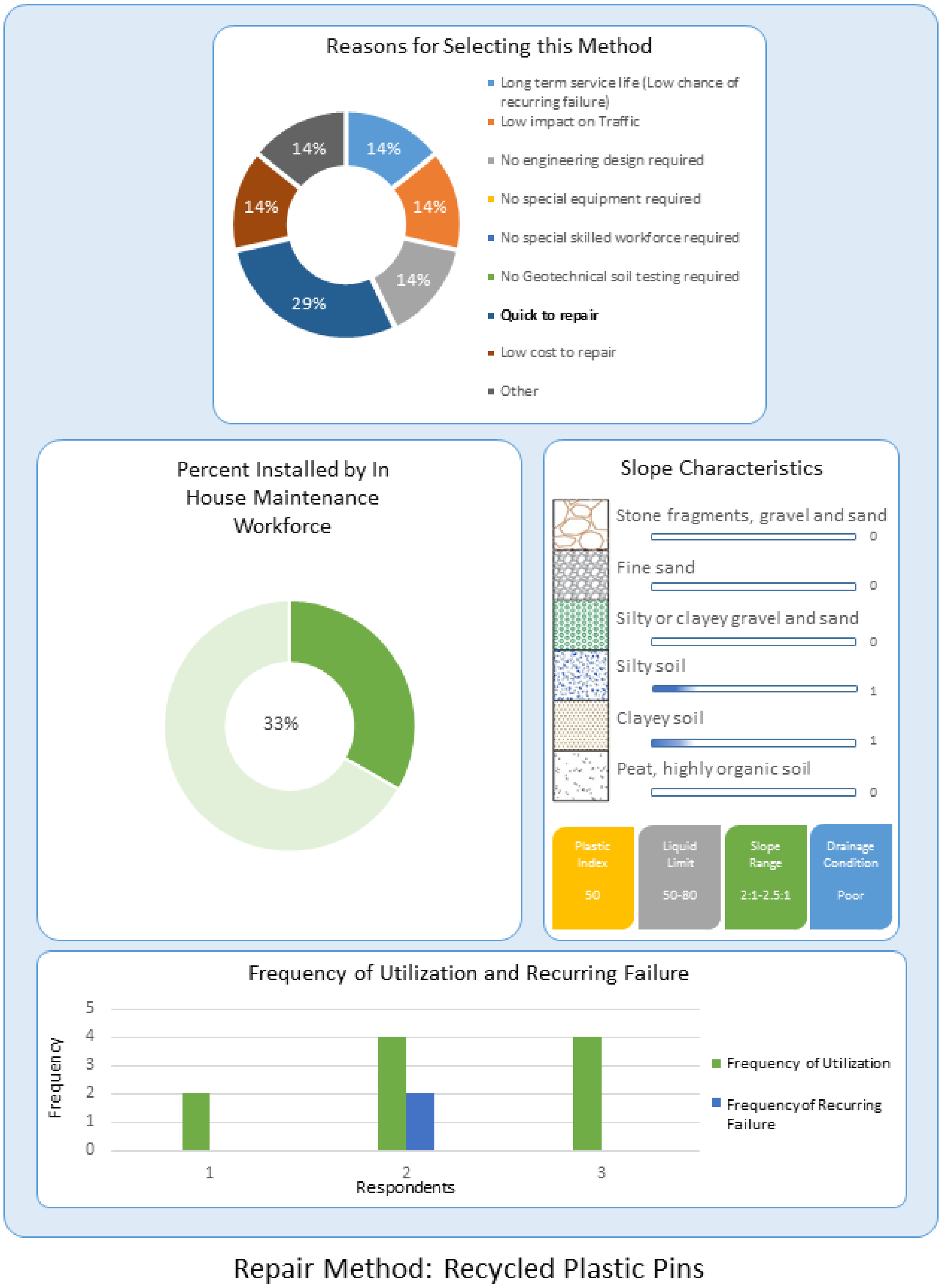


Figure 4-7. Summary of survey results for the recycled plastic pin method (Shahandashti et al. 2019)

4.7. Ground Anchors

Figure 4-8 illustrates the information achieved from survey responses for ground anchors method. One of the five respondents, which have used this method for repairing slopes in Texas, has experience of recurring failure. These are the main reasons for adopting this method by respondents:

- It has long-term service life.
- It has low impact on traffic.

Ground anchors have been used to repair steep slopes and even vertical walls. Respondents used this method in slopes with various soil types (such as clayey soil, fine sand, silty soil, and silty or clayey gravel and sand) with poor drainage condition. Repair of slopes using ground anchors method mostly has been done by professional contractors.

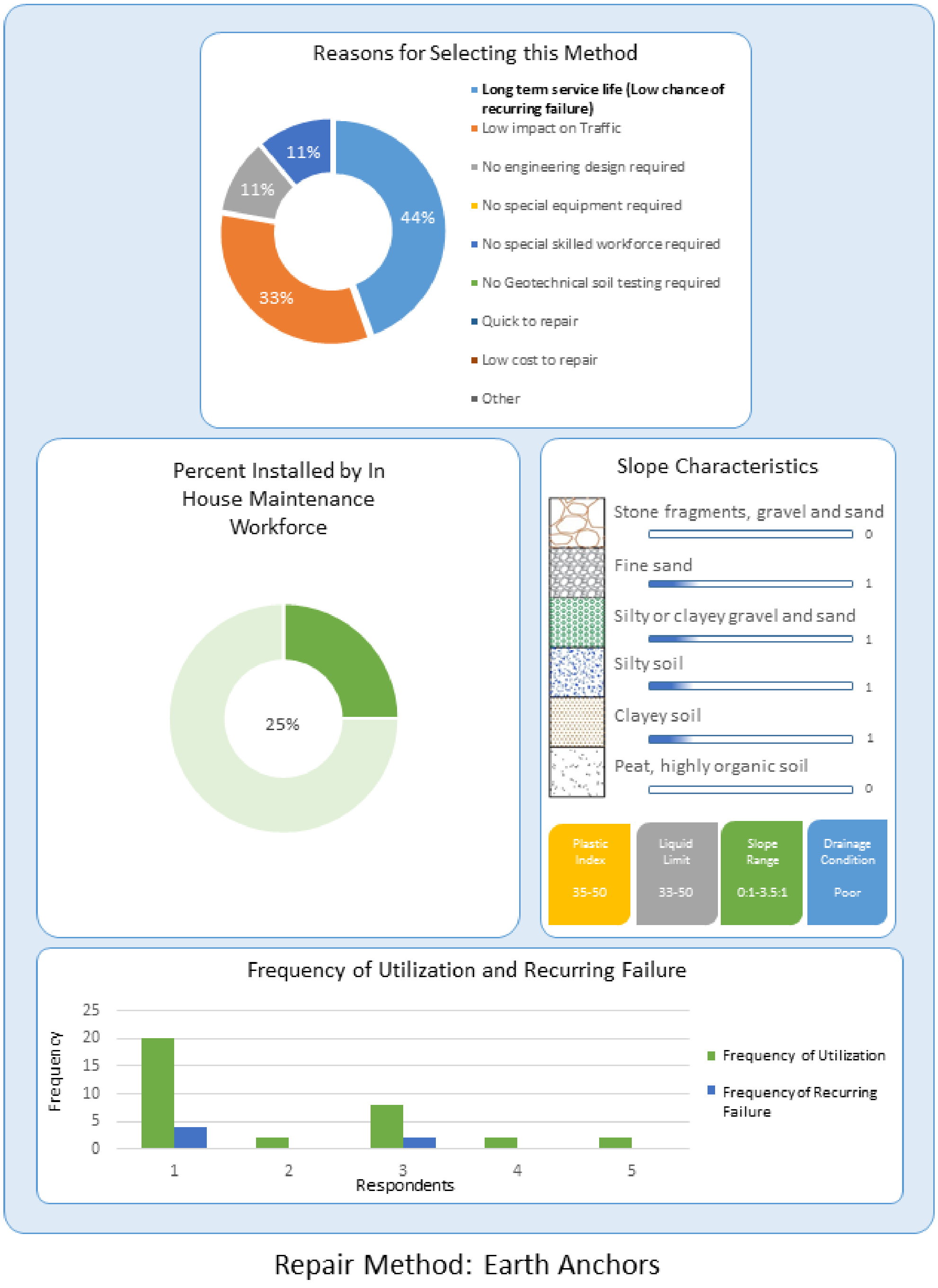


Figure 4-8. Summary of survey results for ground anchor method (Shahandashti et al. 2019)

4.8. Piles

Figure 4-9 illustrates the information achieved from survey responses for pile method. Three of the five respondents, which have used this method for repairing slopes in Texas, have experience of recurring failure. The main reason for selection of this method by respondents is having long-term service life. Respondents used this method in slopes with different drainage condition and where the slope angle is less than 3:1 (H:V). Piles has been used for repairing slopes with clayey and silty soils. This method has been implemented by in house maintenance workforce.

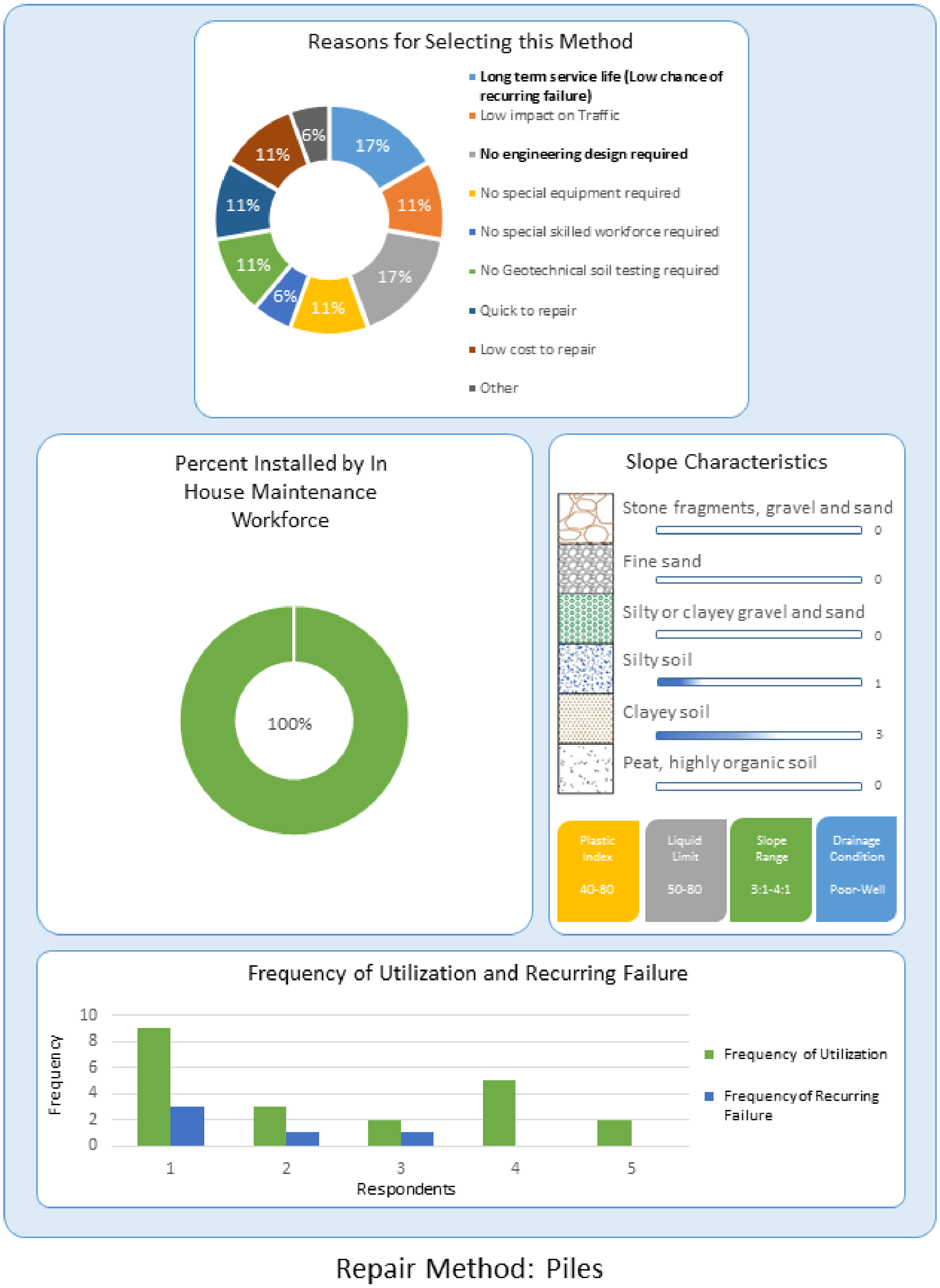


Figure 4-9. Summary of survey results for pile method (Shahandashti et al. 2019)

4.9. Sheet Piles

Figure 4-10 illustrates the information achieved from survey responses for sheet piles method. Repairing slopes using this method is also popular in Texas and ten Respondents had experience of using this method. Six of these respondents selected this method because of its long-term service life, but still there are cases of recurring failure of slopes repaired using this method. They also stated that this method is rapid, cost effective and has low impact on traffic. Respondents used this method in slopes with different drainage condition and where the slope angle is less than 2:1 (H:V). Sheet piles has been used for repairing slopes with clayey soils and fine sand. This method has been implemented mostly by professional contractors.

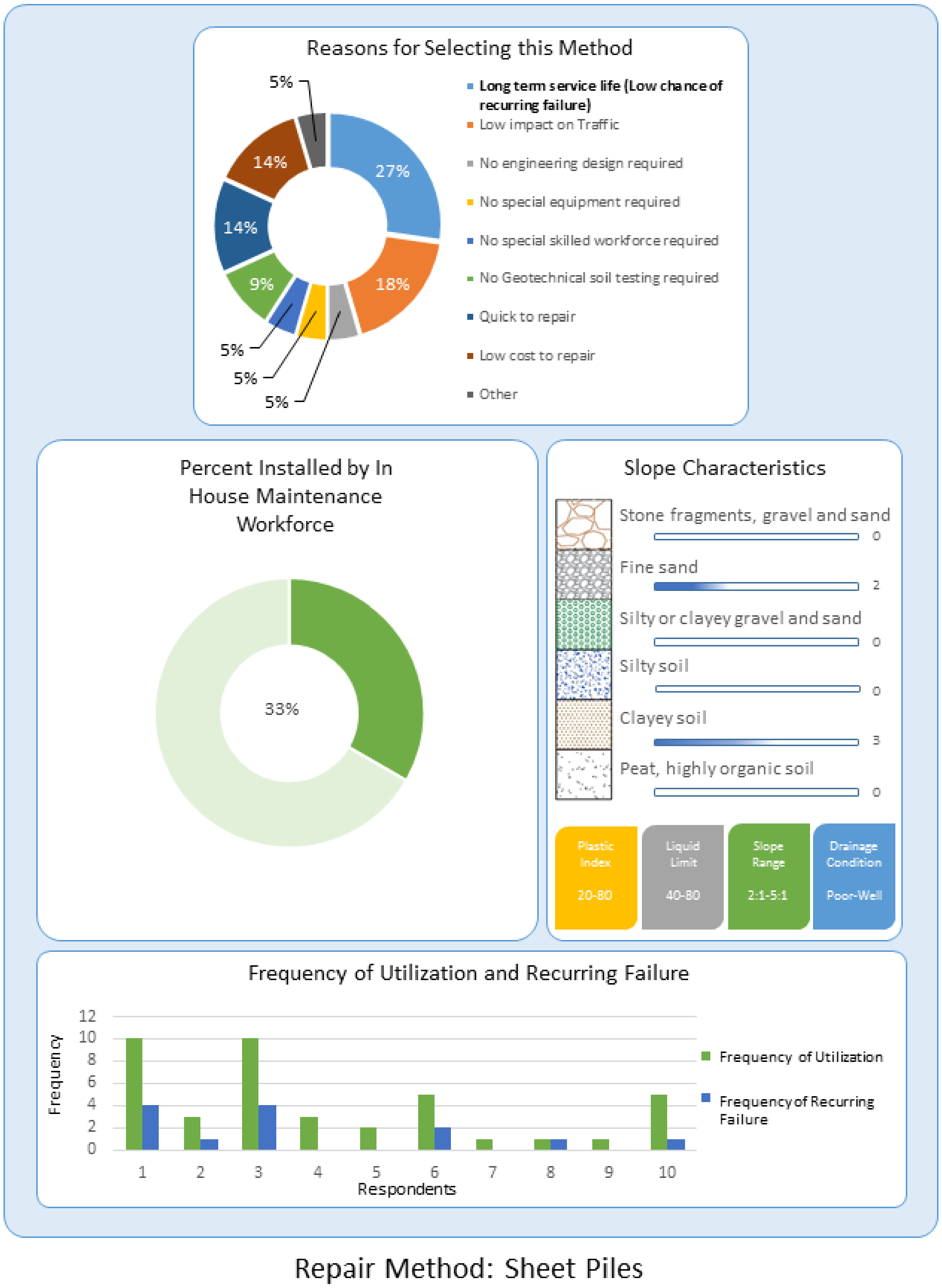


Figure 4-10. Summary of survey results for sheet pile method (Shahandashti et al. 2019)

4.10. Soldier Piles and Lagging

Figure 4-11 illustrates the information achieved from survey responses for soldier piles and lagging method. Only one of our 33 respondents used this method for repairing slopes. This respondent used this method four times successfully without any recurring failure. These are the main reasons for adopting this method by this respondent:

- It is a rapid method.
- It has long-term service life.
- It does not need any skilled workforce.

Results also show that professional contractors performed slope repair projects using soldier piles and lagging.

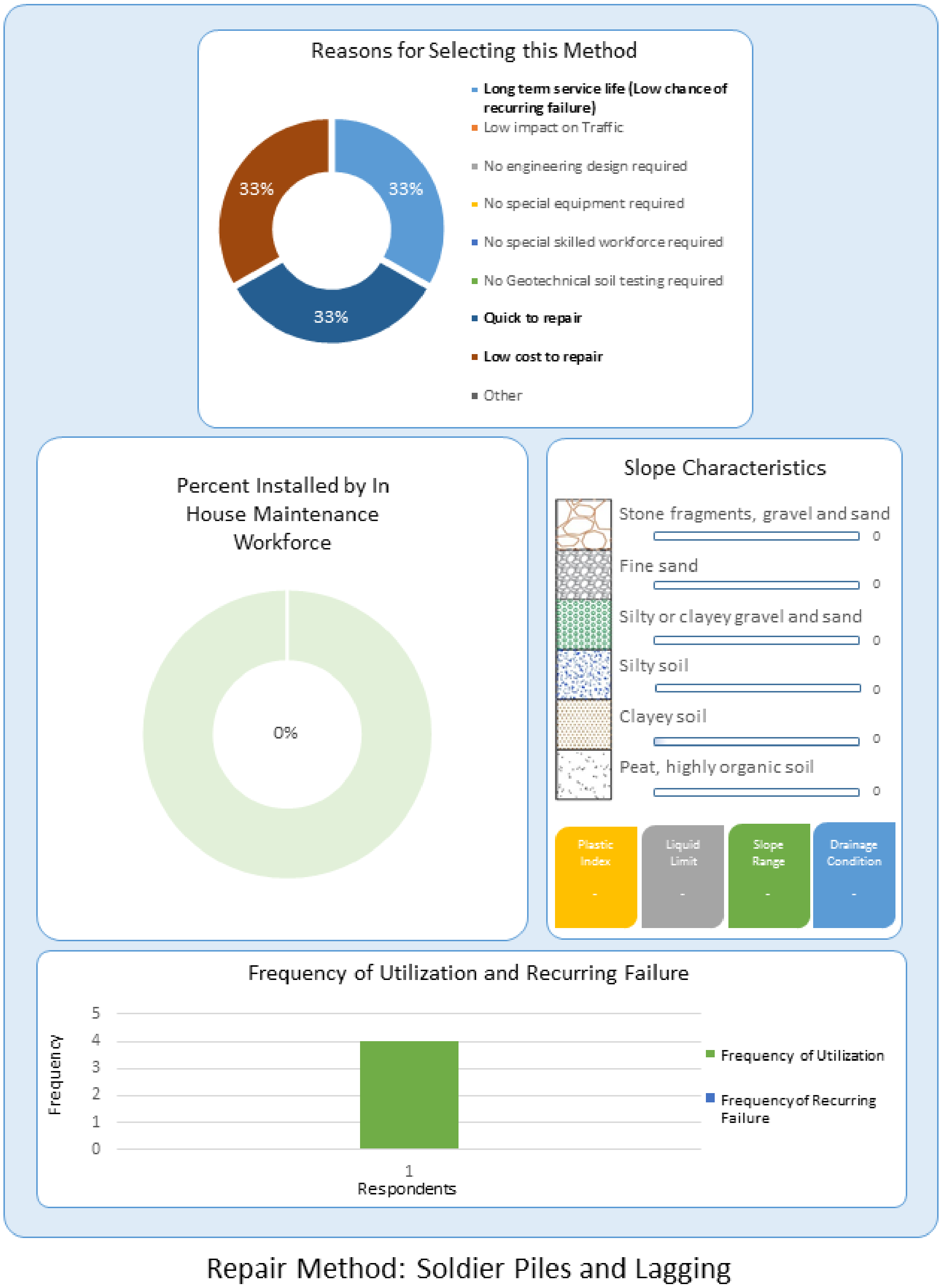


Figure 4-11. Summary of survey results for soldier pile and lagging method (Shahandashti et al. 2019)

4.11. Gabions

Figure 4-12 illustrates the information achieved from survey responses for gabions method. This method also is one of the most popular slope repair methods used in Texas, and fifteen respondents had experience of using that. Results shows that recurring failure happened in only a few cases for slopes repaired using this method. These are the main reasons for adopting this method by the respondents:

- It has long-term service life.
- It is a rapid method.
- It does not need any skilled workforce.
- It is an appropriate method for repairing slopes near streams

Gabions have been used to repair steep slopes and even vertical walls. Respondents used this method in slopes with various soil types (such as clayey soil, fine sand, and silty soil) with different drainage condition. Repair of slopes using gabions method mostly has been done by professional contractors.

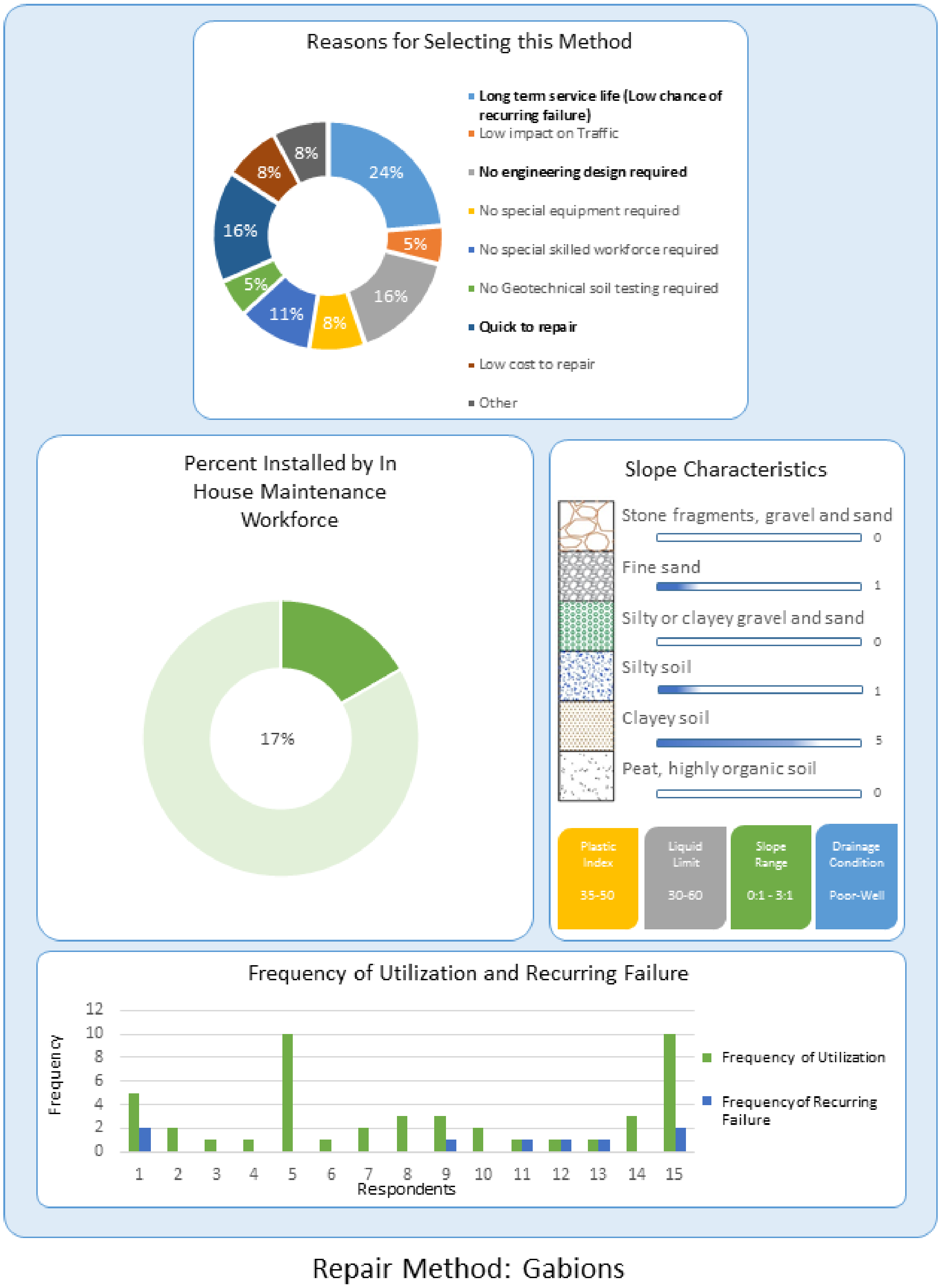


Figure 4-12. Summary of survey results for gabion method (Shahandashti et al. 2019)

4.12. Rebuilding and Compaction

Figure 4-13 illustrates the information achieved from survey responses for rebuilding and compaction method. Rebuilding and compaction is the most popular slope repair method used in Texas, and 31 of our 33 (94 percent) respondents had experience of using that. They believed this method is one of the most economical slope repair methods. The other key reason for selecting this method is the fact that it does not need any skilled workforce. Results also shows that about 80 percent of the respondents, which used this method, had experience of recurring failure after this method was used to repair slopes. Respondents used this method in slopes with different drainage condition and where the slope angle is less than 2:1 (H:V). Rebuilding and compaction has been used for repairing slopes with various soil types, including stone fragments, gravel and sand, clayey soil, silty soil, and silty or clayey gravel and sand. This method has been implemented mostly by in house maintenance workforce, and only 10 percent of slope repair projects using this method has been outsourced.

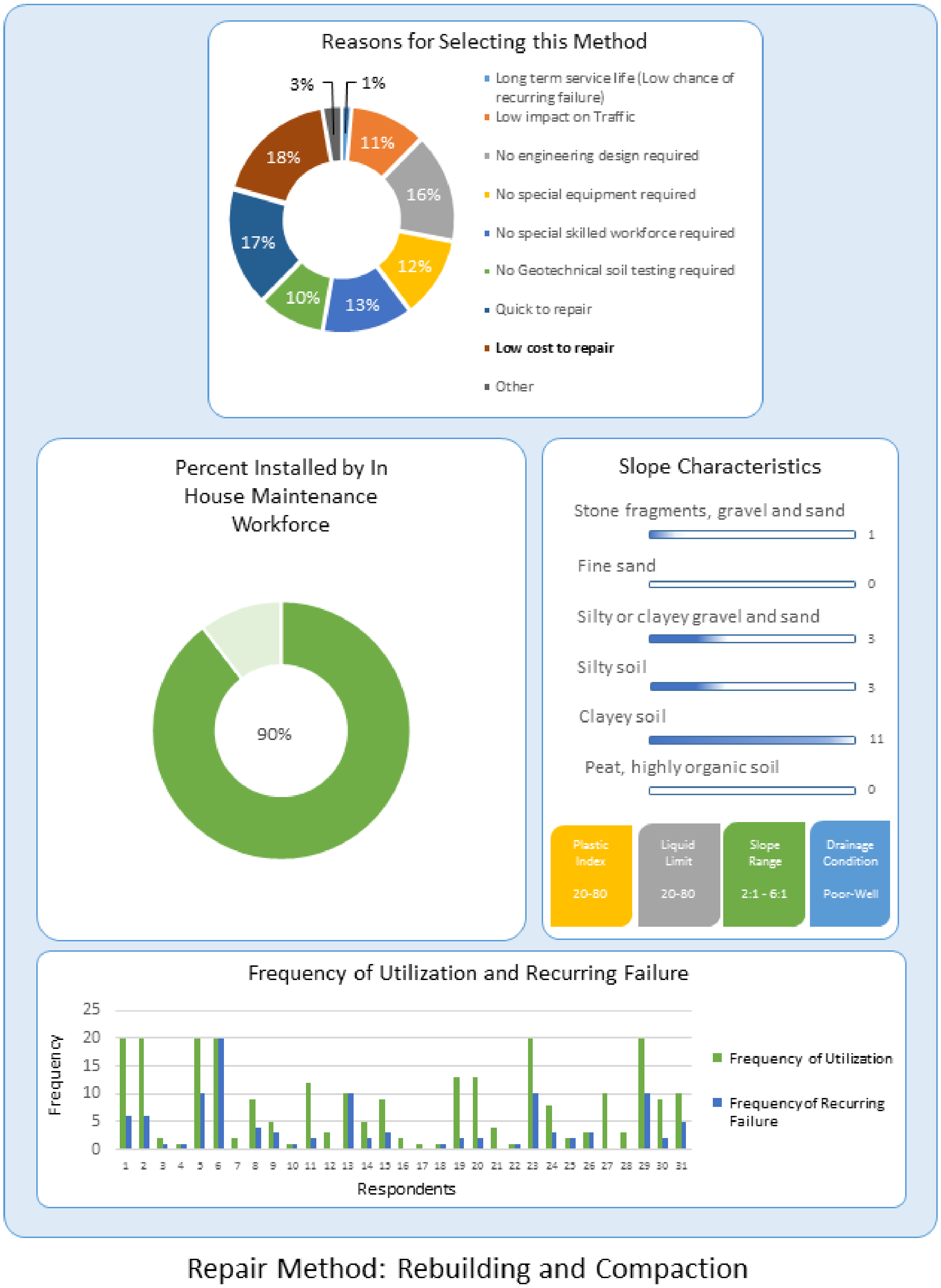


Figure 4-13. Summary of survey results for the rebuilding and compaction method (Shahandashti et al. 2019)

4.13. Benching and Stepping

Figure 4-14 illustrates the information achieved from survey responses for benching and stepping method. Two of the four respondents, which have used this method for repairing slopes in Texas, has experience of recurring failure. These are the main reasons for adopting this method by respondents:

- It is a rapid slope repair method.
- It is a low-cost repair method.

They used this method in slopes with high plasticity clayey soil, and where the slope angle is less than 2.5:1 (H:V). Repair of slopes using benching and stepping method has been done mostly by professional contractors.

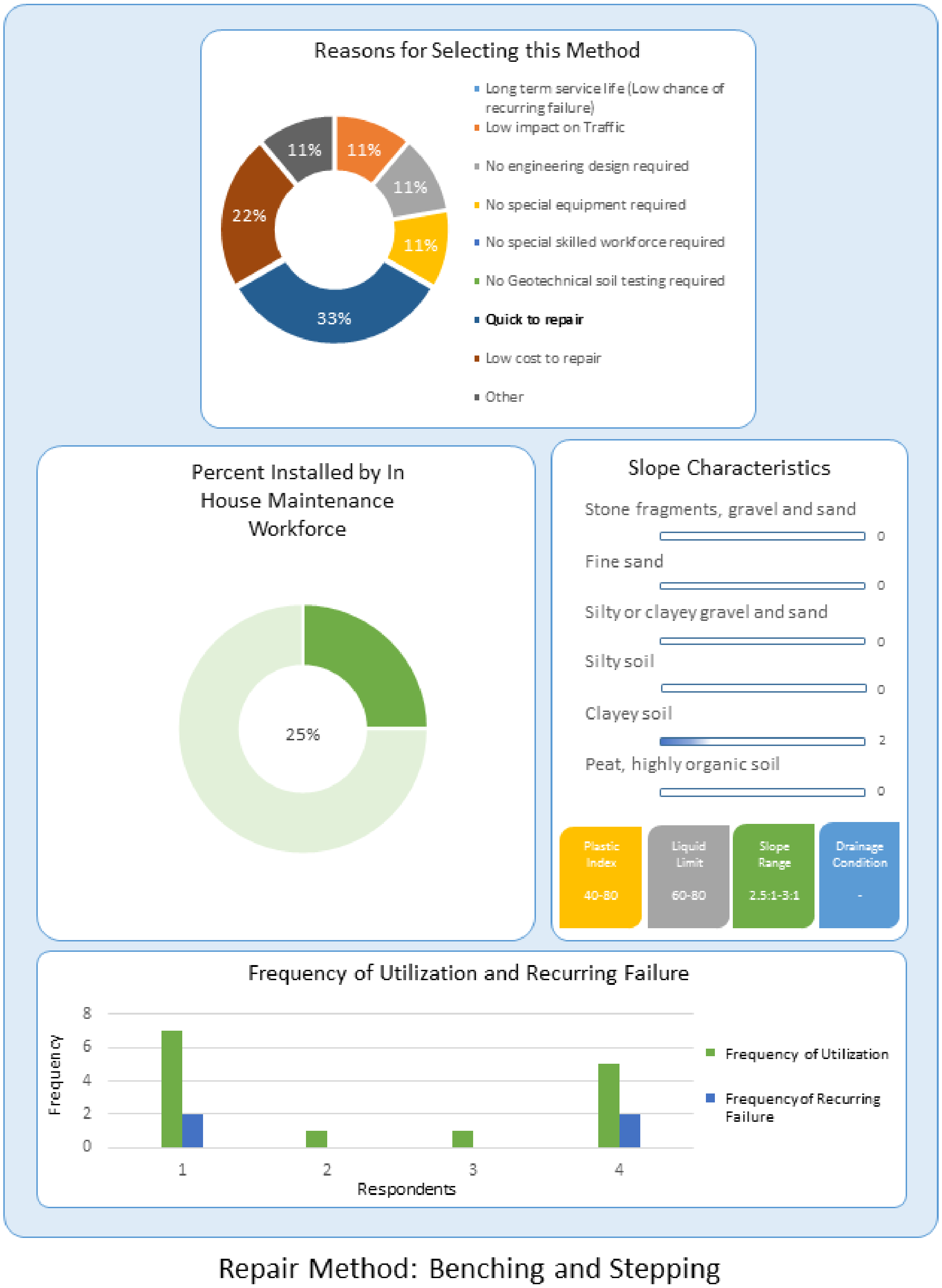


Figure 4-14. Summary of survey results for the benching and stepping method (Shahandashti et al. 2019)

4.14. Slope Flattening

Figure 4-15 illustrates the information achieved from survey responses for slope flattening method. Four of the ten respondents, which have used this method for repairing slopes in Texas, have experience of recurring failure. Being quick to repair is the main reason for selection of this method by respondents. They also selected this method because it does not need geotechnical soil testing and it is a low-cost repair method. Survey respondents also stated that this method could be a part of other slope repair methods. Respondents used this method in slopes with different drainage condition and where the slope angle is less than 2.5:1 (H:V). Slope flattening has been used for repairing slopes with various soil types including fine sand, silty soil, and clayey soil. This method has been implemented mostly by in house maintenance workforce.

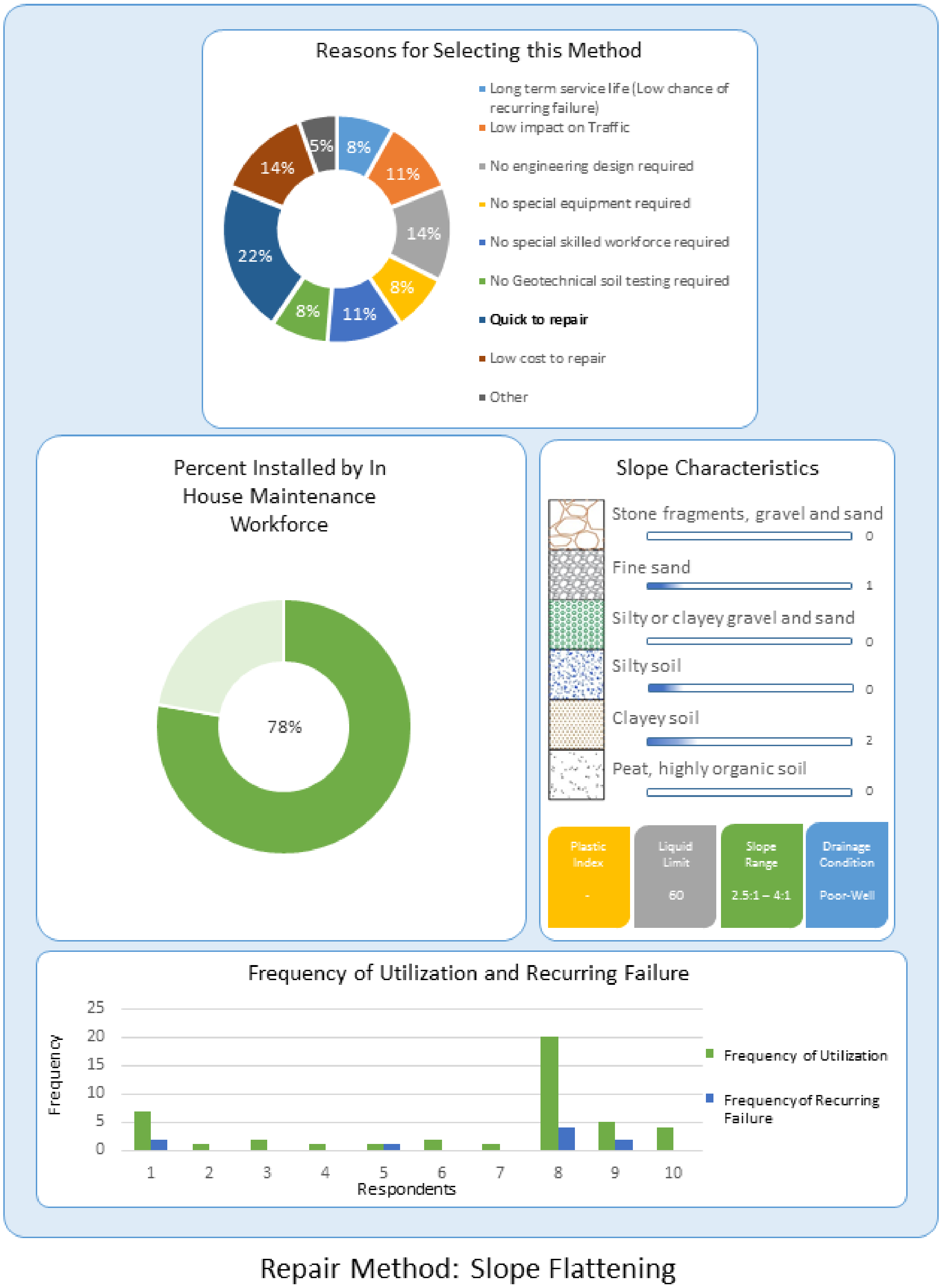


Figure 4-15. Summary of survey results for the slope flattening method (Shahandashti et al. 2019)

4.15. Soil Substitution

Figure 4-16 illustrates the information achieved from survey responses for soil substitution method. Five of the eleven respondents, which have used this method for repairing slopes in Texas, have experience of recurring failure. Like other earthwork methods, being quick to repair is the main reason for selection of this method by respondents. The other reasons for selection of this method by respondents were Long-term performance, low impact on traffic, and no specialized equipment or engineering design requirements. Respondents used this method in slopes with different drainage condition and where the slope angle is less than 2:1 (H:V). Soil substitution has been used for repairing slopes with clayey and silty soils. This method has been implemented mostly by professional contractors. Repair of slopes using soil substitution method has been done both by in house maintenance crews and contractors.

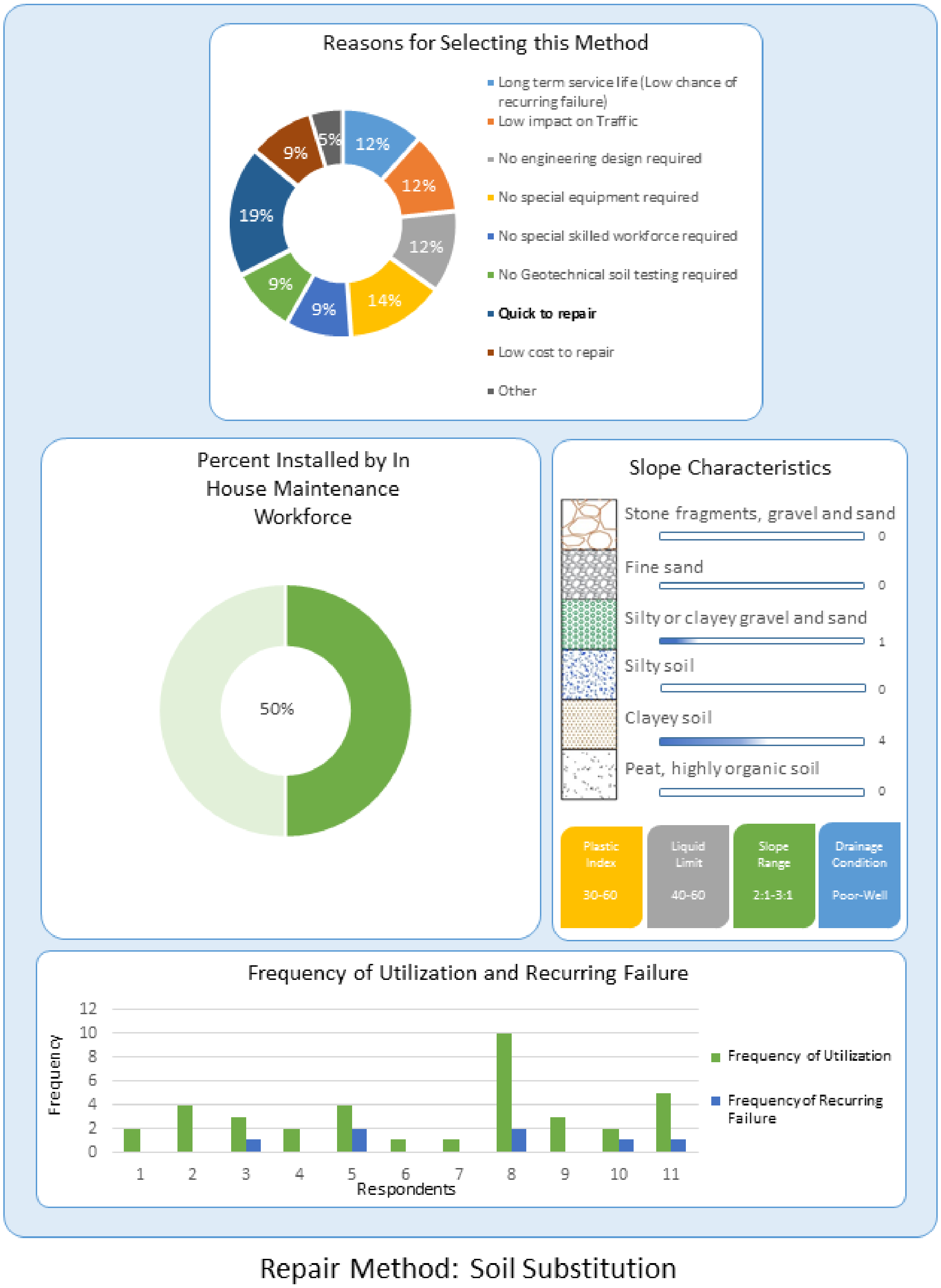


Figure 4-16. Summary of survey results for the soil substitution method (Shahandashti et al. 2019)

4.16. Buttressing

Figure 4-17 illustrates the information achieved from survey responses for buttressing method. This method is not very popular in Texas and only had been used by two respondents. One of these respondents had failure experience for a slope repaired using this method. These are the main reasons for adopting this method by respondents:

- It has long-term service life.
- It does not need any special equipment.
- It does not require geotechnical soil testing.
- It is a low-cost repair method.

They used this method in slopes with good drainage condition and where the slope angle is less than 1:1 (H:V). This method has been used in silty or clayey gravel and sand and silty soils. Repair of slopes using buttressing method has been done both by in house maintenance crews and contractors.

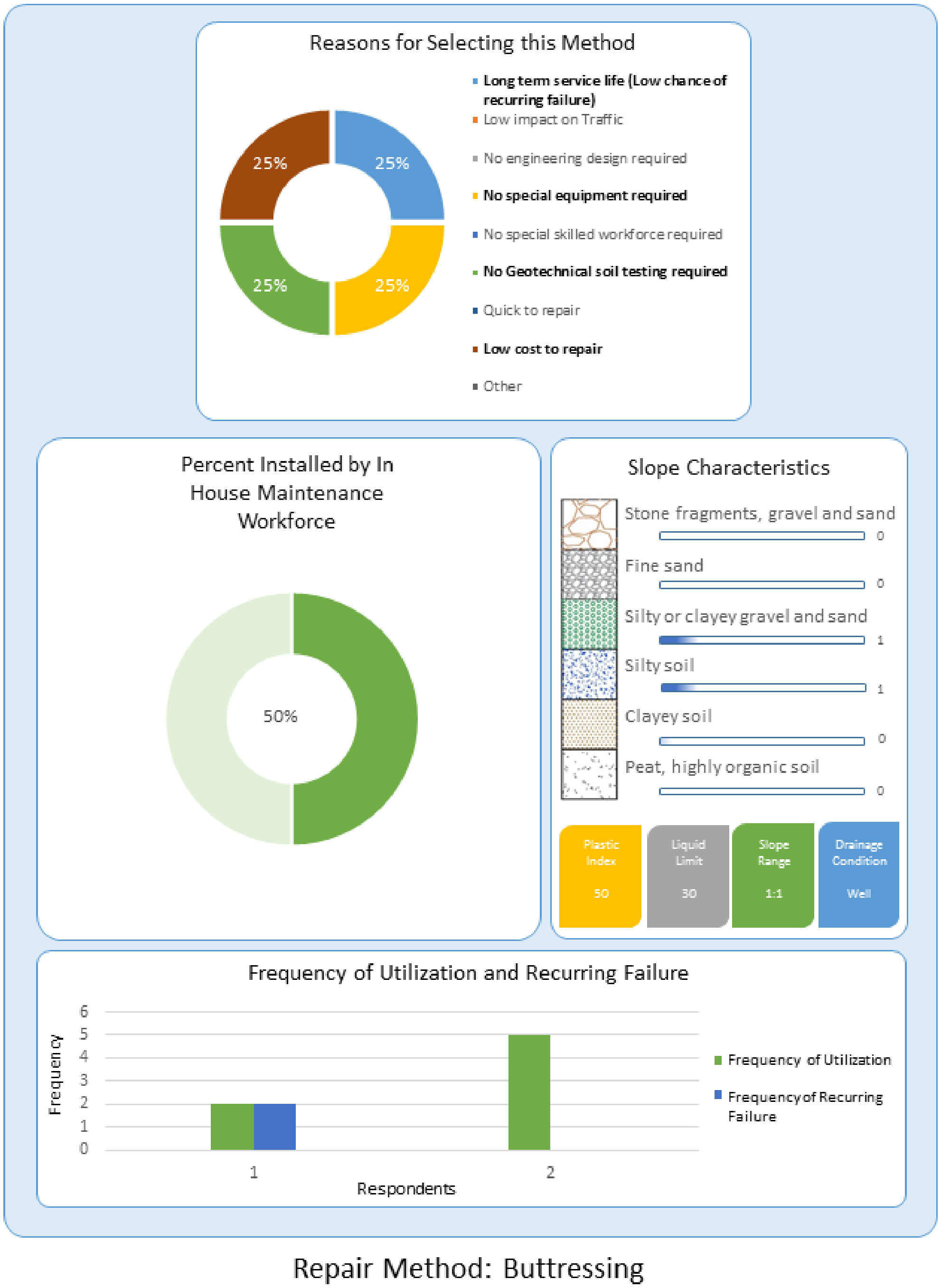


Figure 4-17. Summary of survey results for the buttressing method (Shahandashti et al. 2019)

4.17. Biotechnical Methods

Figure 4-18 illustrates the information achieved from survey responses for biotechnical method. This method only had been used by two respondents, and one of these respondents had failure experience for a slope repaired using this method. These are the main reasons for adopting this method by respondents:

- It has long-term service life.
- It does not need any special equipment.
- It does not need skilled workforce.
- It does not need engineering design.
- It does not require geotechnical soil testing.
- It is a low-cost repair method.

They used this method in slopes with good drainage condition and clayey soils. Repair of slopes using biotechnical method has been done both by in house maintenance crews and contractors.

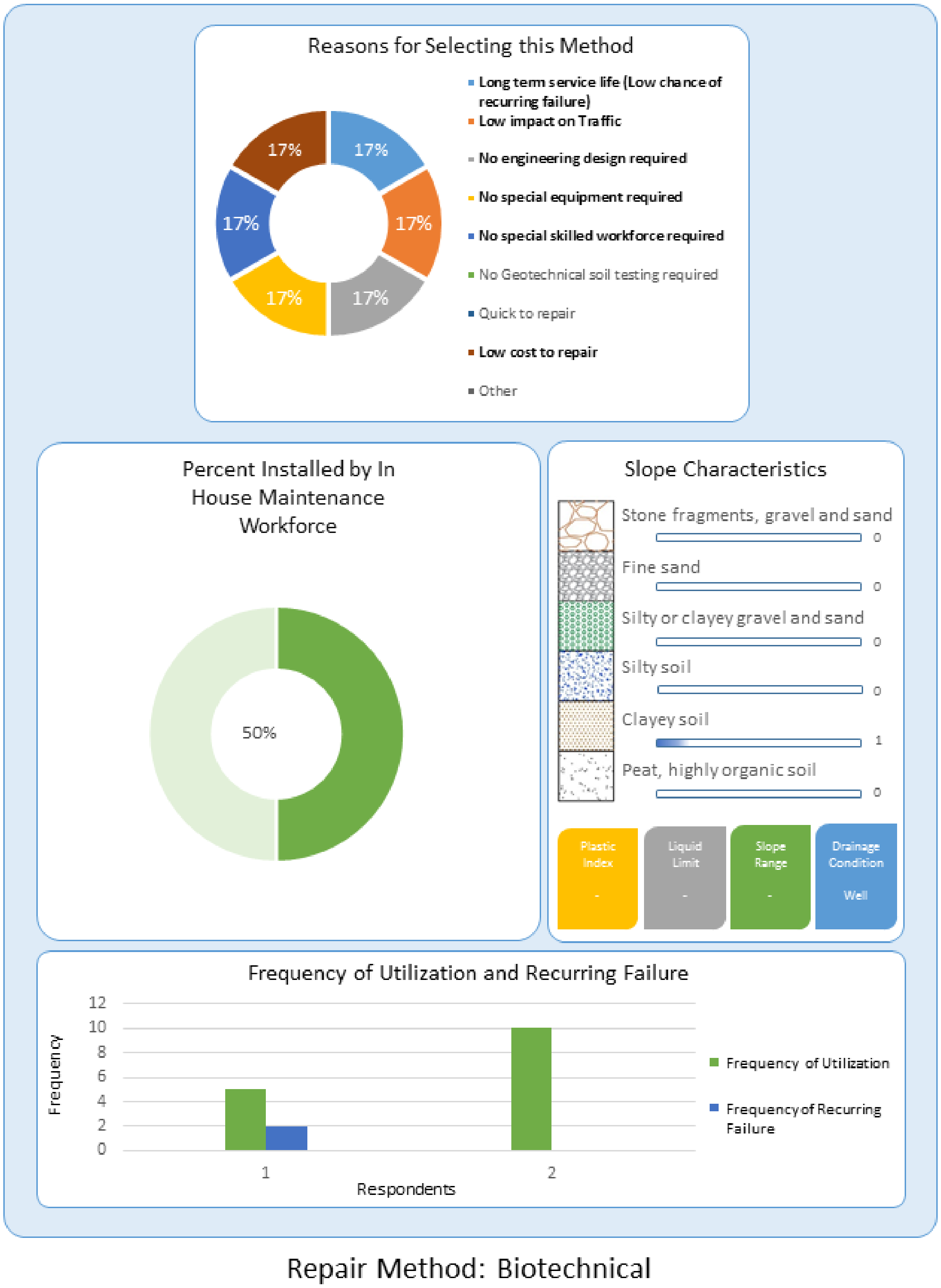


Figure 4-18. Summary of survey results for the biotechnical method (Shahandashti et al. 2019)

4.18. Chemical Method (Additives)

Figure 4-19 illustrates the information achieved from survey responses for chemical (additive) method. Three of the five respondents, which have used this method for repairing slopes in Texas, have experience of recurring failure. Stabilizing slopes by adding cements and lime are more popular than using fly ash. No special equipment requirement is the main reason for selection of this method by respondents. The other key reasons for selection of this method by respondents were low cost of repair and no requirement for engineering design. They used this method in slopes with good drainage condition and where the slope angle is less than 1:1 (H:V). This method has been used in slopes with stone fragments, gravel and sandy soils, as well as clayey soils. Repair of slopes using additives method has been done both by in house maintenance crews and contractors.

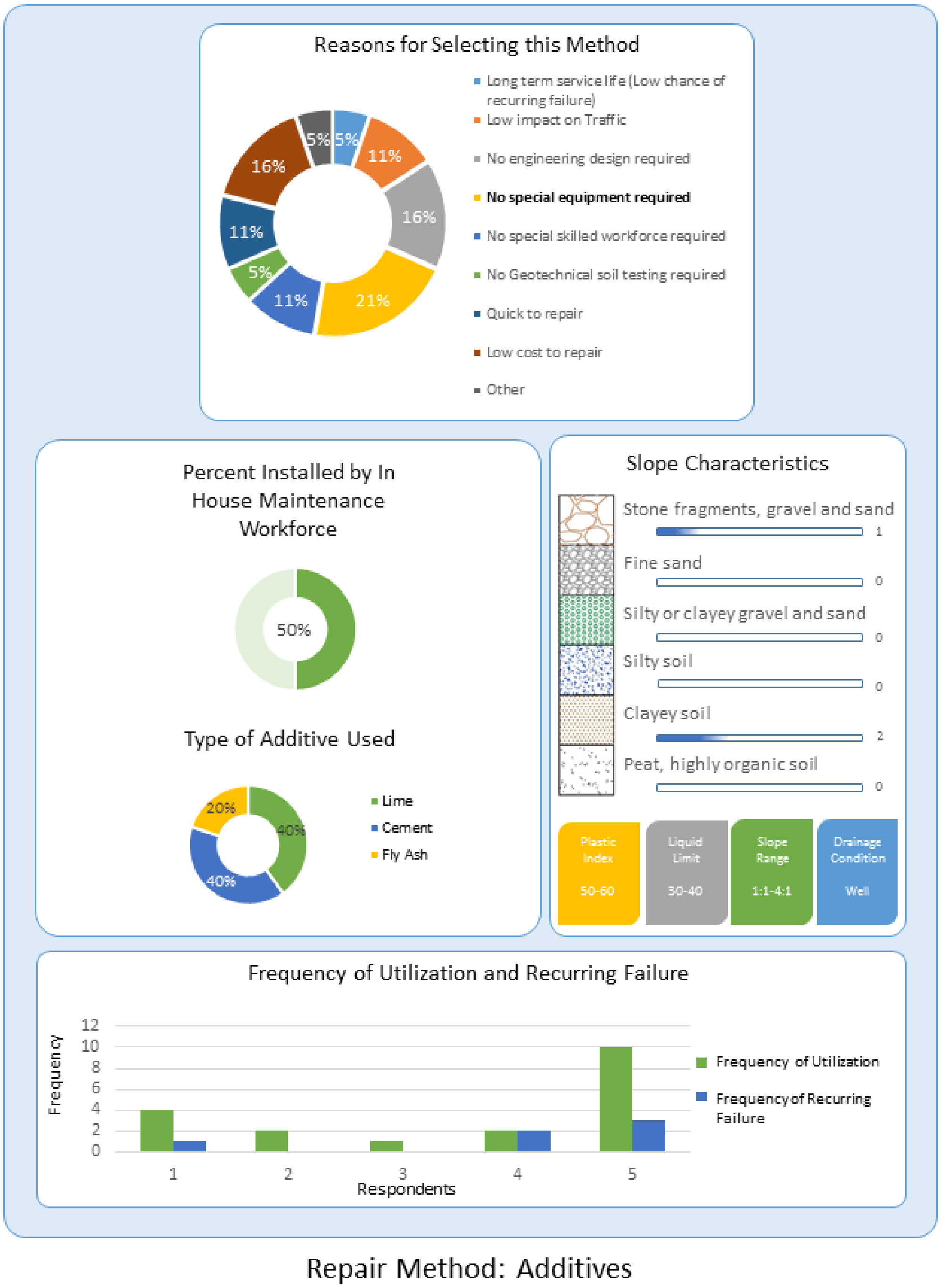


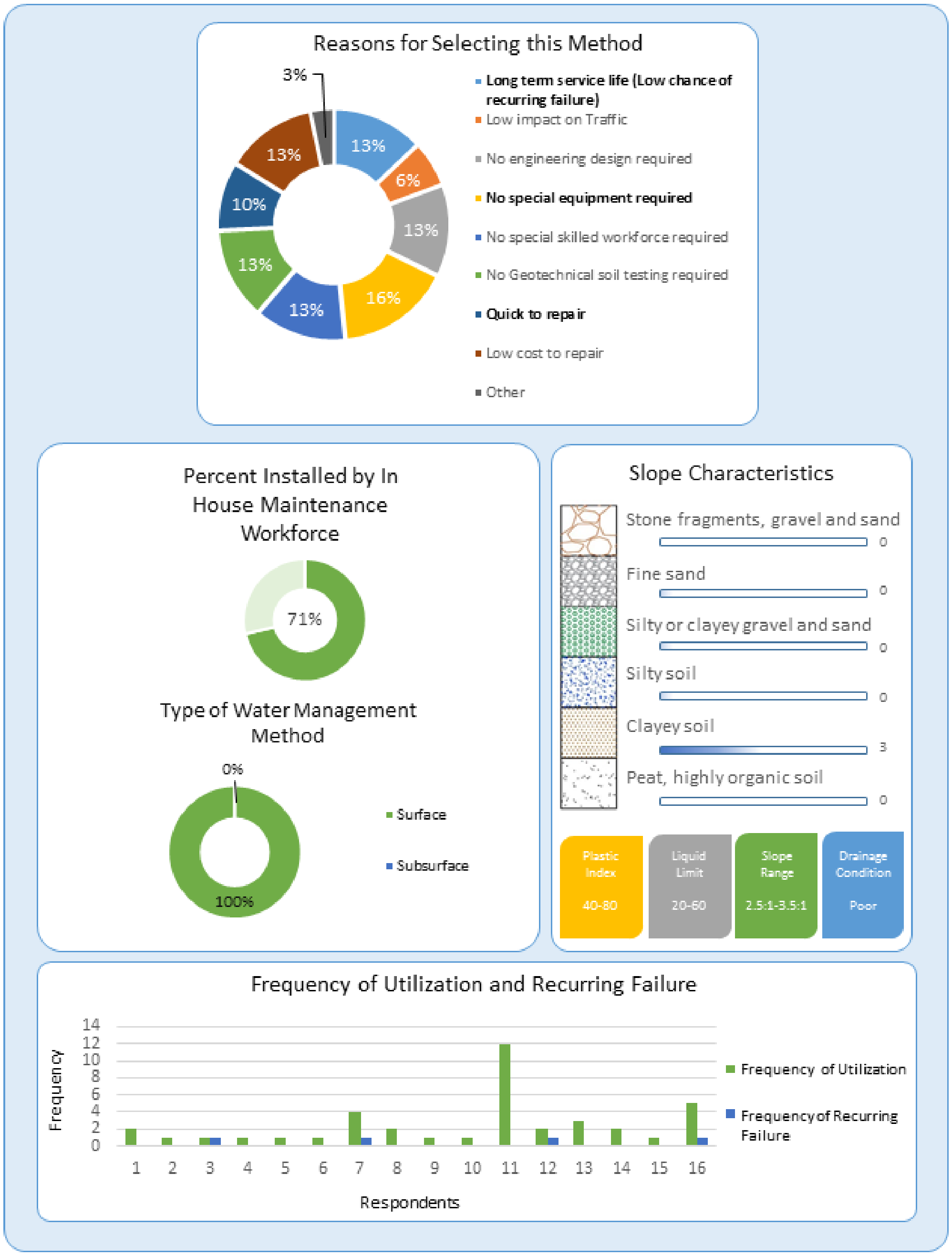
Figure 4-19. Summary of survey results for the chemical method (Shahandashti et al. 2019)

4.19. Water Management Methods

Figure 4-20 illustrates the information achieved from survey responses for water management methods. All sixteen respondents which have used this method, used surface water drainage for repairing slopes, and four of them reported recurring failure for some slopes repaired using this method. These are the main reasons for adopting this method by respondents:

- It is a low-cost repair method.
- It has long-term service life.
- It is a rapid slope repair method.

The respondents used this method in slopes with poor drainage condition and where the slope angle is less than 2.5:1 (H:V). This method only has been used in slopes with clayey soils, as well as clayey soils. Repair of slopes using water management methods have been done mostly by in house maintenance workforce.



Repair Method: Water Management

Figure 4-20. Summary of survey results for water management method (Shahandashti et al. 2019)

Chapter 5

Results

All the data collected from reviewing the existing literature, survey, and interviewing subject matter experts were synthesized to evaluate the identified embankment slope repair methods and recognize recommendations for their successful implementation. Table 5-1 to 5-5 present the recommended practices to avoid recurring failures or at least reduce the number of recurring failures.

Table 5-1. Recommendation for Successful Implementation of mechanical slope repair methods (Shahandashti et al. 2019)

Repair and Stabilization Methods	***Type of Slope Failure***	***Recommendation for Successful Implementation***
Tire Bales	Deep	Use subsurface drainage (pipe drainage system) to drain the water from tire bales and slope. Use surface drainage (a combination of a curb, flume, and riprap) to prevent water from entering the slope. Geogrids could be laid in the soil under tire bails. Temporary soil nail walls could be used behind tire bales.
Geosynthetics	Shallow to deep	These methods are very technical in terms of design and installation. Thus, professional designers and construction companies are recommended for these projects. Installation of geotextiles should take place from the top of the slope downwards. Use surface drainage (a combination of a curb, flume, and riprap) to prevent water from entering the slope. It is necessary to overlap the new geogrids with the already existing ones to avoid future failure. Use vegetation after rebuilding the slope and take good care of that until the vegetation is fully established. It is essential to install geogrids horizontally into the slope. Cut the failed slope beyond the failure surface. Remove the damaged geogrids and replace with new ones. Careful installation (not to damage the material and follow the correct procedure) of geogrids is important. Inspection during installation is recommended.
Launched Soil Nails	Shallow to deep	Use of proper subsurface drainage is recommended. Use of material that is not vulnerable to sulfurs. It is not recommended to be used in acidic soils containing sulfur. It could be used for temporary retaining of soil in construction projects (shoring).

Retaining Structures	Shallow to deep	It is recommended to follow a well engineering procedure including engineering observation of the failed slope, geotechnical soil testing, surveying, and engineering design. For MSE walls it is recommended to: • Increase the embedment height at the toe of the wall from 1 foot to at least 2 feet. • Flatten the slope behind the wall from 3:1 to at least 4:1. Use surface and subsurface drainage systems.
Recycled Plastic Pins	Shallow	In case of stiff soils: • Pre-drill a smaller diameter hole compared to RPPs, and then insert the pins, or • Derive steel nails first and follow with inserting RPPs
Sheet Piles	Shallow to deep	Sheet piles are one of the best solutions for retaining road or railroad embankments in location with many flat swamp areas Design sheet piles properly; select a right cross-section (e.g., Z or PZ shape) Use surface and subsurface drainage systems to reduce the driving forces on the sheet piles Sheet piles are able to absorb the vibration from the road or railroad (and do not break!)
Gabions	Shallow to deep	Careful construction procedure is necessary for their long-term performance. Gabion cages should be tied together tightly and fixed to the ground. Using roadside curbs or ditches will help to divert excess water from entering the repaired slope area. For the use of Gabions around bridge abutments, it is recommended to extend the length of thrie beam curb beyond the bridge abutment for least 10 to 15 feet. Beyond this length, filters and protection with gabion or riprap should be installed. This length should be enough to protect bridge piers and abutment from the stream. This practice lowers the chance of gabion or riprap failure. It is recommended to excavate a gabion's intended location deeper to install gabions on a deeper level. Temporary maintenance, such as repairing the gabion mesh or replacing damaged segments is recommended. Gabions are easy to maintain. The damaged parts can be detached and replaced with new ones while the undamaged ones can be remained fixed. Gabions are used for channel linings to slow down the velocity of the water by causing natural turbulence. Gabions are used to naturally control the stream silt load, which cleans the water. Gabions are also utilized as erosion proof for channels.

Table 5-2. Recommendation for Successful Implementation of earthwork slope repair methods (Shahandashti et al. 2019)

Repair and Stabilization Method	***Type of Slope Failure***	***Recommendation for Successful Implementation***
Rebuilding and Compaction	Shallow to deep	The following procedure is recommended to avoid recurring failures: (1) The failed mass should be removed from the area and the skid plane should be broken both vertically and horizontally. (2) The removed soil should get dry before replacing back. (3) The removed soil should be placed back and compacted properly in a stepwise manner. (4) The embankment should be vegetated to assure a long-term performance. Preventing the slope to get saturated using roadside curbs or ditches. These techniques will help divert excess water from entering the slope area
Benching and Stepping	Shallow to deep	It can be combined with gabions to improve stability A drainage system should be installed for each bench to convey runoff to a suitable discharge outlet.
Slope Flattening	Shallow to deep	Use new crushed stone or another appropriate material for substitution, if necessary. Use suitable surface water management systems such as roadside curbs and flumes to divert the water from entering the slope area. Flatten the slope to an angle lower than 4:1.
Soil Substitution	Shallow to deep	The extra cost of hauling may affect the selection of this method. The existence of excessive water is the primary reason for recurring slope failure after soil substitution. Preventing the slope to get saturated using roadside curbs and ditches. These techniques will help divert excess water from entering the slope area. Use this method if appropriate substitution material is available nearby. The general procedure is as follow: over-excavate the failure mass, used benching method or a geotextile layer at the failure envelope and haul back new and better material with lower PI to rebuild the slopes. A 6-inch cover of topsoil and vegetation is also suggested for the success of this method. Along with soil substitution, adding additives (lime and/or cement) is recommended.

Table 5-3. Recommendation for Successful Implementation of vegetation slope repair method (Shahandashti et al. 2019)

Repair and Stabilization Method	***Type of Slope Failure***	***Recommendation for Successful Implementation***
Vegetation	Shallow	It is not suitable for acidic soils where the soil PH is low around 4.5. Add lime to the soil prior to vegetation helps to increase the PH (around 5.5) of the soil and lower the soil acidity. It also helps to stabilize the soil as a cementation agent.
		Sometimes vegetation does not establish or grow because of dry soil and hot weather. Use irrigation at the early stages of vegetation for the growth and establishment of plants. Water the newly planted seeds or plants with water tanks or temporary irrigation systems until full establishment of vegetation cover and root systems. The irrigation system could include PVC pipes, gardening sprinkles connected to watering trucks and pumps.
		Although Yaupon or Pampas grass are two recommended plants for mass vegetation, they are not applicable for every location. It is recommended to use native plants with a good rooting system.
		Mowers should be careful not to damage slope vegetation cover. Revegetation is necessary if mowers damage the vegetation.
		It is recommended to include vegetation in repair contracts.
		Surface water drainage systems including roadside curbs, ditches, and ripraps could be used.

Table 5-4. Recommendation for Successful Implementation of slope repair methods with additives (Shahandashti et al. 2019)

Repair and Stabilization Method	***Type of Slope Failure***	***Recommendation for Successful Implementation***
Lime	Shallow to deep	Adding lime to the soil prior to vegetation helps to increase the PH (around 5.5) of the soil and lower the soil acidity. It also helps to stabilize the soil as a cementation agent. Surface water management is essential for the success of this method Stabilization using lime should be avoided under the sun and should never be applied to a frozen soil mass This method should be implemented in 40-degree Fahrenheit temperature or higher. Also, the water content should be 1 to 3 percent more than the optimum to make sure the clay reaction is complete Mix well an adequate amount of lime with soil to reach a homogeneous mixture Multiple-phase lime and cement treatments could be used as an innovative approach to take advantage of the benefits of both additives.
Cement	Shallow	The recommended repair procedure of shallow slope failures using soil-cement consists of the complete removal of the failed soil mass, benching the sublayer, placing the soil-cement mixture, and compaction to at least 90% of the Modified Proctor maximum unit weight Mixing cement with the soil mass and placing back the mixture into the slope should take place in one day. Surface water management, adequate depth of treatment, and homogeneous soil and cement mixture are essential for the success of this method Multiple-phase lime and cement treatments could be used as an innovative approach to take advantage of the benefits of both additives.

Table 5-5. Recommendation for Successful Implementation of water management slope repair methods (Shahandashti et al. 2019)

Repair and Stabilization Method	***Type of Slope Failure***	***Recommendation for Successful Implementation***
Surface Water Management	Shallow to deep	Collect and divert water on top of the slope using roadside curbs. Use a concrete flume to guide the water from the top of the slope to the bottom of the slope. Use riprap protection at the bottom of the flume to discharge the water far from the slope and highway structures (i.e., do not discharge water close to the slope). Detailed engineering design is essential Damaged roadside edges (or damaged curbs) could create a water pathway along the edge and eventually result in runoff on the slope. Undesired vegetation along the roadside edge could damage edges. Frequent maintenance of roadside edges is necessary.
Subsurface Water Management	Shallow to deep	Detailed engineering design is essential Drainage system for retaining structures is necessary Improper design of subsurface drainage systems. Many design errors reveal themselves during the construction (e.g., wrong location of the pipes considering the site topography). The designers need to consider the topography of the site and design the drainage system accordingly. Drainage system can be designed a little bit higher to ensure they are not buried behind or beneath the wall after construction. Consider a proper location for the discharge of subsurface drained water. A high pore water pressure under the concrete ripraps creates buckling on the concrete cover and eventually collapses. Incorporate undersurface water drainage systems (weep holes) to dry out the slope from excess water and reduce the pore water pressure. This can be done using PVC pipes.

Chapter 6

Conclusion and future work recommendation

Embankment slope failures are one of the common stability issues on Texas highway structures. TxDOT spends a large amount of money to repair slope failures every year to keep the Texas transportation system functional. While result of repairing slopes using common repair methods are satisfactory in many cases, some repaired slopes fail again after a period of time. This study presents a review and evaluation of most common slope repair methods for shallow slope failures. Attempts were made to capture and integrate the current state of knowledge and practice to identify and present slope repair practices that ensure the long-term performance of embankment slopes along roads and highways.

Different sources of literature were investigated to identify the most common slope repair methods. Identified methods were classified into five major categories of mechanical methods, earthwork methods, biotechnical methods, and chemical methods (additives), and water management.

Findings of this research provided recommendation for successful implementation of existing slope repair methods which can reduce recurring slope failures. Reduction in recurring slope failures could considerably decrease construction operations and maintenance costs. Other benefits of reduction number of recurring slope failures are Improving safety, infrastructure service life, environmental sustainability, and transportation system reliability. Moreover, the results of this study benefit the state to reduce administrative costs and traffic congestion.

Although the main focus of this research was the state of Texas, the findings can be used for other states with similar conditions (e.g., soil and weather). Nevertheless, further research is required to obtain more information on slope repair techniques adopted in other states. Many slope repair methods are used in a region because the workforces are more accustomed to them. However, other methods may exist that could result in a better performance on a long-run. Likewise, innovative slope repair methods may exist around the U.S. that could help transportation agencies reduce the number of recurring failures.

Since cost plays a vital role in the selection of slope repair methods, It is recommended that life-cycle benefit-cost analysis, investment and financing analysis are conducted for methods. Examples of such analysis for underground construction are provided in Zahed et al. (2018a), Zahed et al. (2018b), Janbaz et al. (2018c), and Zahed et al. (2017).The result of that study would help the maintenance supervisors and decision makers to manage their budget better and to repair and maintain more slope failures using cost-effective methods. Future research could also be focused on the management and quality assurance practices for slope repair projects.

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Biographical Information

Milad Nabaei earned bachelor's degree in Civil Engineering from the International University of Qazvin, Iran in 2008 and a Master of Science degree in Water Resource and Management from Sharif University of Technology, Iran in 2011. He also earned his master's degree in Civil Engineering focusing on Construction Engineering and Management at the University of Texas at Arlington in May 2019. He has hands on experience in Project Management and Control in real estate projects and is also a PMI ® certified Project Management Professional (PMP).

His research was about recommendation of practices for successful implementation of slope repair methods. He was working on this topic for 16 months under the supervision of his advisor, Dr. Shahandashti.

As a student, Milad was offered a Graduate Teaching Assistant position (GTA) for two semesters. He was the TA for Building Information Modeling course during his education at the University of Texas at Arlington. Presently he is a Structural Engineer and his ultimate career goal is to be a Project Manager.