UNIVERSITY OF TEXAS ARLINGTON

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Synthesis on Rapid Repair Methods for Embankment Slope Failure: Final Report

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16. Abstract

Although the majority of slope repairs using common repair approaches show a satisfactory performance, some repair attempts have shown a recurring failure after a period of time. Recurring slope failures happen frequently in Texas, due to the extreme weather and soil conditions. The Texas Department of Transportation (TxDOT) annually spends millions of dollars to repair embankment slope failures along the state roads and highways. The primary objectives of this research project were to (1) synthesize and critically evaluate existing methods for rapid repair of embankment slope failures, and (2) recommend appropriate implementation procedures to avoid recurring failures considering different district conditions. These methods were evaluated and compared based on various factors, such as (1) long-term performance and applicability to the embankment soil; (2) constructability considering the minimal impact to existing roadway and traffic conditions; and (3) ease of implementation by TxDOT maintenance workforces.

The project findings clearly show that there are practices that could reduce the chance of recurring failures of repair methods, even for those methods that are highly prone to failure (e.g., rebuilding and compaction method). These recommended practices, representing the invaluable collective experience of several TxDOT engineers, supervisors, and maintenance crews, are highlighted in this research. Moreover, the results show that repair methods could be combined to prevent recurring failures. Case studies highlighted in this research present excellent examples of these combinations. The reduction in recurring slope failures could significantly reduce construction operations and maintenance costs.

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DISCLAIMER

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EXECUTIVE SUMMARY

Although the majority of slope repairs using common repair approaches show a satisfactory performance, some repair attempts have shown a recurring failure after a period of time. Recurring slope failures happen frequently in Texas, due to the extreme weather and soil conditions. The Texas Department of Transportation (TxDOT) annually spends millions of dollars to repair embankment slope failures along the state roads and highways. Critical examination of existing slope repair methods is needed to recommend appropriate implementation procedures to avoid or reduce recurring failures considering different district conditions. The primary objectives of this research project were to (1) synthesize and critically evaluate existing methods for rapid repair of embankment slope failures, and (2) recommend appropriate implementation procedures to avoid recurring failures considering different district conditions. These methods were evaluated and compared based on various factors, such as (1) long-term performance and applicability to the embankment soil; (2) constructability considering the minimal impact to existing roadway and traffic conditions; and (3) ease of implementation by TxDOT maintenance workforces.

The research findings were obtained through an extensive literature review, fact-finding surveys, structured follow-up interviews, and case studies. A thorough review of the literature was conducted to identify and critically examine the related research on slope failure repair methods. 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 individuals from all 25 TxDOT districts and other states department of transportation (DOT) to gather information from professionals and practitioners on the current slope repair practices being used regionally and nationally. Thirty seven responses were collected from the surveys distributed between professionals from in-state and out-of-state departments of transportation. These include 33 responses from TxDOT districts and four out-of-state responses. Most of the survey respondents were among area engineers and maintenance supervisors who have the most interaction with slope repair projects. Based on the survey responses, structured follow-up interviews were performed with individuals that were more experienced in the successful implementation of slope repair projects, in order to identify their best practices and lessons learned from real projects. In total, the research team conducted 10 detailed follow-up interviews. The interview participants were asked to provide detailed information on actual recent repair projects that could be presented as case studies. The application of one or a combination of several slope repair methods have been illustrated in the case studies.

The data collected from literature, survey questionnaire, interviews, and case studies were critically analyzed and synthesized to present the advantages and disadvantages of various slope repair methods along with recommended practices to avoid recurring failures. The results clearly show that there are practices that could reduce the chance of recurring failures of repair methods, even for those methods that are highly prone to failure (e.g., rebuilding and compaction method).

These recommended practices representing invaluable collective experience of several TxDOT engineers, supervisors, and maintenance crews are highlighted in this research. Moreover, the results show that repair methods could be combined to prevent recurring failures. For instance, the surface water management (a combination of a curb, flume, and riprap) and vegetation (e.g., cellular fiber mulch seeding and soil retention blankets) could be combined with other methods, such as rebuilding and compaction to prevent recurring failures. Case studies highlighted in this research present excellent examples of these combinations.

The reduction in recurring slope failures could significantly reduce construction operations and maintenance costs. The benefits of reduction in recurring failures go beyond reduced construction and operation costs by enhancing safety, customer satisfaction, infrastructure conditions and service life, environmental sustainability, and transportation system reliability. Moreover, the results of this study could reduce administrative costs, and traffic congestion.

Chapter 1. INTRODUCTION

1.1. PROBLEM STATEMENT

Slope failures cause significant economic and casualty losses in the U.S. (White et al. 2005). According to the U.S. Geological Survey (2003), the United States is experiencing an excess cost of $1 billion in damages and about 50 deaths annually 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). Although the majority of slope repairs using common repair approaches show a satisfactory performance, some repair attempts have shown a recurring failure after a period of time. Recurring slope failures happen frequently in Texas, due to the extreme weather and soil conditions. The Texas Department of Transportation (TxDOT) annually spends millions of dollars to repair embankment slope failures along the state roads and highways. Synthesis and critical examination of existing slope repair method is needed to recommend appropriate implementation procedures to avoid or reduce recurring failures considering different district conditions. This reduction in recurring slope failures could significantly reduce construction operations and maintenance costs (Appendix A). The benefits of reduction in recurring failures go beyond reduced construction and operation costs by enhancing safety, customer satisfaction, infrastructure conditions and service life, environmental sustainability, transportation system reliability (Appendix A). Moreover, the results of this study benefits the state to reduce administrative costs, and traffic congestion (Appendix A).

1.2. RESEARCH OBJECTIVES

The primary objectives of this research project were to (1) synthesize and critically evaluate existing methods for rapid repair of embankment slope failures, and (2) recommend appropriate implementation procedures to avoid recurring failures considering different district conditions. These methods were evaluated and compared based on various factors, such as (1) long-term performance and applicability to the embankment soil; (2) constructability considering the minimal impact to existing roadway and traffic conditions; and (3) ease of implementation by TxDOT maintenance workforces.

1.3. RESEARCH APPROACH

The information presented in this report was obtained through an extensive literature review, fact-finding surveys, structured follow-up interviews, and case studies. A thorough review of the literature was conducted to identify and critically examine the related research on slope failure repair methods. The results of literature analysis are presented in Chapter 2. 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 individuals from all 25 TxDOT districts and other states department of transportation (DOT) to gather information from professionals and practitioners on the current slope repair practices being used regionally and nationally. The survey was conducted using an online survey platform (SurveyMonkey.com). The information obtained from survey analysis is presented in Chapter 3. Based on the survey responses, structured follow-up interviews were performed with individuals that were more experienced in the successful implementation of embankment slope failure repair projects, in order to identify their best practices and lessons learned from real projects. The interview participants were asked to provide detailed information on actual recent repair projects that could be presented as case studies. The application of one or a combination of several slope repair methods have been illustrated in the case studies. The results of follow-up interview analysis and case studies are presented in Chapters 4 and 5, respectively. The data collected from literature, survey questionnaire, interviews, and case studies were critically analyzed and synthesized in Chapter 6. Chapter 6 presents the advantages and disadvantages of various slope repair methods along with recommended practices to avoid recurring failures.

Chapter 2. LITERATURE REVIEW

2.1. INTRODUCTION

Although many slope repairs using common repair approaches show a satisfactory performance, some repair attempts have shown recurring failures after a period. Recurring slope failures happen frequently in Texas, due to the extreme weather and soil conditions (Hossain et al. 2017). Several conventional slope repair methods have been used in Texas. These methods include randomly oriented reinforcement fibers, lime conditioning, replacement of the failed material with granular sub-base, and the use of "H-beam" walls (Prikryl 2005). During recent years, innovative methods such as recycled plastic pins and scrap tire bails have also been adopted to repair Texas highway slope failures. However, records do not show there is a central repository of information summarizing different available slope repair methods that have been used within and beyond the Texas Department of Transportation (TxDOT) work scope. Therefore, the objective of this report is to summarize the most common repair methods for highway embankment slope failures and to identify best practices that can be easily implemented by the TxDOT maintenance workforce, while providing long-term term performance. The following sections provide an introduction to slope failures, classification of slope repair methods, and a discussion of each method.

2.2. SLOPE FAILURE

Embankment slope failure is one of the most common issues regarding the stability of highway structures (TxDOT 2017a). Slope failures occur when the soil mass between the slip surface and the slope moves downward. This process can take place gradually or suddenly when the shear strength of the soil cannot resist the gravimetrical forces moving the soil mass down the slope. Any change in the soil condition can disturb the balance between the resisting and driving forces. This lack of balance can lead to the loss of stability in soil mass and eventually to slope failure (Hossain et al. 2017). For instance, fluctuation in soil moisture content of expansive soils, which are especially common in Texas, causes swelling and shrinkage (Puppala et al. 2013). The seasonal swelling and shrinkage of expansive soil on a slope with the forces of gravity causes soil movement down the face of the slope. Figure 2-1 shows different soil types in TxDOT districts based on assigned colors with their distribution range locations superimposed on top of the TxDOT district map. Moreover, Figure 2-1 shows that most TxDOT districts are to some extent prone to clays with high swelling potential. Hence, highway slope failure is an ongoing concern all over the Texas.

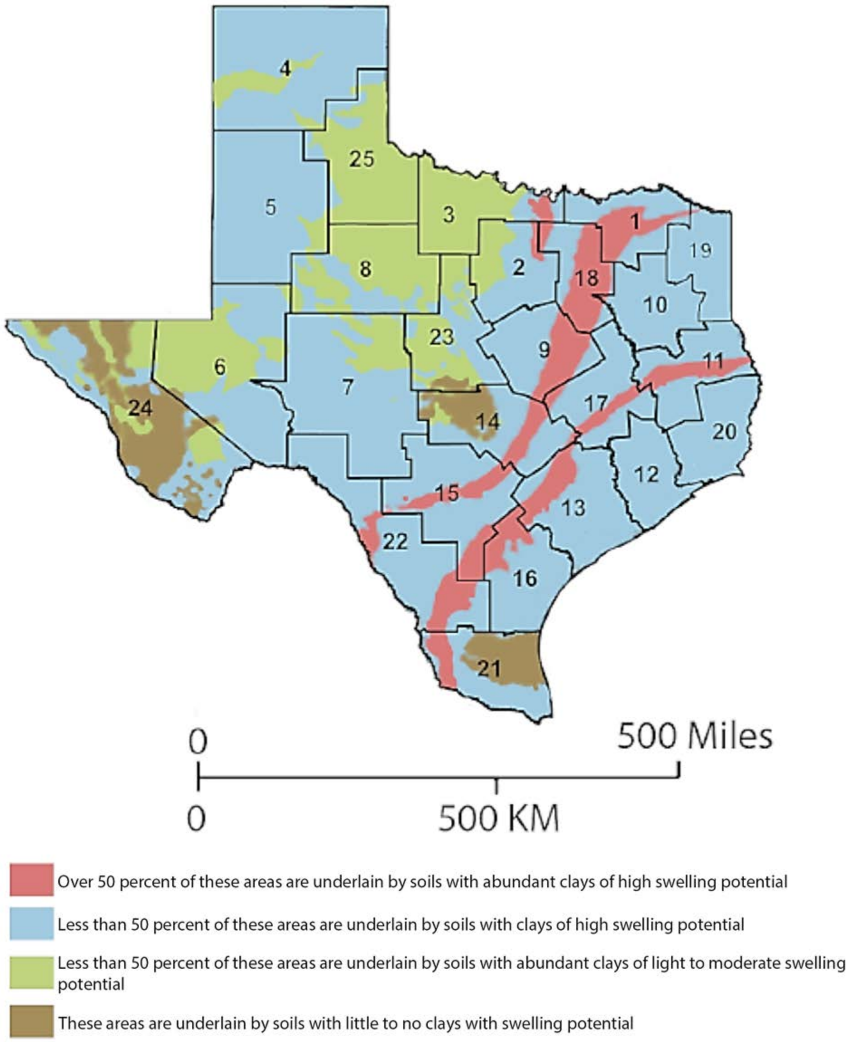

Figure 2-1 Soil map of Texas (Adopted from Olive et al. (1989))

Soil movement and depth of failure depend on four factors: soil type, soil stratification, the geometry of slope, and soil water content (Titi and Helway 2007). Abramson et al. (2002) categorized slope failures in translational failure, plane or wedge surface failure, circular failure, noncircular failure and a combination of the mentioned failures. Slope failures can also be classified by two major failure mechanisms: (1) deep-seated rotational failure and (2) shallow progressive failure. Figure 2-2 illustrates basic types of failure in clay slopes presented by Skempton and Hutchinson (1969).

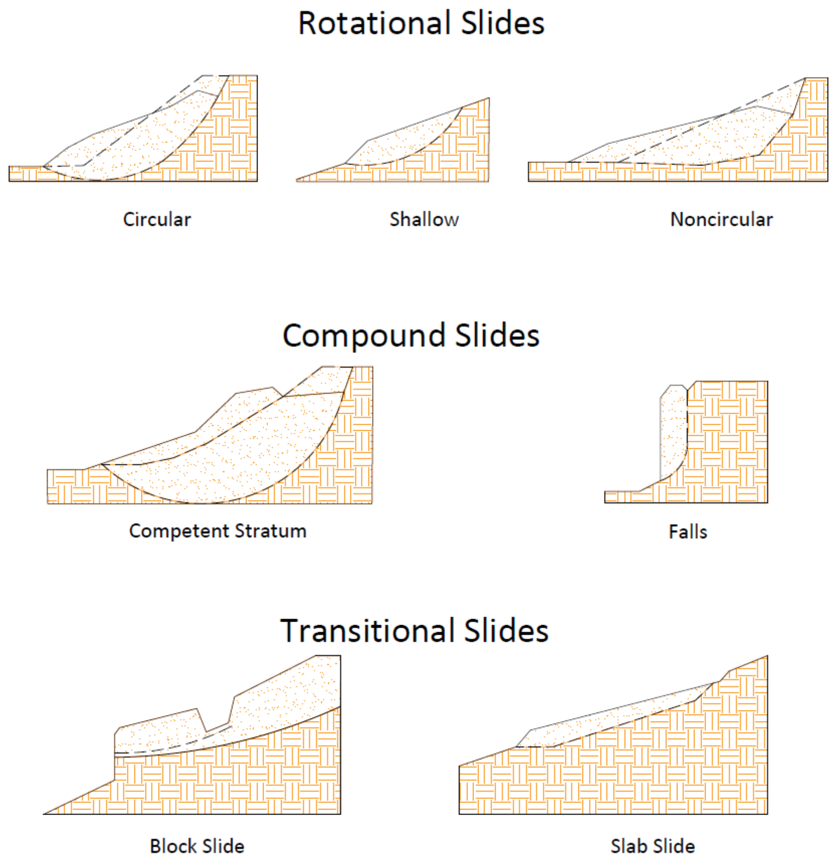

Figure 2-2 Basic types of failure in clay slopes
(Adopted from Skempton and Hutchinson (1969))

Shallow slope failure refers to surficial slope failures, which occur in highway cuts, fill slopes and embankments (Hossain et al. 2017). This type of failure happens due to fine-grained soils and mostly after continued rainfall. Mackay and Mathews (1973) used the term “Skin slides” to describe these types of failure as the downslope gliding of a thin layer of soil with minimum internal disruption. Shallow slope failure depth does not usually exceed four feet and is considered an 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 slopes do not lead to major damage nor are they a threat to human life, they can cause damage to infrastructure systems, such as bridges, culverts, guardrails, shoulders, pavements, drainage facilities, and landscape. Sometimes, the debris of the failed slope flows onto highways and roadways and interrupts traffic flow. Therefore, identification of slope repair methods and selection of the most suitable one (based on the conditions) is necessary to keep transportation infrastructure systems functional.

2.3. SLOPE REPAIR METHODS

There are various methods to repair and stabilize surficial embankment slope failures. Slope repair and stabilizing methods can be classified into five categories shown in Figure 2-3. Each category includes, but is not limited to several repair methods that are listed in Figure 2-2, as well. The following sections discuss each slope repair category and corresponding repair methods.

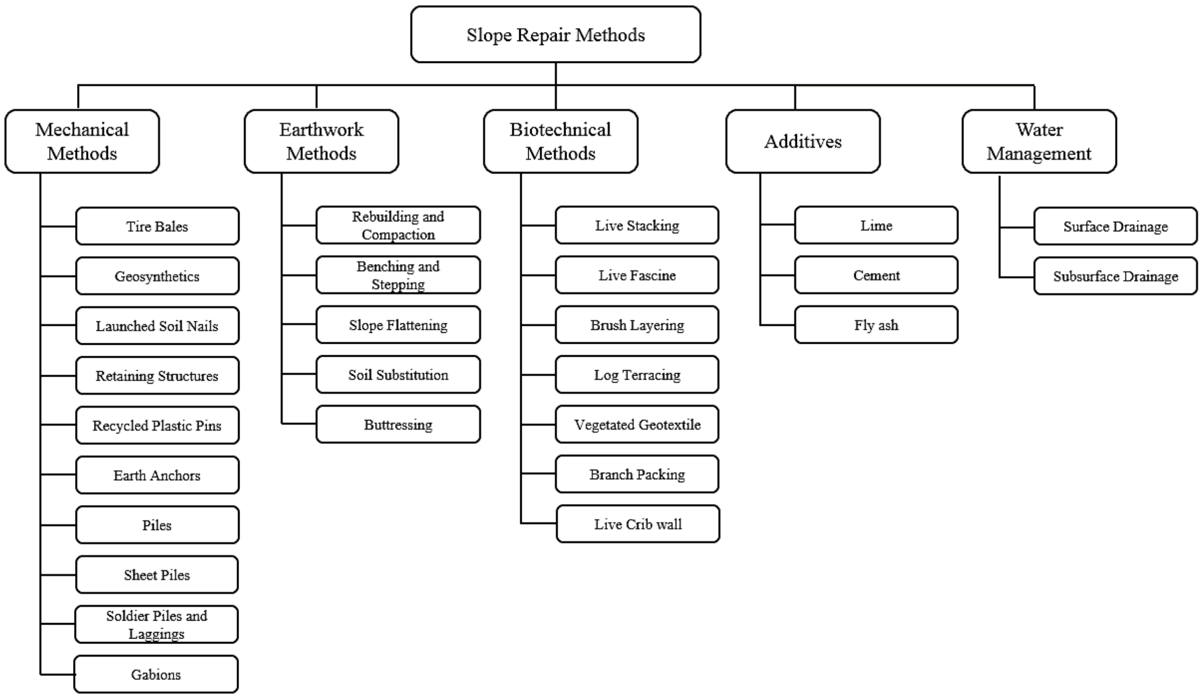

Figure 2-3 Classification of slope repair methods

2.4. MECHANICAL SLOPE REPAIR METHODS

Mechanical slope repair methods are physical processes established to repair and stabilize the slope soil, either by altering the physical composition of the soil or placing a barrier in or on the soil to obtain the desired effect. These methods utilize non-vegetative and nonliving materials such as rocks, gabion baskets, concrete, geosynthetics, and steel pins to reinforce slopes (Fay et al. 2012). Compared to other methods, mechanical slope repair methods provide a higher level of resistance to lateral earth pressures and higher shear stresses (Tuttle et al. 1992; Onyelowe Ken and Okafor 2006). 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.

2.4.1. Tire Bales

Tire bales are economical material, which are light, strong, porous, and can be rapidly used in slope failure repairs (Zornberg et al. 2005). The application of tire bales is not only limited to lightweight and non-structural fills, but they are also suitable for structural fills (Zornberg 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. Figure 2-4 illustrates a standard tire bale and its dimensions.

Simm et al. (2004) reported that the porosity and permeability of tire bales are approximately 50% and 0.4 m/s, respectively. These two characteristics indicate the suitability of tire bales for slopes with high-drainage requirements; thus, they support the long-term stability of embankment slopes (Prikryl et al. 2005). This method effectively prevents repeating failures and potentially doubles the slope safety factor due to the lower unit weight of the recycled rimless tires compared to soil (Team Consultant Inc. 2003). Tire bales are technically suitable where the in-situ soil is highly moisture sensitive and fundamentally unstable (Prikryl et al. 2005). High plasticity clay soil is one of the soils that sits in this category.

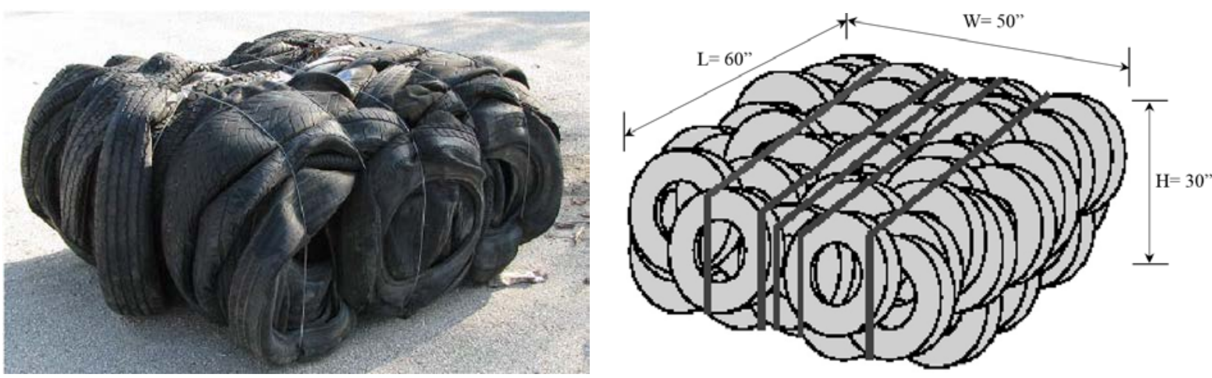

Figure 2-4 Tire bale photo and schematic of bale with dimensions (Freilich and Zornberg 2009)

Considering the standard tire bale dimension, they do not seem suitable for repairing shallow slope failures. However, they can be used in cases where it is necessary to remove a relatively large volume of failed material and replace it with competent material.

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). Regulations and legislations, such as the Colorado rebate program, can make the cost of tire bales as embankment material significantly less than conventional soil alternatives (Zornberg et al. 2005). Assuming the Colorado rebate program, Zornberg et al. (2005) reported the unit cost of tire bales to range between \$3.70 and \$9.70/m3 (\$2.80 to \$7.40/cy) in comparison to the average annual cost of embankment material backfill of \$12.60/m3 (\$9.6/cy). 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) provided a good insight into implementation of tire bales for embankment slope repairs. They determined that tire bales facilitate construction operations due to size, weight and their compacted nature prior to delivery. They 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.

Several states such as California, Colorado, New York, and New Mexico have used tire bales in embankment construction and rehabilitation. For instance, New Mexico successfully adopted this technique for at least five erosion control projects in the 1990s (Bandini et al. 2008). Moreover, TxDOT used this method for repairing several embankment failures, such as the failure in Interstate Highway 30 (I-30), West of Oakland Blvd, Fort Worth, in 2002. Initial assessment showed that this method improved the slope factor of safety by 2-3 times, compared to the original soil slope (Team Consultant Inc. 2003). Post-project observations indicated that the repaired slope had remained stable and porosity increased since the tire bales allow water to flow through the slope (Prikryl et al. 2005). Figure 2-5 shows the use of tire bales for the I-30 project.

Figure 2-5 Tire bales in I-30 slope repair project, Tarrant County, Texas, 2002 (Prikryl et al. 2005)

2.4.2. Geosynthetics

Geosynthetic is a generic term that encompasses flexible polymeric materials used in geotechnical engineering (Elias et al. 1997). There are eight major types of geosynthetics: geotextiles, geogrids, geonets, geomembranes, geosynthetic clay liners, geofoams, geocells, and geocomposites (Koerner 2012). Geosynthetics have been increasingly used to reinforce soil structures since the early 1980s (Berg et al. 2009).

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. Fill materials typically borrow materials with high drainage characteristics, or they are the original in situ soil if it has sufficient drainage potential and strength. In essence, geosynthetics are tensile reinforcing elements that significantly increase the strength of the soil (Nelson et al. 2017).

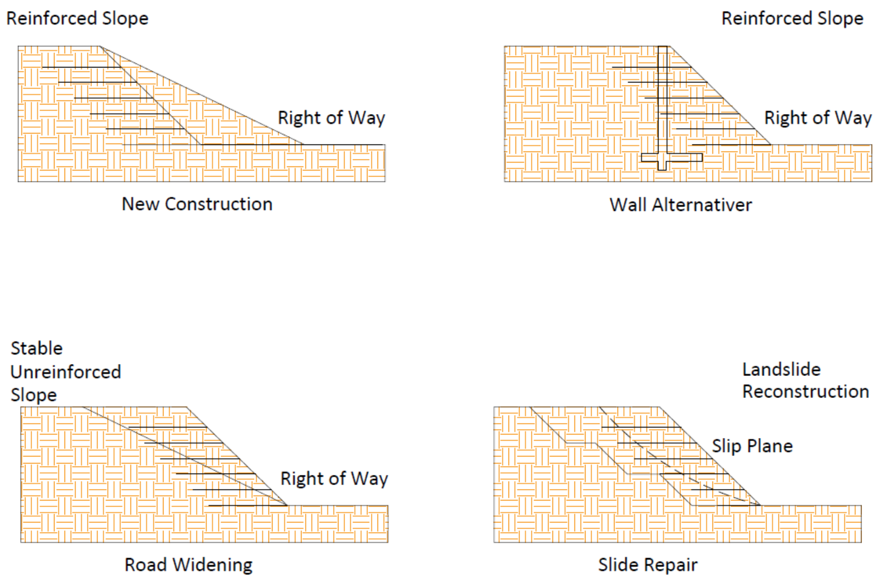

Figure 2-6 Different applications of RSS (reinforced soil slopes) (Adopted from Berg et al. (2009))

Mechanically stabilized earth (MSE) walls are constructed like reinforced soil slopes (RSS) with reinforced facing (usually reinforced concrete blocks). The MSE walls are used for various applications, such as retaining walls, access ramps, waterfront structures, and bridge abutments (Berg et al. 2009). MSE walls and RSS are cost-effective soil-retaining structures that can tolerate much larger settlements than reinforced concrete walls (Elias et al. 1997). The economics and successful performance of geosynthetic reinforced soil walls and slopes have resulted in a significant growing use of these structures (Christopher and Stulgis. 2005). Berg et al. (2009)

established a step-by-step design approach for MSE walls and RSS that have been verified through extensive experimental evaluation by FHWA.

A significant advantage of geosynthetics is their flexibility and long-term performance (Reddy et al. 2003). The geosynthetic material allow 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. Elias et al. (2009) showed that the installation damage could severely affect the allowable design strength of geosynthetics (mainly tensile strength), especially for permanent applications. Application of geosynthetics requires following explicit engineering design criteria. 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.

2.4.2.1. 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). Although there are numerous specific applications known for geotextiles, they always perform at least one of four following functions: separation, reinforcement, filtration, and/or drainage (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).

Niroumand et al. (2012) highlighted three ways that geotextiles help the stability of the slopes:

1) Reducing the pore water pressure within the slopes (especially during the rainy season). This can be achieved by placing geotextiles in horizontal layers within the slope, which cuts off or blocks potential sliding surfaces.
2) Increasing the shear strength of the soil by reinforcing the soil along potential sliding zones or planes.
3) Preventing internal erosion within the slope. Geotextiles act as a filter, which prevent the migration of the soil if placed along the slope.

Geotextiles are cost-effective methods compared to conventional slope stabilization methods. In 1993, the Pennsylvania Department of Transportation conducted a slope repair project using geotextiles that resulted in a cost savings of approximately $200,000 (1993 dollars) based on a cost comparison of a method that substituted old with new soil for stabilization (Kim et al. 2016).

2.4.2.2. 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). The extensive use of geogrids to reinforce earth in the United States started around 1983, and geogrid reinforcement has been growing ever since (Berg et al. 2009). 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). Geogrids increase tensile reinforcement by interlocking with granular materials after implementation. An appropriate design can guarantee the success of this method for repairing slopes. 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 is applicable for repair of a variety of embankment slope failures (Reddy 2000). However, it 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).

Like other geosynthetic methods, geogrids are quite cost-effective compared to conventional slope stabilization methods. For example, using geogrids for a reinforced embankment project in Winter Park, Florida showed a 50% cost saving compared to alternative methods (slope flattening or building a retaining wall) (Kim et al. 2016).

2.4.2.3. 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). This process can be conducted in situ or in a fixed plant. Geofoam blocks are primarily expanded polystyrene (EPS) or extruded polystyrene (XPS) (Koerner 2012). 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.

There are numerous applications for EPS geofoams, such as constructing a sub-base for road and airfield pavements and railway track systems, or placing beneath refrigerated storage buildings, sports arenas and storage tanks (Stark et al. 2012). Figure 2-7 illustrates several applications of geofoams. EPS geofoams offer special advantages for construction on soft ground, retaining walls, slope stabilization, and repair. Their lightweight helps to reduce the gravitational driving forces causing slope failures.

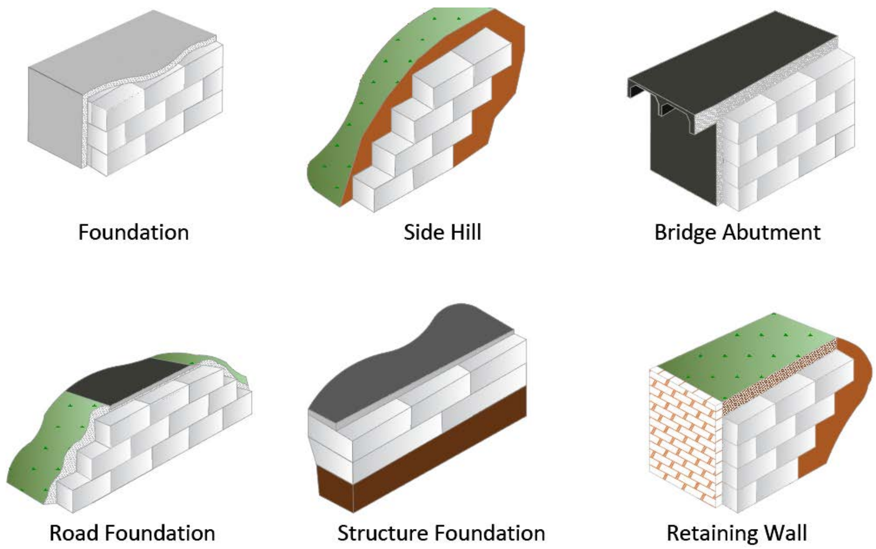

Figure 2-7 Different geofoam applications (Adopted from Benchmark Foam Inc. (2017))

This method is environmentally friendly and has a promising long-term performance (Lin et al. 2010; Aaboe 2000). EPS geofoams are environmentally friendly and safe during manufacturing, construction, and after they have been put in the ground (Riad et al. 2003). These products do not emit any harmful gas during manufacturing and implementation (Elragi 2000). In addition, there is no potential for chemical changes or the creation of toxic substances after they are buried 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).

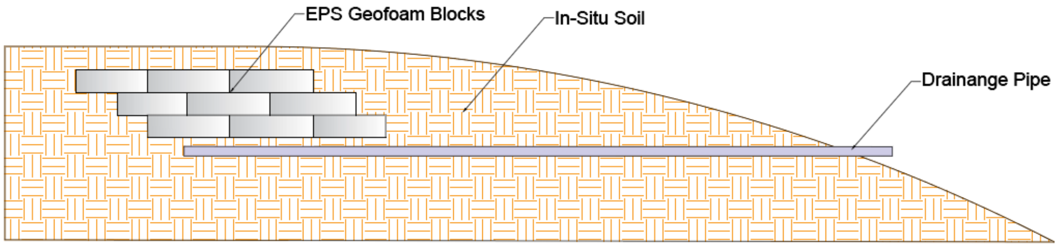

Figure 2-8 Application of geofoam for repairing slope (Adopted from Stark et al. (2012))

In this method, the failed mass has to 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).

In 2010, TxDOT used this method for embankment rehabilitation of the US 67 bridge over SH 174 in Johnson County, Cleburne, Texas (Ruttanaporamakul 2016). The results show a promising performance of this method. Figure 2-9 illustrates the application of geofoams in this project.

Figure 2-9 Application of geofoam in the US 67 bridge over SH 174 project (Ruttanaporamakul 2016)

2.4.3. Launched Soil Nails

In this method, an array of soil nails are inserted in the face of the slope to penetrate into a stable region. These nails reinforce the soil mass by transferring the tensile and shear resistance of nails to the sliding soil (USDA Forest Service 1994). Compared to the traditional soil nailing method in which nails are inserted into pre-drilled holes and then being grouted in place, launched soil nails (LSN), use compressed air to accelerate a steel nail or rod into the ground 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. Figure 2-10 illustrates the installation of launched soil nails by adding an extension to a hydraulic excavator. 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).

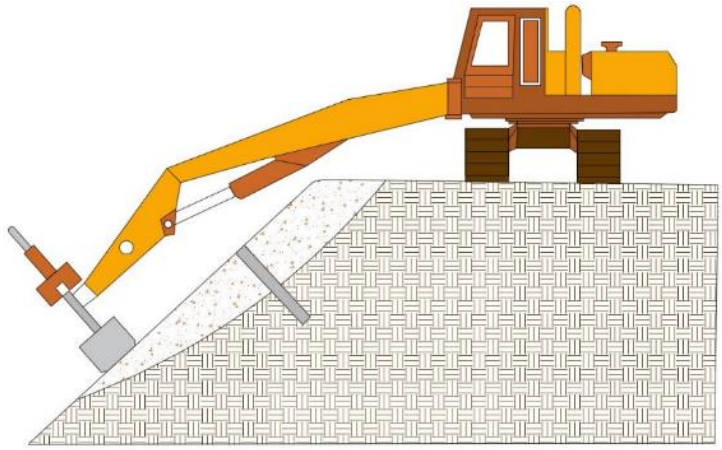

Figure 2-10 Installation of LSN using a launcher mounted on a hydraulic excavator (USDA Forest Service 1994)

The LSN method is one of the most cost-effective methods for repairing shallow slopes (Fay et al. 2012). 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. This method often requires a small right of way (single lane closure for mobilization) (New York DOT 2015a). Other advantages are minimum ground disturbance and installation from the top of the affected slope. This method enhances the repair procedure by locating the equipment on the horizontal surface rather than the distressed slope.

Although the implementation of this method is relatively rapid, construction requires specialized and experienced contractors (Deep Excavation LLC 2017). This method also requires a professional geotechnical evaluation and design procedure for selection of launched soil nail lengths, number, and spacing.

In 2008, Alberta Transportation (AT) used the LSN method to repair an embankment slope failure near the village of New Sarepta about 40 km southeast of Edmonton on Urban Approach Road 172 (Smith et al. 2009). Figure 2-11 shows the use of the SNL method in this project. When the work was completed, the construction cost for slope stabilization was approximately $500 (2008

Canadian dollar) per square meter. Compared to the alternative method (toe berm), the LSN method cost 70% less. No observable movement of slope components were reported from monitoring report on the slope six months after project completion (Smith et al. 2009).

Figure 2-11 Use of SNL method in urban Access Road 172 Slope Repair Project (Smith et al. 2009)

2.4.4. Retaining Structures

Retaining structures are used to stabilize slope failures by holding back the material and 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). In this method, first, the retaining structure is generally placed at the toe of the failed slope, and then the slope is reconstructed to the same degree or even flattened. 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). Retaining structures are appropriate for slope repair projects with limited space where flattening of the slope is not applicable (Nelson et al. 2017).

Different types of retaining structures are used in highway slope repair projects such as cast in place concrete gravity and cantilever walls, crib walls, gabion walls, MSE walls, tieback walls, rock walls, and “H-pile” and laggings. Figure 2-12 shows a number of these retaining structures. 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 more cost-effective and popular than other types of retaining structures when the height of the wall exceeds 10 feet (Berg et al. 2009). The low-height retaining wall is an effective and well-accepted method in the industry. However, it could be less effective, when applied in fine-grained soil, because of less sliding resistance (Hossain et al. 2017).

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

TxDOT is quite experienced in using retaining structures to protect slopes and bridge abutments. MSE walls are the most popular type of retaining structure used by TxDOT. For instance, more than 3 million square feet of MSE walls were used in TxDOT projects between August 2010 and September 2011 (Delphia 2012). MSE walls were 72% of all retaining structures used by TxDOT during that period.

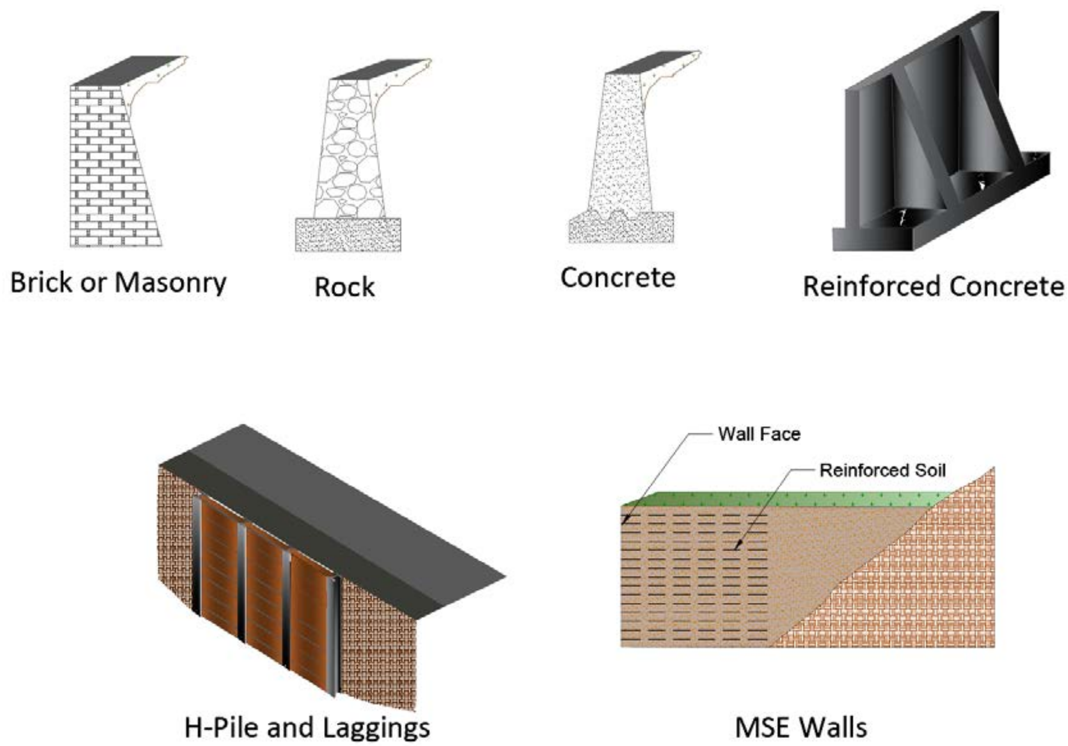

Figure 2-12 Examples of Common Retaining Structures (Adopted from Sheng (1990))

2.4.5. Recycled Plastic Pins

Recycled Plastic Pins (RPPs) have 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). Typically, RPPs are fabricated from recycled plastics and waste materials (polymers, sawdust, and fly ash) (Chen et al. 2007). 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). Figure 2-13 shows a pile of plastic pins manufactured from recycled plastic bottles. 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). RPPs increase the factor of safety by providing an additional resistance along the slope failure plane (Hossain et al. 2017). RPPs could provide a sustainable and cost-effective solution to shallow slope failures. 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).

Figure 2-13 Recycled plastic pins (Hossain et al. 2017)

RPPs were first utilized in the state of Missouri and Iowa, as a sustainable option to stabilize highway slopes where few field studies were conducted (Khan et al. 2017). Observations after slope repair with RPPs showed no further slope failure for this project (Loehr and Bowders 2007). In 2011, TxDOT conducted a slope stabilization project using RPPs on the southbound side of U.S. Highway 287 near the St. Paul overpass in Midlothian, Texas (Figure 2-14). Five years of monitoring the repaired slope showed minimal settlements proving the successful utilization of RPPs for this project (Khan et al. 2017). Studies showed a cost savings of 50 to 80 percent for this method compared to conventional methods, such as retaining structures (Hossain et al. 2017).

Figure 2-14 Installation of recycled plastic pins on U.S. Highway 287 near the St. Paul overpass in Midlothian, Texas (Khan et al. 2017)

2.4.6. Earth Anchors

Earth or ground anchors are structural elements installed in soil or rock to transmit an applied tensile load into the ground. Since, earth anchors are typically installed in grout filled drill holes, they are referred as “grouted earth anchors” or “tiebacks” (Sabatini et al. 1999). Various anchoring systems are available in the market. A general earth anchor system consists of three main parts: (1) anchorage, which includes an anchor head and bearing plate; (2) the unbonded tendon (free stressing length); and (3) bonded tendon that transmits the applied tensile load into the ground (Sabatini et al. 1999). Figure 2-15 shows different components of a general earth anchor. Earth anchor systems (components) vary in shape, length, material, and implementation procedure, which makes them different in application. Earth anchors have been used as a temporary and permanent earth-supporting method. U.S. transportation agencies use earth anchors for different applications, such as flexible anchored walls, slopes supported by ground anchors, slope stabilization systems, and structures that incorporate tie-down anchors (Juran and Elias 1991). 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.

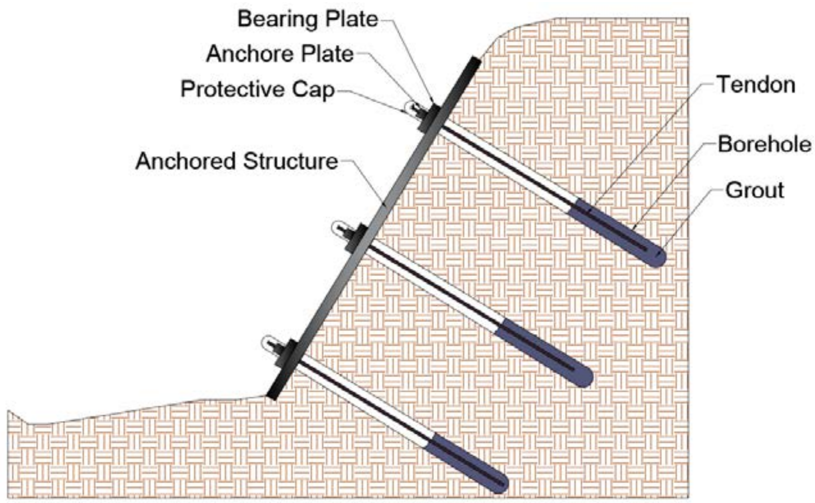

Figure 2-15 Components of a general earth anchor system

Different earth anchors require different installation techniques. For instance, the installation of regular earth anchors 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 special earth anchor, manufactured by Platipus Anchors, for shallow slope repair. They reported the use of this system by different state departments of transportation including the North Carolina DOT, California DOT, and Hawaii DOT. In this method, first the failed slope is reprofiled 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 earth anchors and landscaping (Platipus Anchors 2017). The installation of earth anchors are 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). These anchors work like plate anchors in some retaining structure anchor systems.

Improvements in design methods, construction techniques, anchor component materials, and on-site acceptance testing has made the earth 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. Earth 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).

2.4.7. Piles

Although piles are mostly used for foundation stabilization (Tarquinio and Pearlman 1999), they have been proven as an effective solution for slope stabilization (Wei and Cheng 2009). Piles provide passive resistance against lateral force from the surrounding soil (Wei and Cheng, 2009). This method requires minimal or even no excavations (Fay et al. 2012). Piles are vertically inserted into slopes using hydraulic hammers. There are several types of piles with different shapes (pipe, cylindrical, rectangular, and H-pile.) and materials (steel, wood, and concrete). Plate piles and pin piles (micropiles) are the two most commonly used pile systems for slope repair.

Shallow slope repair 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 (typically 4 feet) and pattern (Geopier® Foundation Company Inc. 2016). Figure 2-16 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.

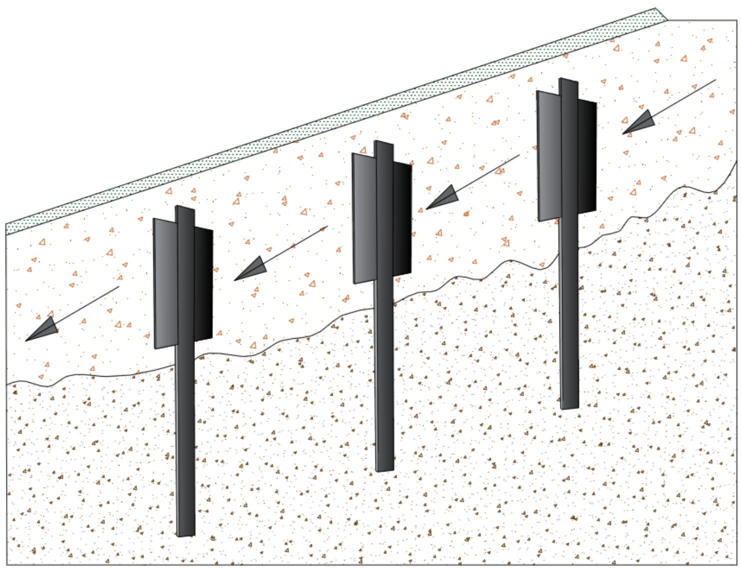

Figure 2-16 Plate piles installation pattern and resisting mechanism (adopted from Geopier® Foundation Company Inc. (2016))

Plate piles are suitable for shallow slopes and unstable fills with less than 3 feet depth (Fay et al. 2012). Plate piles are among the latest slope repair innovations that 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 have passed the field tests demonstrating the effectiveness of using this method for shallow slopes stabilization (Fay et al. 2012).

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). Specifically in Texas with hundreds of miles of freeways with Beaumont clay slopes, this method seems to be an effective method for slope stabilization (Short et al. 2006).

Pin piles are small-diameter, high-capacity drilled or grouted piles (Richards and Rothbauer 2004). Their applications have been increased in recent years due to their flexible applications. Pin piles are ideal for foundations stabilization (Pearlman 2000; Richards and Rothbauer 2004). However, they are a suitable option for slope stabilization projects addressing deep-seated slope failures (Fay et al. 2012). Pin piles can be installed at different angles to stabilize loose soil mass on slopes. Figure 2-17 illustrates the installation of pin piles into a slope face at different angles.

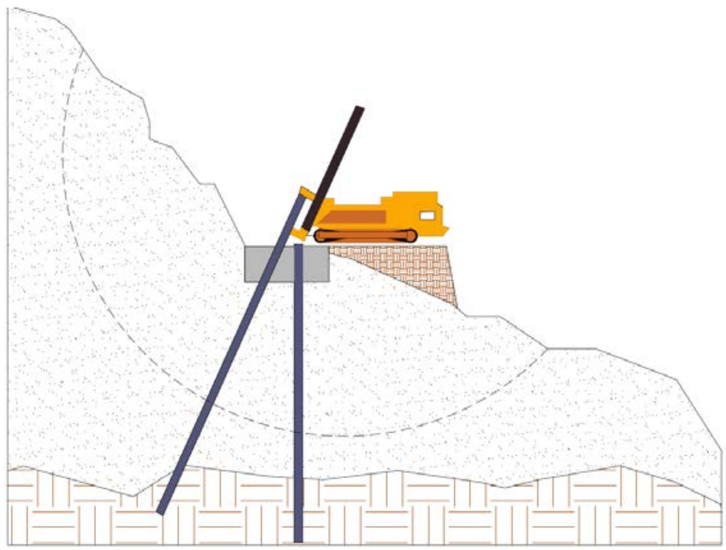

Figure 2-17 Installation of pin piles at different angles
(Adopted from Hayward Baker Inc. (2017))

Pin piles have been successfully utilized by different states for repairing and stabilizing shallow slopes, such as Idaho and Montana (Fay et al. 2012). In a case at the Blue Trail area of Highway 89 down to Snake River in Alpine, Wyoming, pin piles were used to stabilized the adjacent slope of the road (Hayward Baker Inc. 2017). The installation of pin piles are more challenging compared to launched soil nails (Fey et al. 2012).

2.4.8. Sheet Piles

Sheet piles are continuous walls, created by interlocking long structural sections together to resist horizontal water or soil pressures (King 1995; Škrabl 2006). They are used for different purposes, such as building waterfront structures and cofferdams, controlling erosion, and stabilizing slopes (Poulos 1995; Eskandari and Kalantari 2011). Sheet piles are appropriate solution for stabilizing slopes where the water table is high and near ground surface (Niroumand et al. 2012). 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). Figure 2-18 illustrates the mechanism of slope stabilization using sheet piles.

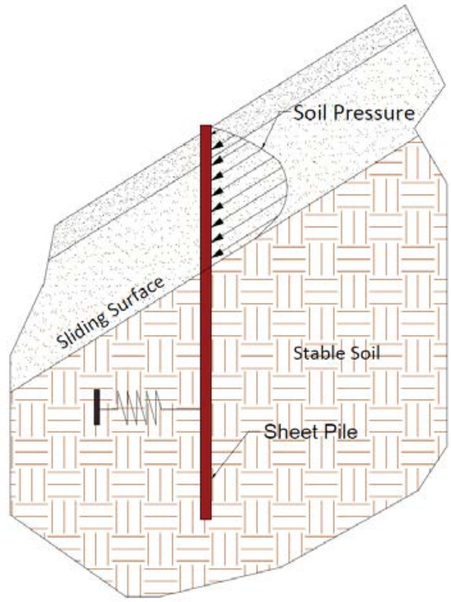

Figure 2-18 Sheet Pile Slope Stabilization Mechanism
(Adopted from Ashour and Ardalan (2012))

Sheet piles are in two types of (1) cantilever sheet piles and (2) anchored sheet piles (Figure 2-19). Typical sheet piles are also called cantilever sheet piles because they behave like cantilever walls. These piles should be driven to a sufficient depth so that the passive pressure exerted on the embedded portion, can resist the active earth pressures acting on the cantilevered section (New York DOT 2015b). Anchored sheet piles are supported by anchors at a suitable depth to provide extra resistance against active pressures on the retaining system (Niroumand et al. 2012). Anchor sheet piles are more cost-effective than cantilever types when deep cantilever sheet piling is required (Tsinker 1983).

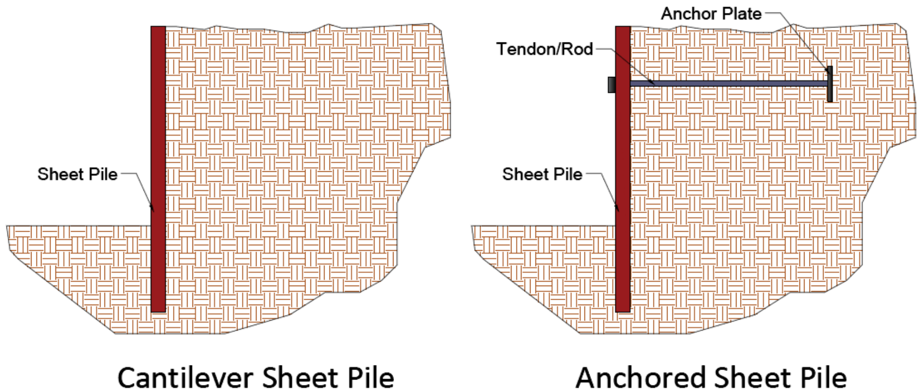

Figure 2-19 Sheet pile systems

Sheet piles are made from different materials, including wood, reinforced concrete, vinyl (synthetic resin or plastic), and steel (Shao and Kouadio 2002). The allowable design forces are different for each material (Bowles 1996). The most important factor and the driving criterian 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.

In 2005, Sawwaf (2005) conducted several experiments to compare the performance of rounded steel piles and sheet piles for slope stabilization. The experiments were done in a slope with a medium to dense sand. The results showed that sheet piles improve the bearing capacity of the soil, more than piles.

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). Osório et al. (2010) conducted a reliability analysis on the service life of sheet piles used in the Port of Hamburg, Germany. Their study showed a promising performance of more than 50 years for this method. 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).

Sheet piles are widely used around the world. For example, they have been used for stabilizing the slope of East Garden Grove-Wintersburg Channel (city of Huntington Beach, CA) (ASCE LA Section 2017). In this project, two rows of steel sheet piles were installed. Soil cement mixed columns were also inserted between the sheet piles.

2.4.9. Soldier Piles and Lagging

Soldier piles and lagging is an earth retention technique that retains soil using vertical steel piles and a horizontal lagging system. Soldier piles are usually in the form of steel (galvanized) 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. Figure 2-20 illustrates a typical design of this system. 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 (Figure 2-21). In most cases, a drainage system must be implemented behind these structures (Day 1996).

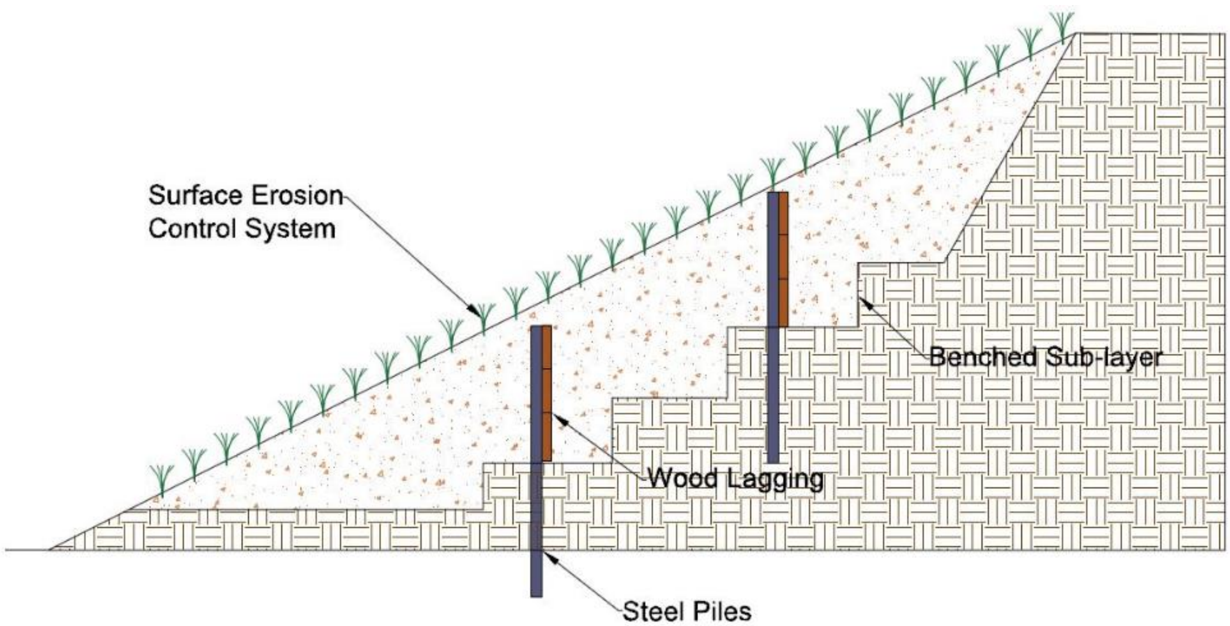

Figure 2-20 A schematic of soldier piles and wood lagging repair (Adopted from Day (1996))

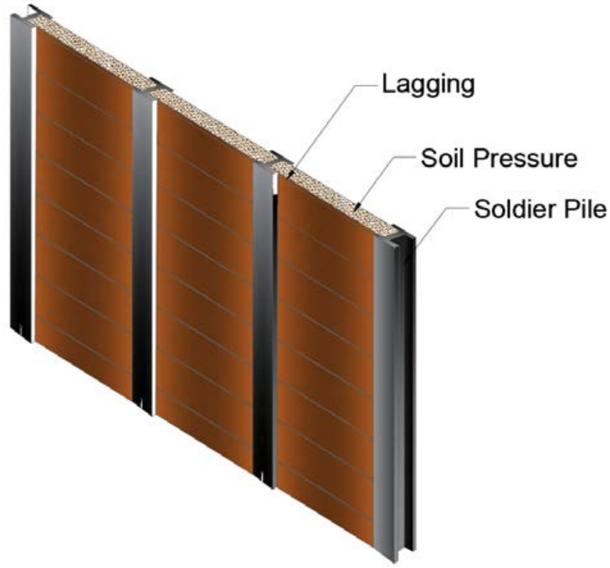

Figure 2-21 Soldier piles and lagging components

Soldier piles and lagging systems usually work as cantilever walls against soil mass. 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 (Deep Excavation LLC 2017). 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).

2.4.10. Gabions

Gabions are rectangular baskets made of heavy wires, filled by selected rocks and stones, such as cobbles or crushed rock. These baskets are connected together to form a retaining wall. 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). Gabions have been widely used in several slope stabilization and erosion control projects, all around the world (Giani 1992 and Kandaris 1999). They have numerous applications, such as bed protection, bank stabilization, and retaining walls (Freeman and Fischenich 2000). Figure 2-22 illustrates two examples of slope stabilization using gabions.

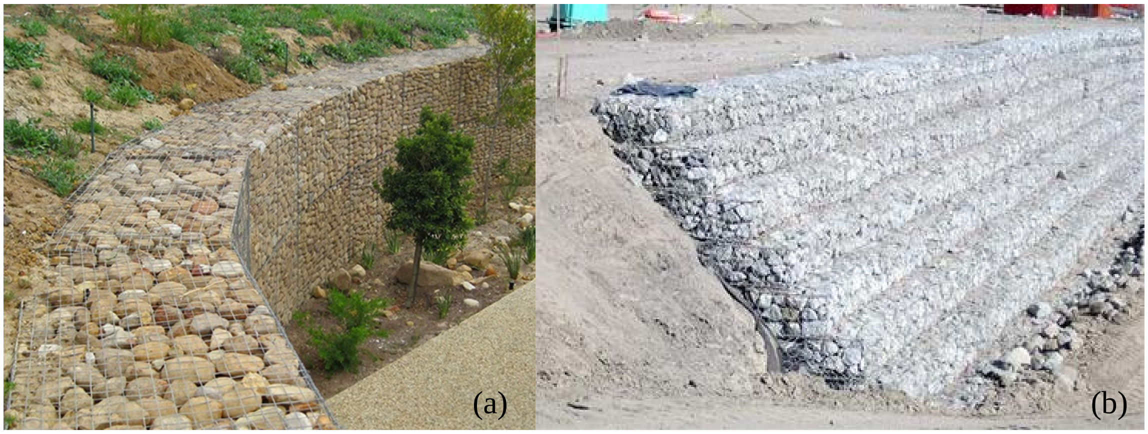

Figure 2-22 (a) Gabion retaining wall and (b) gabion mattress (Reprinted from “Slope Protection“ by BlueStone Supply LLC, by permission of Daniel Hill, Year of first publication: 2017)

Different connections between gabions with various inclinations make them suitable for a wide range of slopes (Greenway et al. 2012). Generally, gabions are implemented in two ways. They can be placed along the slope to create gabion revetments (gabion mattress) (Figure 2-22-b) or be stacked vertically on top of each other to form gabion walls (Figure 2-22-a). Gabion walls can accommodate settlement without rupture and provide free drainage through the wall (Kandaris 1998). Thus, 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 2-23 shows the use of diaphragms in gabions.

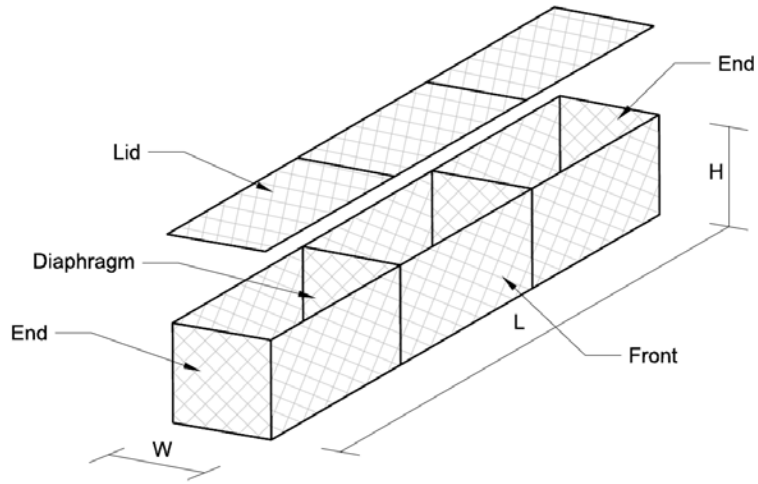

Figure 2-23 Supporting long gabions using diaphragms

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). Figure 2-24 illustrates the components of vegetated rock gabions.

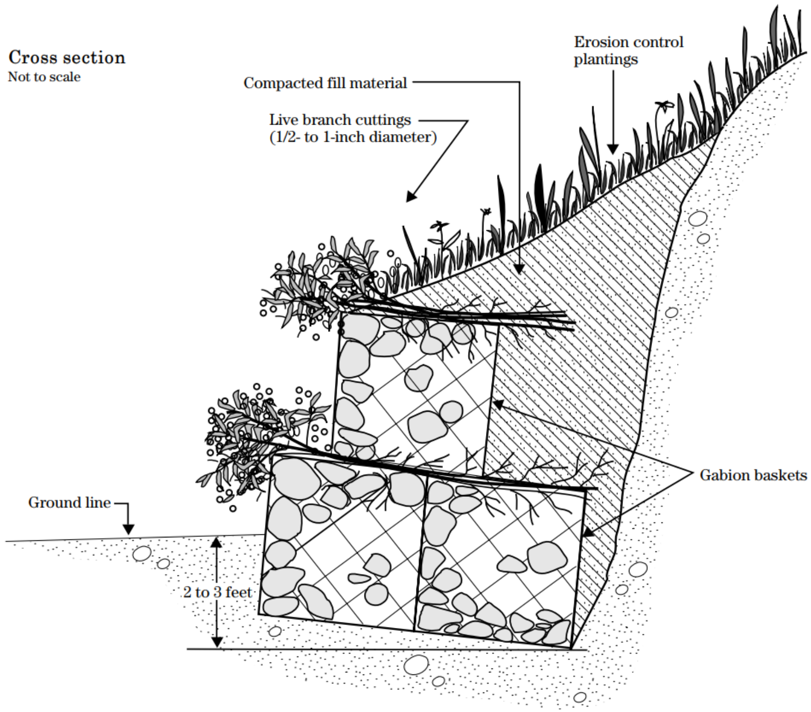

Figure 2-24 Vegetated rock gabion components (USDA 1992)

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).

The life expectancy of gabions is not too long; 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 such as live fascines.

2.5. EARTHWORK SLOPE REPAIR METHODS

Earthwork slope repair methods involve the physical movement of soil, rock, and/or vegetation to control and repair slope failures. 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 involves reinforcing and reshaping the slope surface by methods, such as rebuilding and compacting the slope, creating terraces, benches and steps, and flattening the steep slopes. 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.

2.5.1. 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. Soil compaction is commonly performed with heavy equipment and application of different types of loads such as vibration, impact, or soil compression, rolling, or kneading (Shillito and Fenstermaker 2014). Compaction expels the air from the soil mass without a significant change in the amount of water in the soil. While this method increases the strength and the density of a soil mass, it decreases the permeability, compressibility, shrinkage, and swelling potentials (Collin et al. 2008). Although rebuilding and compaction is generally used in combination with other slope repair methods, it can be used separately to repair and stabilize embankment slopes.

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 (such as geofoams) after repairing slopes with this method.

Slope rebuilding and compaction is the simplest and most common method of repairing the surficial slope failures (Sutterer 2000). 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. In the compaction method, maximum compaction will generally be achieved under a specific moisture content, which depends on the soil type (Das 2010). 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).

2.5.2. Benching and Stepping

Benching is the transformation of a high slope to several lower ones by excavating horizontal cutouts periodically along the slope. The purpose of benching and stepping is to stabilize temporary excavations or permanent embankments (Nelson et al. 2017). The exposed face of benches can be shaped vertically (rock slopes) or with an angle. 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). Long or steep slopes may require many short benches, while less steep slopes may be stabilized with steps (Fay et al. 2012). Figure 2-25 shows examples of benched slopes and stepped slopes. 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).

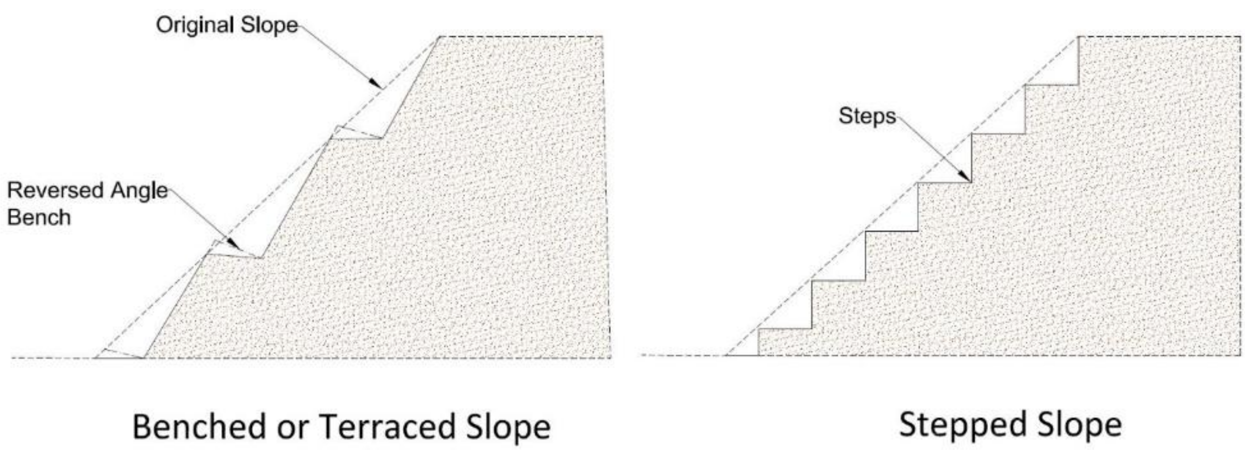

Figure 2-25 Benched, terraced, and stepped slopes

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). This procedure provides interlocking between the new fill material and the existing slope to reduce the chance of shallow failure at their interface. 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 along temporary construction excavations provides a convenient flat surface for workers and equipment (Nelson et al. 2017).

However, there are limitations on benching geometry in this case. 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 (TIRRS 2001). 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).

2.5.3. 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). Sometimes, flattening the slope is achieved by excavating the top slope soil and replacing at the base of the slope (Fay et al. 2012). Figure 2-26 depicts an example of slope flattening. 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).

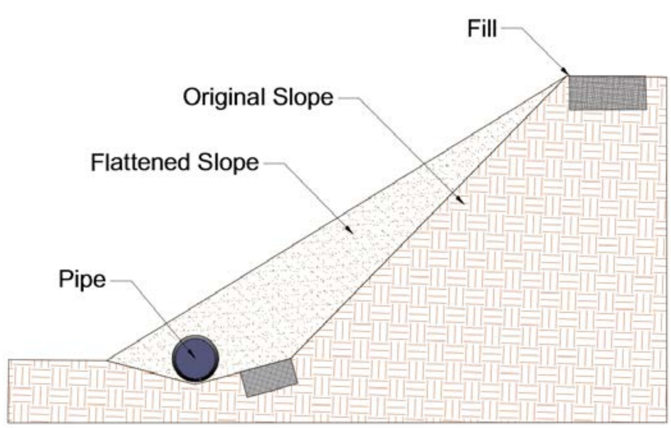

Figure 2-26 Schematics of slope flattening (Adopted from Collin et al. (2008))

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). Figure 2-30 also shows an example of replacing a surface ditch with a drainage pipe after flattening a slope. Slope flattening is not a feasible method for maintaining large slopes (Fay et al. 2012). 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).

2.5.4. 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). Figure 2-27 illustrates a project using this method for slope repair. 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).

Figure 2-27 Typical soil substitution method (Reprinted from "Slope Maintenance and Slide Restoration Reference Manual" by Collin et al., by permission of James Collin, Year of first publication: 2008)

2.5.5. Buttressing

Building a buttress (buttressing) at the toe of slopes is a commonly used slope repair method that loads the toe of the slope with heavy material to increase stabilizing forces and decrease overall slope height (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). Buttressing using pneusol or scrap tires involves excavating failed slope to depths below the failed surface and reconstructing the slope with whole tires filled with soil and held together with plastic or metal clips (Hausmann 1992; Huat et al. 2008).

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). Shear keys are used to increase the resistance of rock/earth fill or buttresses by transferring the failed surface into deeper, high strength, undisturbed strata (Wyllie and Mah 2004). Figure 2-28 shows a typical shear key used in building a buttress. In case of slope failures in fine soil, MSE system helps to stabilize the buttress.

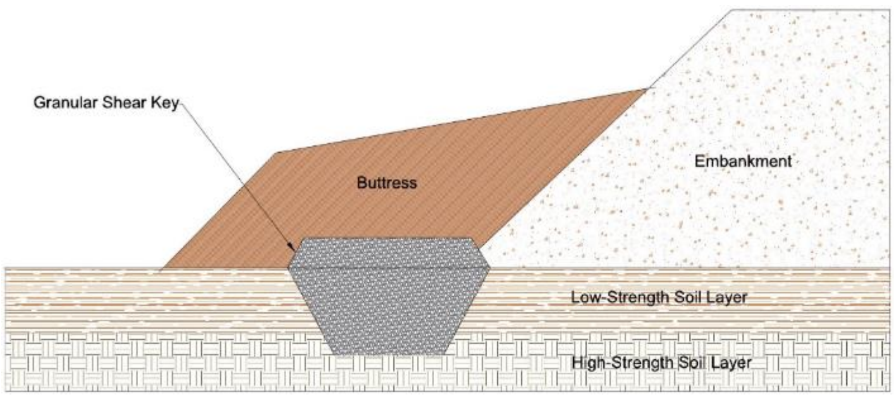

Figure 2-28 Using shear keys in buttressing (Adopted from Lohnes et al. (2001))

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). In addition, temporary rock buttresses can be used in construction projects to support temporary steep slopes (Saftner et al. 2017).

A rock buttress is constructed by placing weighted, large stone materials, such as riprap or erosion stone as fill materials in the lower portion of the slide to increase the resisting forces (Shannon and Wilson Inc. 2012). Fill materials should be placed on fabrics (usually geotextiles) to prevent loss of fines during the service-life of the rock buttress. If the sublayers are not stable enough, granular shear keys are constructed by excavating a keyway through weaker material into stronger material, and backfilling the keyway with high-friction, granular material (Lohnes et al. 2001). Figure 2-29 illustrates components of a rock buttress.

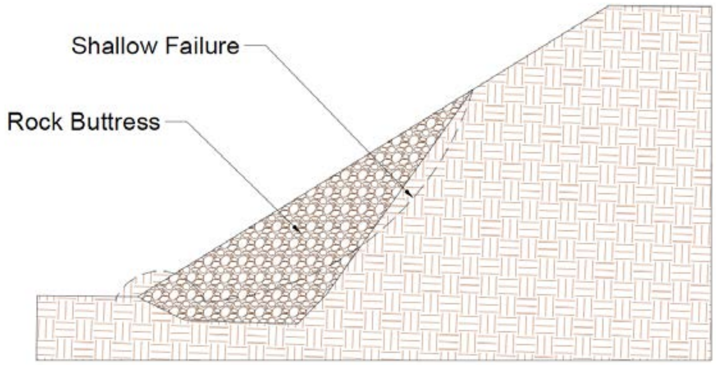

Figure 2-29 Slope repair with rock buttress (Adopted from Lohnes et al. (2001))

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.

In 2013, the Arizona DOT used this method to repair a slope failure on US-89, near Page. They used the rocks removed from the upper slope to construct the buttress. Figure 2-30 shows the schematics of the project and the finished project.

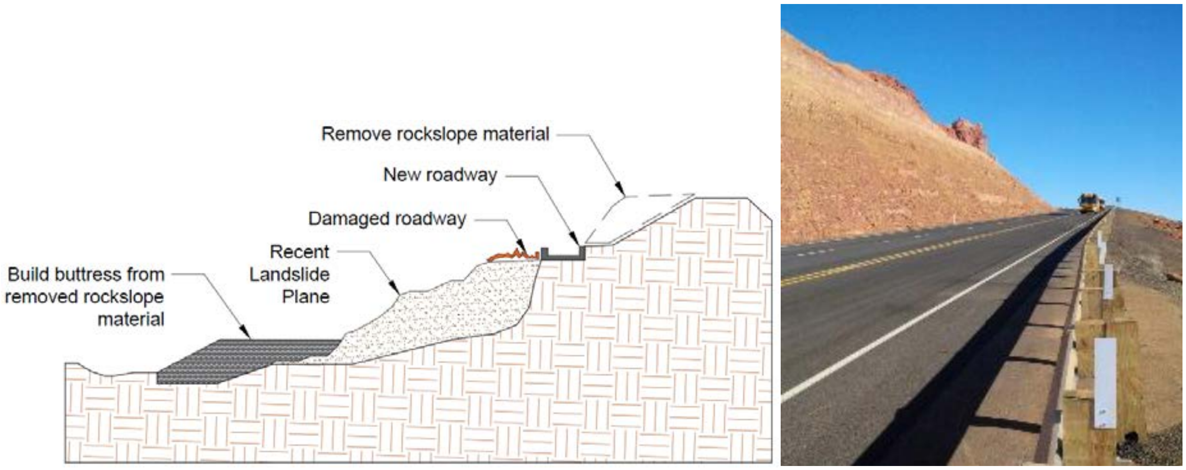

Figure 2-30 Slope repair with rock buttress on US-89, near Page, Arizona (ADOT, 2017)

2.6. 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). These methods are developed empirically and through numerous trial and errors (Donat 1995). In 1936, Kraebel conducted one of the earliest attempts to use biotechnical slope stabilization in the United States (Gray and Sotir 1992). He used the contour wattling (live fascine) method to stabilize steep slopes on the Angeles Crest Highway in southern California. 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.

A detailed review of most commonly used biotechnical methods is provided in the following sections. These methods include live staking, live fascine, brush layering, log terracing, vegetated geotextiles, branch packing, and live crib walls.

2.6.1. Live Staking

Live Staking or joint planting is the insertion and tamping of live stakes or rootable cuttings in joints on the slopes. When the stakes grow, they create a living root mat under the structure and bind with the soil that stabilizes the soil mass and prevents soil erosion (Watson et al. 1994; Adair et al. 2002; Greenway et al. 2012). There are different type of species for live staking but the most commonly used species are dogwood and willow. However, only species that are native in the area is recommended for use.

Stakes range from 2 to 3 feet in length and 1 to 2 inches in diameter. The stakes should be installed quickly after cutting, and their leaves and branches should be removed before installation. Two-thirds of each stake's length is tamped into the ground at an angle of 90 degrees (Figure 2-31). Typically, 2 to 4 stakes can be installed per square feet (Sheng 1990). After installation, they need monitoring and maintenance to ensure that they take root and sprout leaves (Greenway et al. 2012).

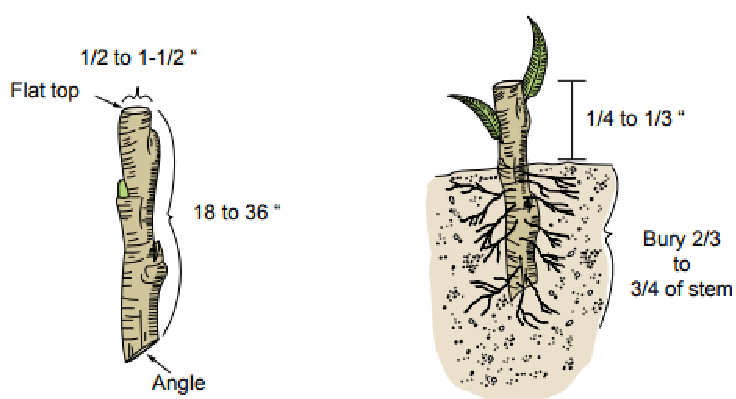

Figure 2-31 Live stakes (Lewis, 2000)

Live staking is typically used on existing or planned rock slopes such as rip-rap or rock revetment (Eubanks and Meadows 2002). This method can also be used in combination with other bioengineering materials, such as geotextile fabric, coconut fiber logs, and live fascines (Figure 2-32) (Eubanks and Meadows 2002).

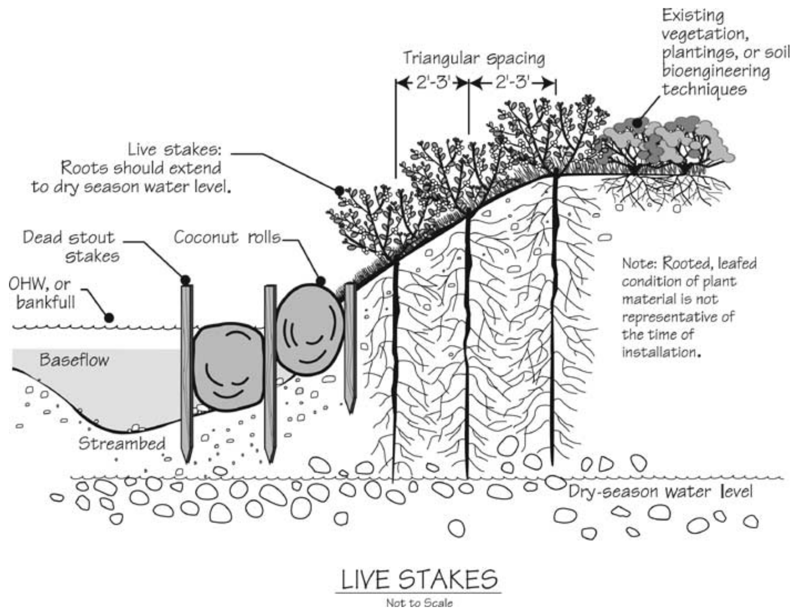

Figure 2-32 Installation of live stake (Eubanks and Meadows 2002)

The installation procedure of the live staking method is rapid and simple (Sheng 1990). This method is mostly used for small earth slips and sites where they need only minor erosion control. Live staking method reinforces the underlying soil when the stakes grow and expand their rooting system (Polster 1997). Moreover, their rooting system improves the drainage of slopes and further increases slope stability.

In comparison with the other methods, such as launched soil nails and earth anchors, live staking is an economical method especially if the slope is covered by rocks (Gray and Sotir 1992). The cost of each stake normally ranges from $2 to $3 (Donat 1995). The total cost can rise to $35 per square feet if additional site work is needed (Donat 1995).

Limitations, such as poor nutrient status and time period affects the performance of the live staking method (Sheng 1990). Stakes should be installed in the fall and spring (Myers 1993). Since development of the rooting systems requires several months, live staking is not a short-term solution to slope stability and erosion control projects (Lewis 2000; Greenway et al. 2012).

2.6.2. Live Fascine

Live fascine is a bundle of cutting branches bound together to control erosion and stabilize slopes (Kraebel 1936; Lewis 2000; Adair et al. 2002). Live fascines are placed in shallow cylindrical trenches parallel to the slope with live stakes, which eventually grow roots and the whole system grows to stabilize the slope (State of Georgia 2000; Greenway et al. 2012). For dry slopes, cylindrical trenches should be placed parallel to the flow, while in case of wet slopes, it is essential to place trenches at an angle to prevent sliding (Natural Resources Commission 2012). Figure 2-33 shows the preparation and installation of live fascines on a dry slope.

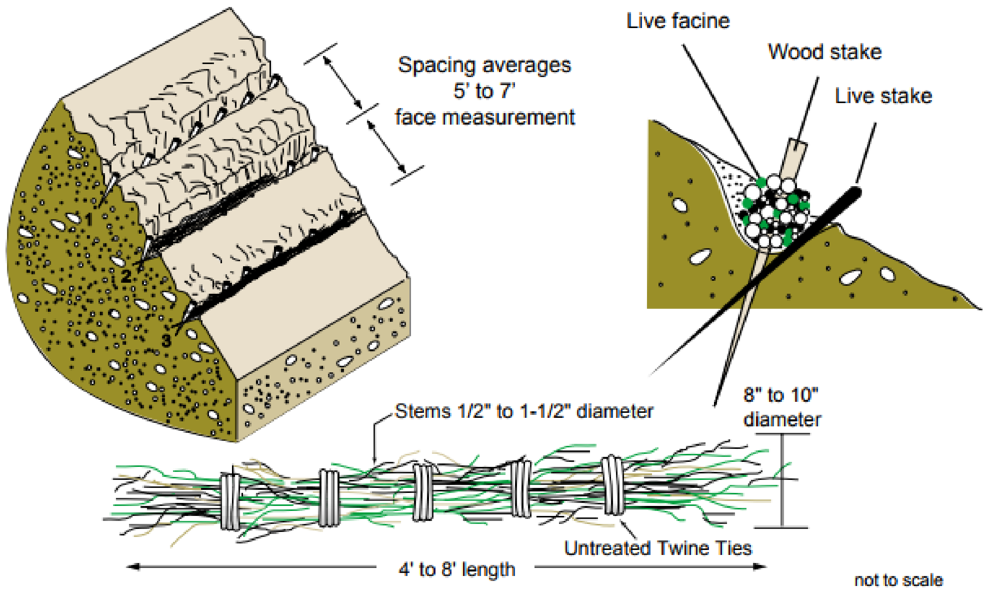

Figure 2-33 Installation of live fascines (Lewis 2000)

Live fascines immediately reduce surface erosion after installment (Fay et al. 2012). They also improve the soil stability, if appropriate angle is considered for trenches. The primary application of live fascines are erosion control and the slope stability improvement. This method is often used with other bioengineering methods, such as live stacking (Natural Resources Commission 2012). The construction procedure is fast and simple for live fascine. Since this method does not require large excavations and materials are usually available on the site, it is cost-effective and causes limited disturbance on the construction site (Fay et al. 2012).

This method is not a proper choice for stabilizing steep slopes (more than 45 degrees) (Donat 1995; Greenway et al. 2012). Since the rooting system requires time to develop, a complete performance of this method is not achieved in a short period of time. When time is an issue, brush layering may be a more appropriate option, as it establishes more quickly than fascines (Fay et al. 2012).

2.6.3. Brush Layering

In brush layering, live branch cuttings are placed in small terraces excavated horizontally along a slope and supported on a small, short log or board (Gray and Sotir 1992; Sheng 1990). This method is similar to live fascines that involve cutting and placement of live branch cuttings into the slopes. The differences between brush layering and live fascines are the depth of brush layers in the slope and the orientation of the branches that are perpendicular to the slope contour (Lewis 2000). Figure 2-34 illustrates the installation of brush layering.

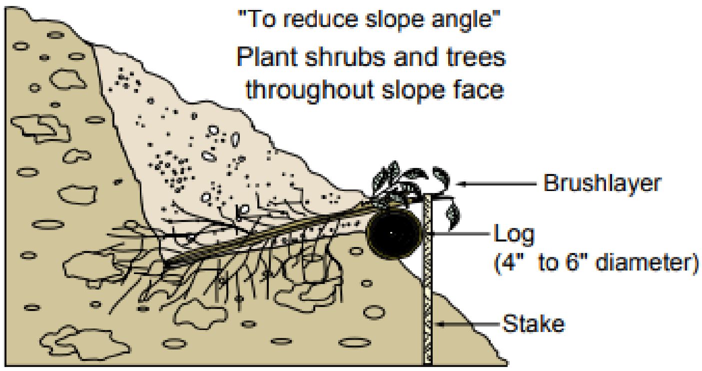

Figure 2-34 Installation of brush layering (Lewis 2000)

The horizontal and vertical plantings of live plant cuttings provide site reinforcement immediately after construction. After a while, when the buried stems grow roots and leaf-out, the secondary stabilization occurs (Adair et al. 2002). The density of plantings is a key factor in stabilization procedure. High density planting helps in drying out the wet slopes and in providing more stability (Eubanks and Meadows 2002). This method provides slope stability and improves vegetative cover establishment. Brush layering also improves the infiltration and drainage of wet slopes (Lewis 2000).

Although the construction of brush layering is simple and fast, it requires more excavation compared to live staking and live fascine methods (Donat 1995). Brush layering can be comparatively expensive and labor intensive especially when large amounts of backfill are needed (Alaska Department of Fish and Game 2005).

Gray and Sotir (1992) reported a brush layering slope stabilization project on Greenfield Road, Route 112, in northern Massachusetts. In this project, environmental concerns were the key criteria in the selection of suitable slope repair method. This method created a visually pleasing landscape and showed a satisfactory performance after installation (Gray and Sotir 1992).

2.6.4. Log Terracing

In log terracing, the log reinforced earthen terraces are used to decrease the slope length and steepness. Log terracing provides more stable areas for planting and growing plants (Adair et al. 2002). In this method, the logs can be placed in different ways. The most effective patterns are shown in Figure 2-44. It is critical to place logs so that no gaps exist between the log and soil surface (Lewis 2000). Figure 2-35 shows a plan view of different log placing patterns. Log terracing increases infiltration, adds roughness, reduces erosion, and helps retain small eroded soil on site (USDA 2017a).

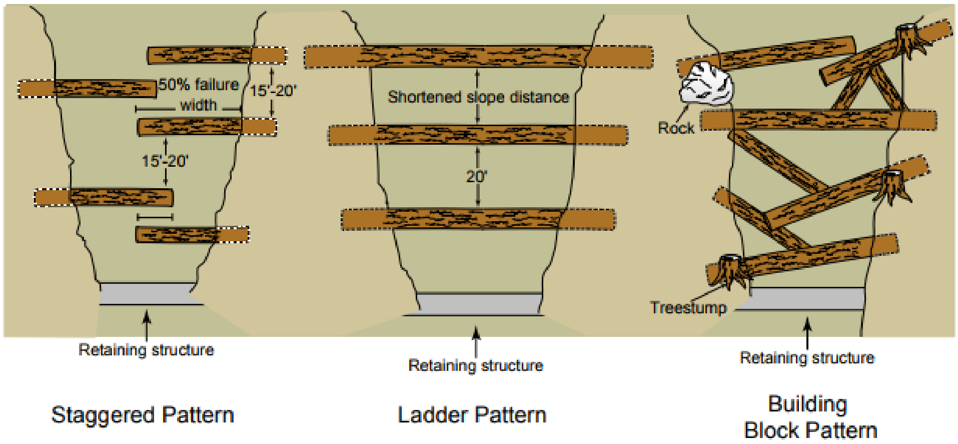

Figure 2-35 Log terrace installation (Lewis 2000)

Although log terraces can be adopted on slopes up to 70 percent, their effect decreases significantly on slopes steeper than 50 percent (USDA 2017a). Log terracing provides short-term protection on slopes (1–3 years) until a permanent vegetation is established to provide a long-term stabilization (USDA 2017a).

This biotechnical slope stabilization method often requires vehicles and equipment to deliver and move heavy logs. Therefore, this method is labor intensive with high potential safety hazards during construction (Lewis 2000).

2.6.5. Vegetated Geotextile

A vegetated geotextile is made of successive soil lifts with a mix of live branches, separated and wrapped by synthetic control fabric (Lewis 2000). Fabrics used in vegetated geotextiles are typically made of biodegradable materials such as jute, kokos, wood-wool, reed, flax, or synthetic fibers, such as cellulose (Donat 1995). These fabrics only last until sufficient rooting is established.

Figure 2-36 illustrates different vegetated geotextile layers. Vegetated geotextiles are mostly used to stabilize the loose topsoil layers of slopes. They can be installed for wall structures as well (Donat 1995).

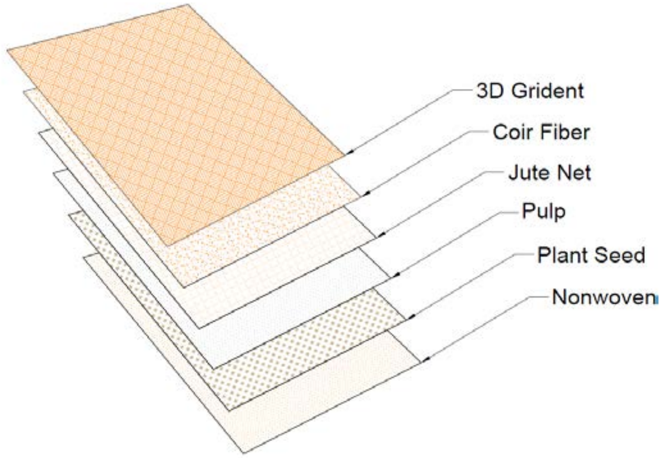

Figure 2-36 Geotextile-vegetation mats, non-woven geotextile (Adopted from BuyKorea (2017))

In this method, the failed soil mass is removed and vegetated geogrids are placed in layers. Then, the branch cuttings are located between layers. Once the live branch cuttings are established, they help to bind geogrids together and stabilize the slope by providing a root structure behind the slope (Greenway et al. 2012). Figure 2-37 shows the profile of a reinforced slope using vegetated geogrids.

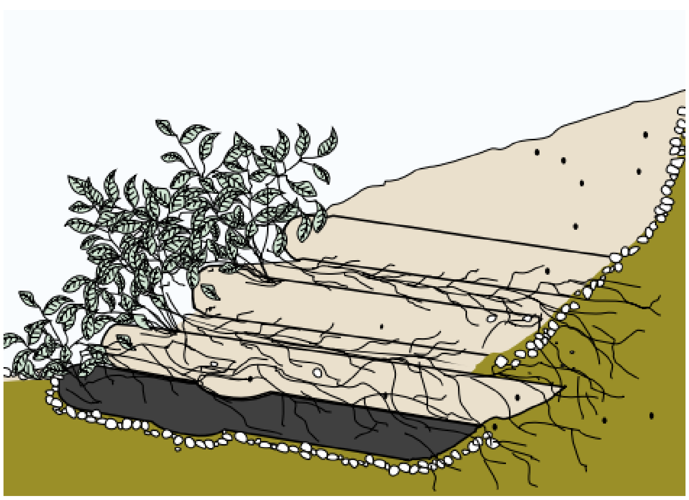

Figure 2-37 Using vegetated geogrids for slope stabilization (Lewis 2000)

This method results in a high quality and long performing slope, because it stabilizes the slope immediately after installment, and once the vegetation and cuttings are established, the slope becomes even more stable (USDA 2017b). In addition, it is considered as an aesthetically pleasing slope stabilization method (Greenway et al. 2012).

Using vegetated geogrids for slope stabilization is labor intensive. In some cases, this method requires heavy equipment for excavation and backfilling (USDA 2017b). However, in comparison with the other retaining wall structures such as gabions or MSE walls, it is less expensive (Lewis 2000). The material cost for this method is estimated form $13 to $30 per linear foot and the total construction costs varies between $50 and $200 per linear foot (NSP 2006).

2.6.6. Branch Packing

Branch packing is a bioengineering technique consisting of alternating layers of live branches and compacted backfill. The branch packing method is used to repair small slope failures or holes by live branch cuttings and compacted backfills (Adair et al. 2002). This method is suitable for slope failures less than 4 feet deep and 5 feet wide on sites with slopes greater than 2H:1V. The goal of branch packing is to repair the missing sections of failed slopes and control top soil erosion (DCR 2004; Greenway et al. 2012). The branch packing method is very similar to brush layering. In the branch packing method, the live material is placed horizontally and fixed using vertically inert material such as branches. However, in the brush layering method the branches are supported with small logs or boards.

Like other biotechnical slope stabilization methods, the branch packing method reinforces the soil in two stages. Immediate reinforcement happens after installing the branches and then the additional protection occurs once the branches and vegetation grow and leaf out (USDA 2002). In addition, this method is proper for repairing holes in embankments or small slumps (Fay et al. 2012). This method is not an expensive method and it does not require special installation skill. Moreover, this method provides an aesthetically pleasing view to repaired slopes.

In addition to general limitations that are attributed to biotechnical slope repair methods, the use of this method is only limited to small slumps and failures (Greenway et al. 2012). Figure 2-38 illustrates repairing a small slump in a slope using the branch packing method.

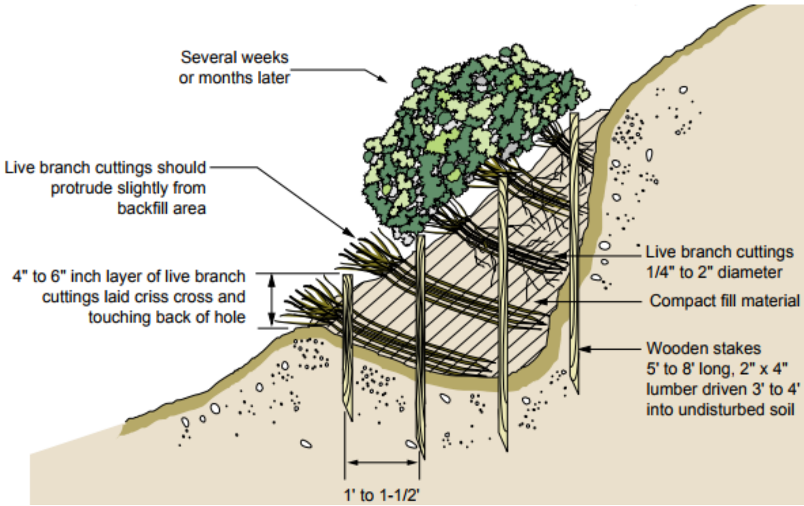

Figure 2-38 Branch packing (Lewis 2000)

2.6.7. Live Crib Walls

A crib wall is a boxlike chamber that can be constructed from untreated logs or timbers. It is filled with layers of rock, gravel, soil or other fill materials. In live crib walls, live branches are mixed with local soil to fill the crib wall. After a while, the live branches take roots inside of the box and extend into the slope. This root system helps to bind the crib wall structure to the slope mass (Greenway et al. 2012).

The live crib walls are mostly built at the toe of the slope with a maximum height of 2 meters to stabilize the toe of the slope, to prevent small failures, and to reduce slope steepness (USDA 1992; Lewis 2000; Greenway et al. 2012). These walls are not applicable to support slope against large lateral stresses (Fay et al. 2012). Figure 2-39 illustrates placing of the crib wall and the branches in a slope. The material used in this method are readily available but for excavation, but heavy equipment is needed (Greenway et al. 2012).

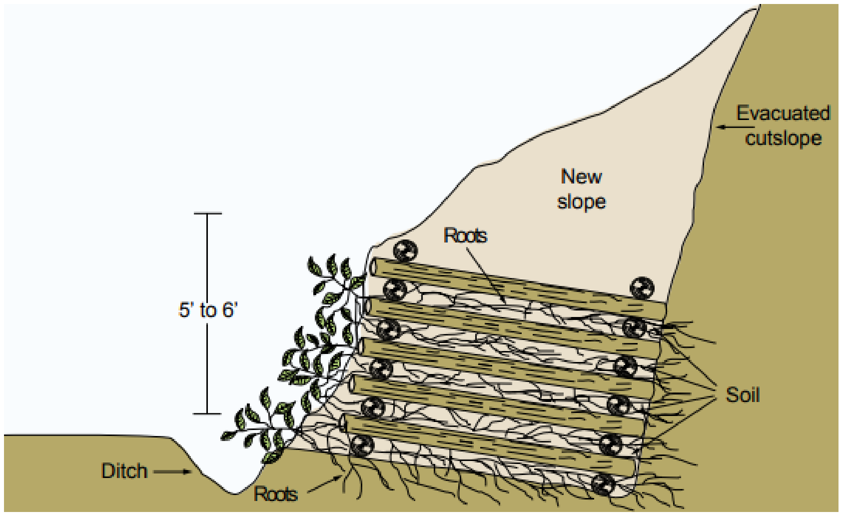

Figure 2-39 Live crib walls (Lewis 2000)

Live crib walls are expensive and labor intensive in comparison with the other biotechnical slope stabilization. The total cost of slope repair with live crib walls is approximately $100 to $400 per linear foot (Kosiw et al. 2008). This method has a short construction time and improves the aesthetics of the slope after growth of the branches (Greenway et al. 2012; Redfield 2017).

One of the most important limitations of live crib walls is that they cannot bear large lateral earth stresses (Lewis 2000). Therefore, their design is limited to a maximum of two meters height (Greenway et al. 2012). Also, this method is labor intensive and requires machinery for transferring and placing the logs.

2.7. SLOPE REPAIR METHODS USING ADDITIVES

Soil stabilization using additives is the process of altering soil properties by adding a certain amount of material such as chemical and biochemical material to the soil. This process may also include blending soils to achieve a desired gradation. In some cases, mixing additives to the soil creates a cementing action that binds soil particles together to increase their shear strength (Collin et al 2008). Hence, 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). For instance, altering soil properties, such as plasticity, gradation, and workability, typically requires smaller amounts of additives in comparison to improving soil characteristics, such as strength and durability (U.S. Army Corps of Engineers 1984).

Although, slope stabilization using additives 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, uncemented 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.

2.7.1. 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 where 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).

Slope stabilization using lime has several advantages, such as increasing soil shear strength, decreasing soil plasticity (increasing workability), increasing slope durability, decreasing consolidation and settlement, and improving compressibility properties (National Lime Association 2004). On the other hand, 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.

2.7.2. 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).

Review of case histories and laboratory test results by Abramson et al. (2002) indicated that the mix designs used for slope stabilization generally consist of 1 to 10 percent cement by weight of the soil to produce cohesive strengths of 25 to greater than 125 pounds per square inch. Amount of the cement and the type of soil are two primary factors, which affect the performance of this method and the degree of soil improvement (Portland Cement Association 1995). Unconfined compressive strength of the soil-cement mixture is significantly affected by the soil type. For instance, the compressive strength of soil-cement in coarser soils including higher percentage of gravel is more than the clayey and silty soils. The reason for the difference is that in coarser soils the grains have greater contact areas that need to be cemented compared to the finer ones. Moreover, the compressive strength of soil-cement mixtures almost doubles between a curing period of seven and 28 days (Haralambos 2009).

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).

2.7.3. 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. Fly ash is classified into two classes of C and F, by its calcium oxide (CaO) content (Onyelowe and Okafor 2012). Class C is a combination of a pozzolan and self-setting material. When fly ash is combined with water, a cementitious reaction occurs, which results in binding of particles together. Class F is a pozzolan that often requires an activator such as lime or cement (TxDOT 2005). The reactions prompted by fly ash occur more slowly than cement but more rapidly than lime (Xu and Sarkar 1993).

Typical highway engineering applications of fly ash are: soil and road base stabilization, flowable fills, grouts, structural fills (embankments), and asphalt fillers (American Coal Ash Association 2003). Fly ash is also used for soil drying and control of shrink-swell (American Coal Ash Association 2003).

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 stored in silos, domes and other bulk storage facilities where it is kept dry. It 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). For long-term stability of fly ash embankments, a factor of safety of 1.5 is recommended using the Swedish circle method of slope stability analysis (FHWA 2016).

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.

2.8. 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 also 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.

2.8.1. 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, regrading 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 2-40 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).

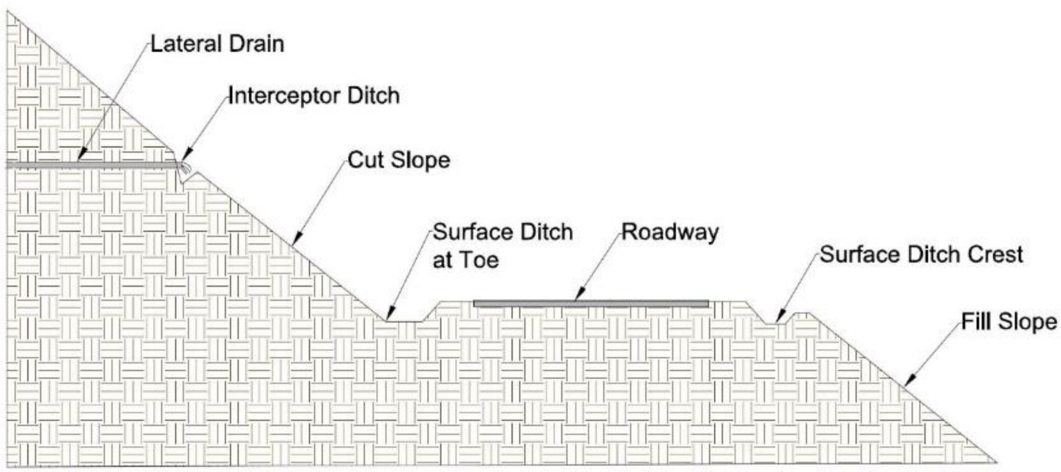

Figure 2-40 Different surface ditches

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. In emergency situations, it is recommended to cover the cracks with plastic sheets to prevent further disruptions, until a more permanent solution is provided.

Regrading and using vegetation are other activities that controls surface water runoff and prevents excessive infiltration of surface water into the slope. Potholes and sloughs should be refilled and regraded to the original slope surface. 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).

2.8.2. 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 a good early treatment to control and discharge groundwater at roadside slopes (Collin et al. 2008). This method can be used where the depth-to-subsurface groundwater is so great that placing drainage trenches is not cost-effective (Abramson et al. 2002). 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). Figure 2-41 illustrates the application of this method for slope stabilization. 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).

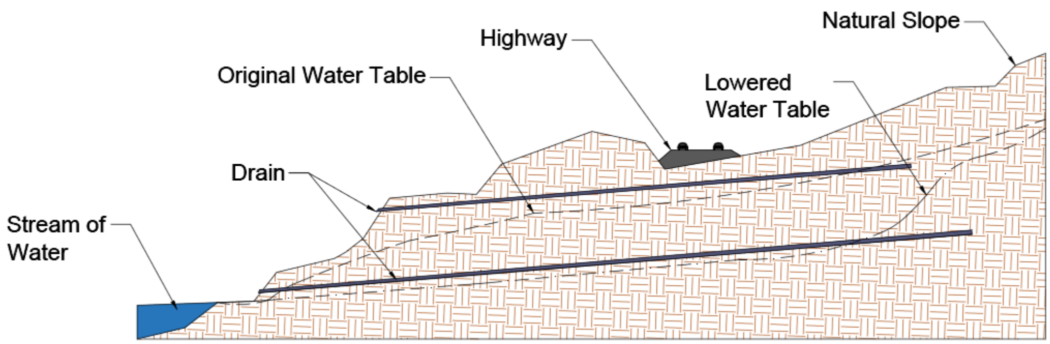

Figure 2-41 Horizontal drains (Adopted from Abramson et al. (2002))

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. Figure 2-42 shows the typical location of the drainage blanket. 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.

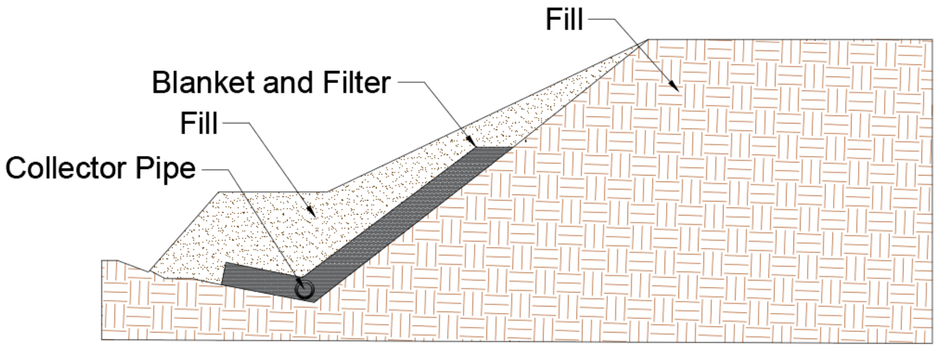

Figure 2-42 Typical drainage blanket (Adopted from Collin et al. (2008))

Wick drains are artificial drainage paths consisting of a central plastic core, which functions as a free-draining water channel, surrounded by a thin geotextile filter jacket (U.S. Wick Drain Inc. 2017). Wick drains used vertically (Fellenius 1999) are also called vertical drains. Horizontal drains direct the underground water away from the slopes and embankments (Santi et al. 2001). A typical wick drain is approximately 4 inches wide, 1/8 inch thick, and comes in rolls of up to 1,000 feet (U.S. Wick Drain Inc. 2017). Figure 2–43 shows a typical wick drain. Wick drains are installed by pushing or vibrating into the ground with specialized equipment, called stitchers, mounted on either backhoes or cranes. Figure 2-44 illustrates an example of wick drain installation.

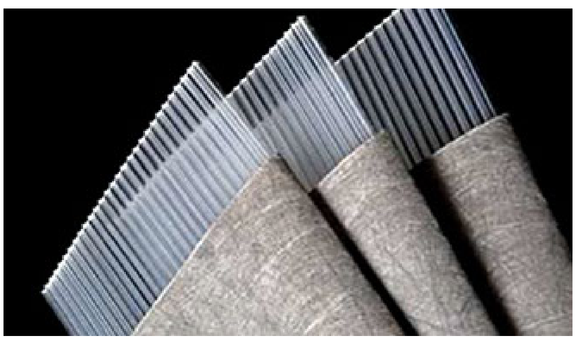

Figure 2-43 Wick drains (Reprinted from "Prefabricated Vertical Drains" by CeTeau, by permission of de Zwart, Year of first publication: 2017)

Figure 2-44 Wick drain installation (Reprinted from “Prefabricated Vertical Drains” by CeTeau, by permission of de Zwart, Year of first publication: 2017)

Horizontal wick drains offer several advantages over conventional horizontal drains. They are inexpensive, resist clogging, and can undergo deformation without rupture (Hossain et al. 2017). Wick drains are suitable for reducing pore water pressure in slopes with fine soils. Furthermore, this method is one of the best options to accelerate settlements in large earthwork projects (Deschamps and Lange 1999).

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. Filtration allows groundwater to drain from the soil without building up pressure (Fey et al. 2012).

Chapter 3. SURVEY ANALYSIS

A survey questionnaire was designed to identify the current state of practice in repairing embankment slope failures. The survey draft was submitted to the TxDOT Research and Technology Implementation (RTI) technical panel for review. The survey questionnaire was revised and finalized based on comments and suggestions received from the panel. After TxDOT technical panel approval, the principal investigator (PI) of the project acquired Institutional Review Board (IRB) approval before conducting the survey. The research team used "SurveyMonkey.com" as an online platform to conduct the survey for this research project. A printable format of the final survey questionnaire is presented in Appendix A. The survey was distributed among experienced area engineers and maintenance supervisors in the field of embankment slope repairs, from all TxDOT districts. The survey was also distributed among members of The Transportation Research Board (TRB) Standing Committee on Engineering Geology to capture the state of practice in the other states. To distribute the survey, an invitation email along with the online link to the survey was sent to survey respondents. In addition, a Portable Document Format (PDF) file of the survey was sent to the respondents upon their request. Appendix B presents the email draft sent to the survey respondents.

3.1. SURVEY QUESTIONNAIRE

The questionnaire starts with a brief description of the project and instructions on how to complete the survey. Section 1 of the survey collects the contact information and location of survey respondents. Section 2 collects information on the frequency of recurring shallow slope failures and the conditions that institute a formal analysis to select a repair method. Section 3 provides a list of 18 slope repair methods and asks for an evaluation of the methods that each respondent has had experience with. This section is designed in a way that the respondents could quickly skip the methods that they had no experience with. For the evaluation of each repair method, respondents are asked about the performance of the method, reasons for selecting the method, the workforce who implemented the method (in-house maintenance crew or private contractor), and general information about the repaired embankment slope, such as soil characteristics and the degree of slope. Finally, Section 4 of the survey asks if the respondents are willing to participate in a follow-up interview.

3.2. SURVEY RESPONSES

In total, 37 responses were collected from the surveys distributed between professionals from in-state and out-of-state departments of transportation. These include 33 responses from TxDOT districts and four out-of-state responses from Colorado, Kansas, Wyoming, and West Virginia DOTs. Figure 3-1 illustrates the location and position of respondents from TxDOT. The location of survey responses covers 17 out of 25 TxDOT districts. Most of the survey respondents were among area engineers and maintenance supervisors who have the most interaction with slope repair projects.

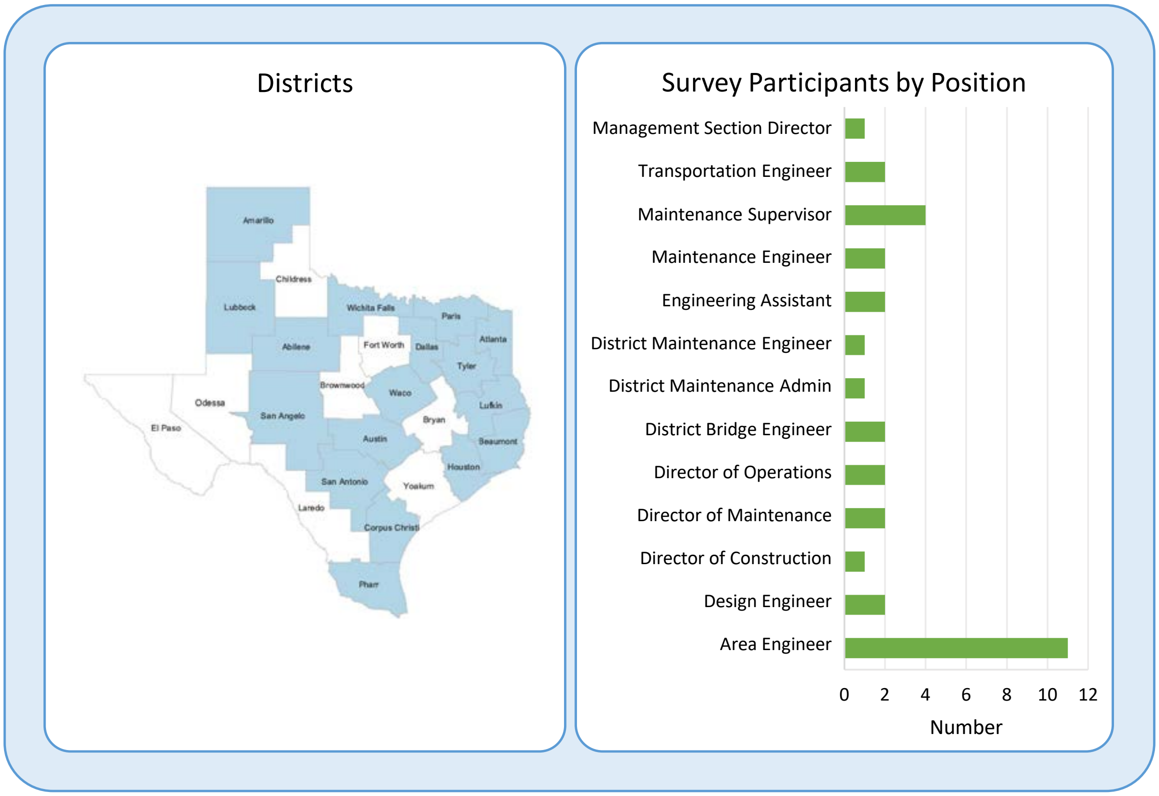

Figure 3-1 Summary of survey responses to Section 1 of the survey

Figure 3-2 summarizes collected information on the frequency of recurring shallow slope failures and the conditions that constitute a formal analysis to select a repair method. The survey results indicate that the rate of recurring slope failures in Texas is more than 50 percent (approximately 55%). This result means that more than half of the slopes that were repaired have been repaired before. Figure 3-2 also illustrates the popularity of each slope repair method in Texas. Rebuilding and compaction, retaining structures, and geosynthetics are the most used methods reported by the survey respondents. Another valuable information contribution acquired from this section of the survey is recognition of the conditions which determine when TxDOT maintenance workforces adopt a formal analysis to select a slope repair method. The results show that the TxDOT maintenance workforces usually select a formal analysis to determine a slope repair method when a slope has failed more than once or when the pavement or adjacent structures such as a bridge are affected by the slope failure.

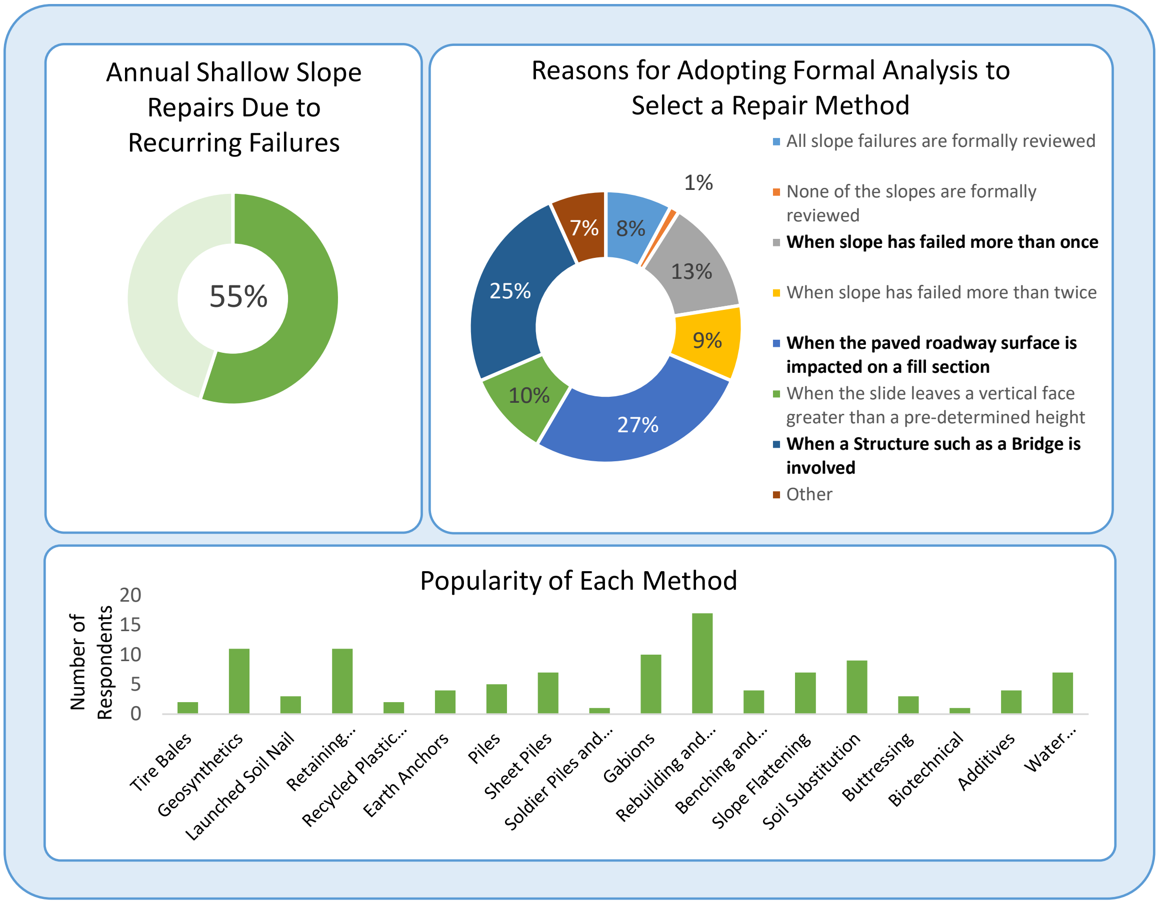

Figure 3-2 Summary of survey responses to Section 2 of the survey

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

3.2.1. Tire Bales

3.2.1.1. In-State Survey Results

Survey results on the evaluation of the tire bale method are summarized in Figure 3-3. Two respondents had used the tire bale method for repairing embankment slope failures. One of the respondents experienced failure for a slope repaired using this method. No special equipment requirements, rapidity, and low cost are among the main reasons for selecting this method. The respondents had only used this method in clayey soil with high plasticity and slope angles up to 3:1 (H:V). Tire bales are used in slopes with good drainage conditions. The tire bale method is traditionally implemented by an in-house maintenance crew or professional contractors.

3.2.1.2. Out-of-State Survey Results

Tire bales have also been adopted in other states, such as Wyoming and West Virginia. Long-term service life and low cost are among the reasons for selecting this method. Tire bales have been used in slopes with angles up to 2:1 in clayey soil and with poor drainage conditions. One of the respondents had experienced failure of a slope repaired using this method.

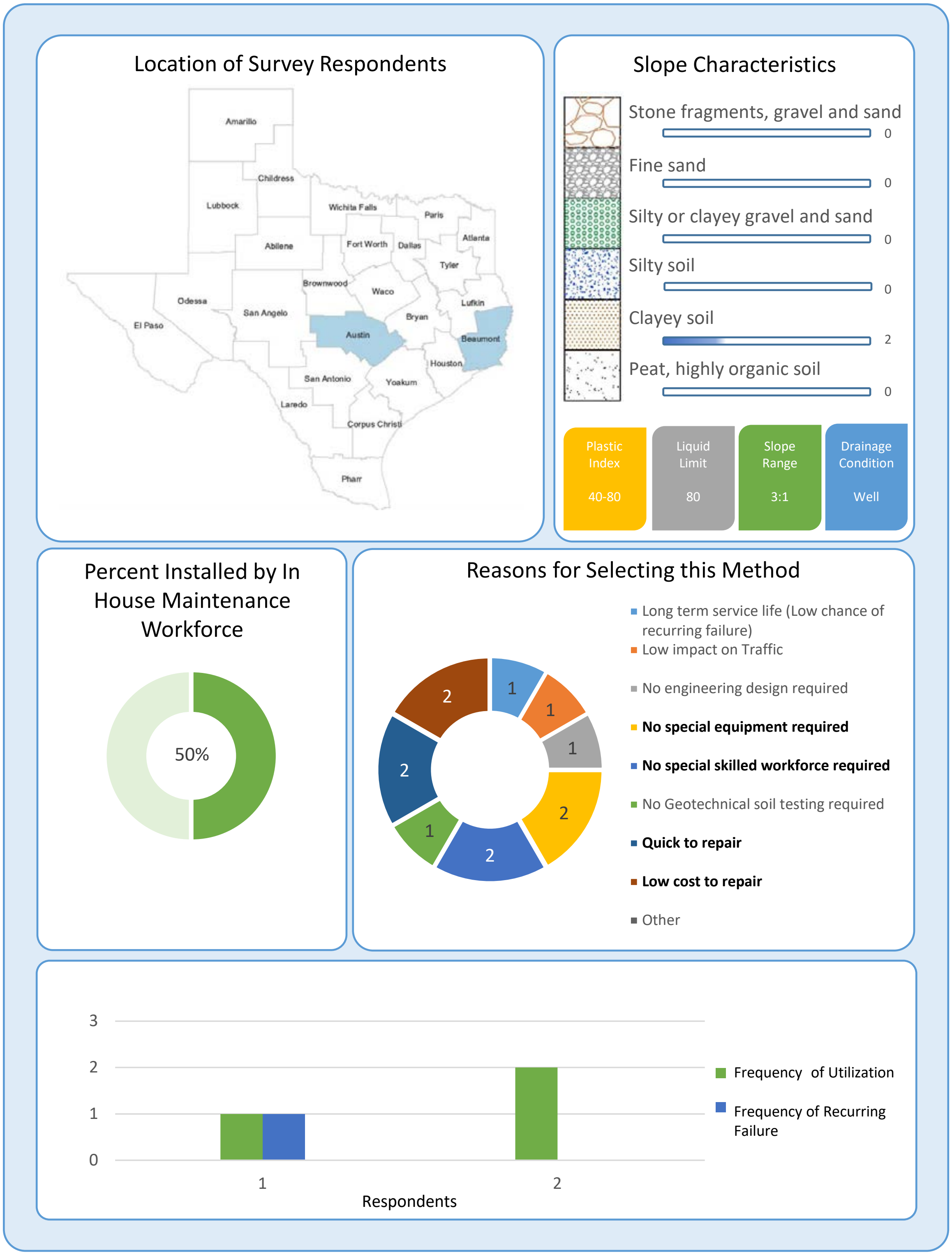

Figure 3-3 Summary of survey results for tire bale method

3.2.2. Geosynthetics

3.2.2.1. In-State Survey Results

Survey results on the evaluation of the geosynthetic method are summarized in Figure 3-4. Sixteen respondents from different parts of Texas had used the geosynthetic method for repairing embankment slope failures. Survey responses show that geogrids are more popular for embankment slope repair projects compared to geotextiles and geofoams. Results illustrate that a few slopes repaired by geosynthetics have failed. Nevertheless, long-term service life is the main reason for the selection of this method by professionals. No specialized equipment and skilled workforce requirements, rapidity, and low cost are among the other key reasons for selecting this method. Survey results show that geosynthetics have been used in various slope grades and soil types including clayey soil, silty soil, silty or clayey gravel and sand, and fine sand. Geosynthetics have been used in slopes with a variety of drainage conditions (poor to good). Results also show that typically, professional contractors perform slope repair projects using geosynthetics.

3.2.2.2. Out-of-State Survey Results

Various types of geosynthetics have been adopted in other states, such as Colorado, Kansas, and West Virginia. Similar to in-state survey results, long-term service life, rapidity, and low cost are among the reasons for selecting this method. Geosynthetics have been used to repair slopes with various angles and poor drainage conditions. No recurring slope failures using this method were reported in the survey responses from the other states.

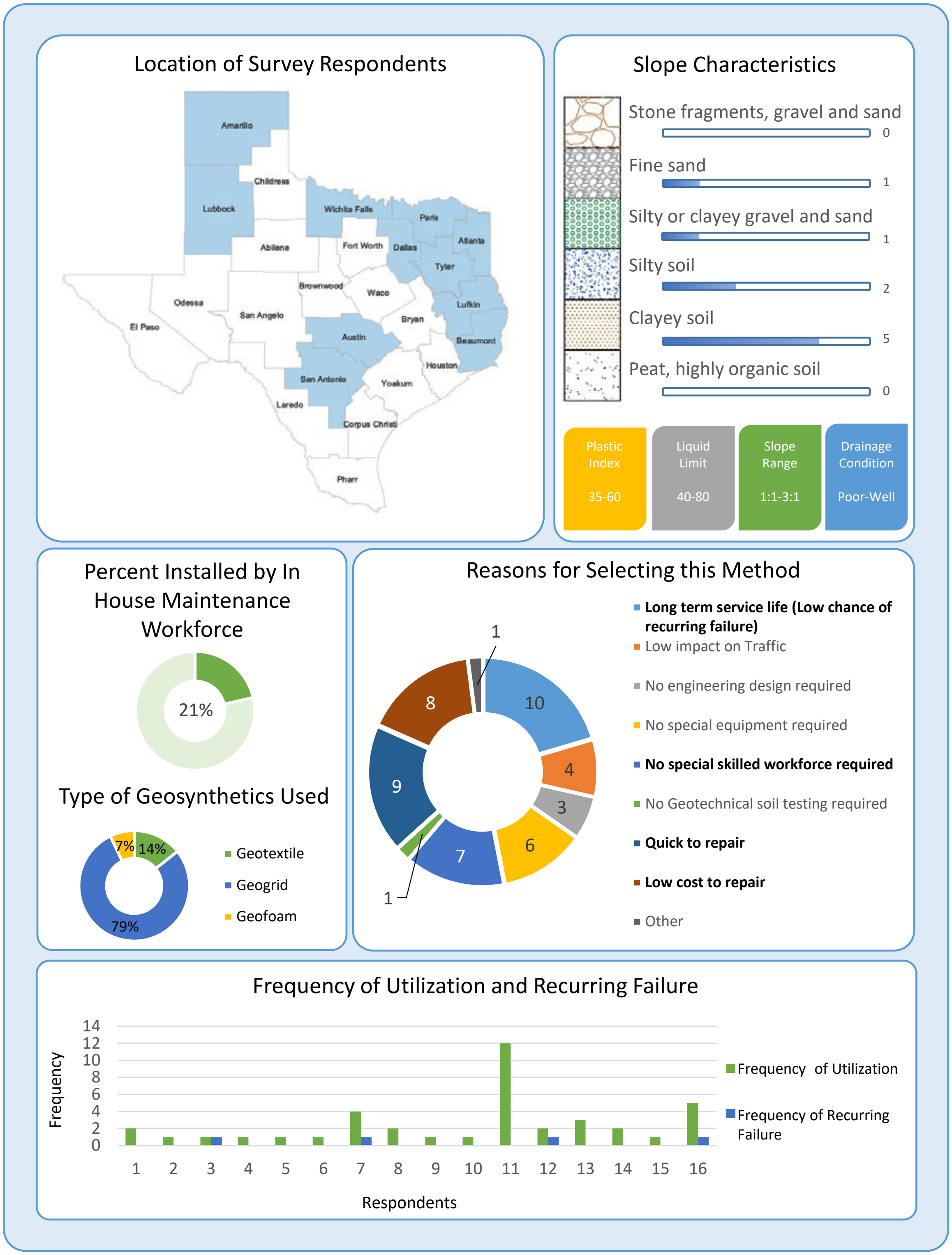

Figure 3-4 Summary of survey results for geosynthetic method

3.2.3. Launched Soil Nails

3.2.3.1. In-State Survey Results

Survey results on the evaluation of the launched soil nail method are summarized in Figure 3-5. Five respondents have used this method for repairing embankment slope failures. Only one of the respondents had experienced failure for a slope repaired using this method. Long-term service life and rapidity are the key reasons why professionals select this method. The respondents had only used this method in clayey soil. This method has been used for slopes with angles up to 1:1. Launched soil nails have been used in slopes with various drainage conditions (poor-good). This method has been implemented by the TxDOT maintenance crew in most of the projects.

3.2.3.2. Out-of-State Survey Results

The launched soil nail method has also been adopted in other states, such as Wyoming and Colorado. Long-term service life, low impact on traffic, rapidity, and low cost are among the reasons for selecting this method. Similar to the in-state survey results, the respondents had used the launched soil nail method in clayey soil.

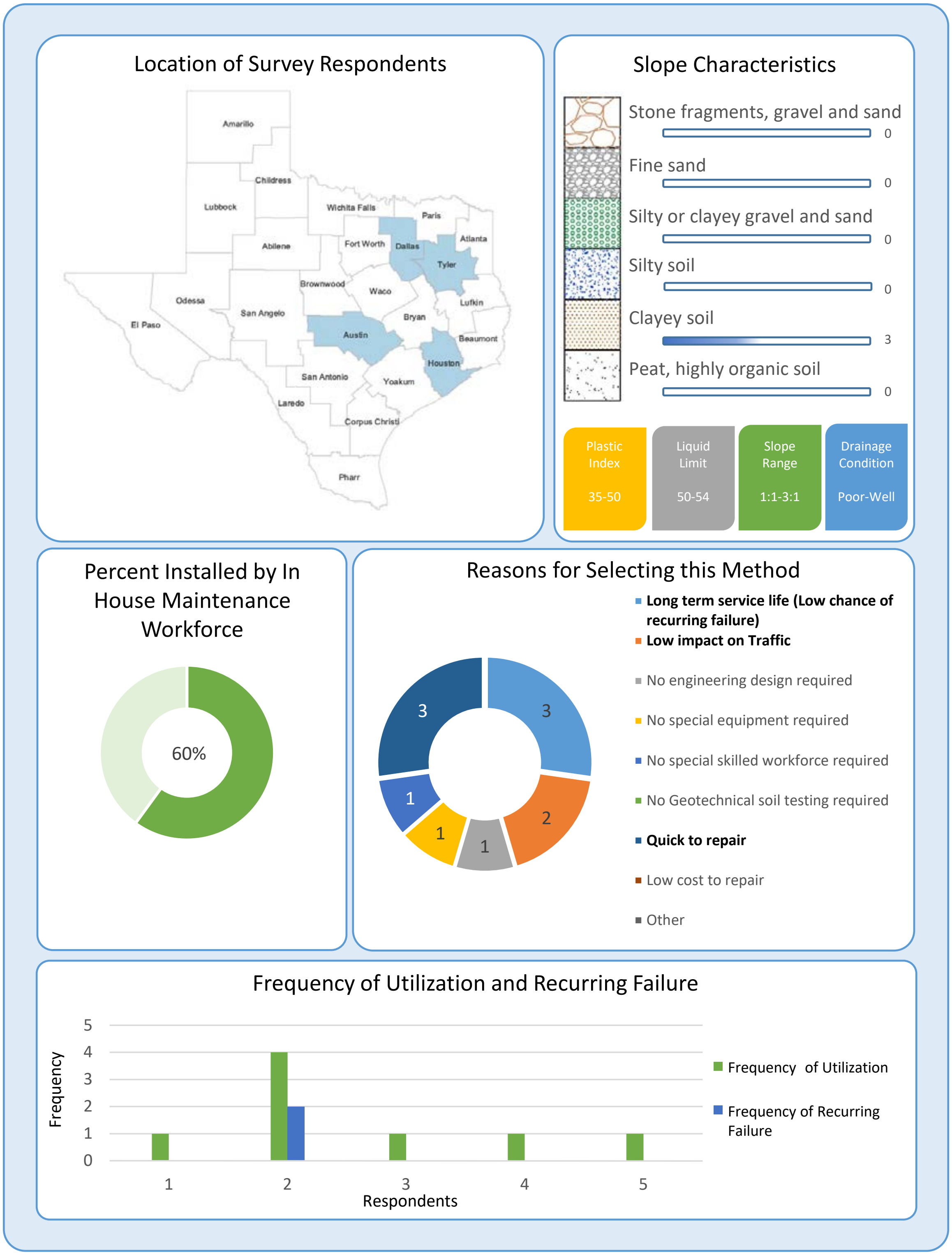

Figure 3-5 Summary of survey results for launched soil nail method

3.2.4. Retaining Structures

3.2.4.1. In-State Survey Results

Survey results on the evaluation of the retaining structure method are summarized in Figure 3-6. This method has been used in many parts of Texas for repairing embankment slope failures. Nineteen respondents had used the retaining structure method. Although the main reason for selecting retaining structures is their long-term performance, five respondents have experienced failure for some slopes repaired using this method. Low cost, rapidity, and no requirements for specialized equipment, skilled workforce, and geotechnical testing are among the other reasons for selecting this method. Retaining structures have been used to repair slopes with angles up to 1:1. They have been used in various types of soils including clayey soil, highly organic soil, and silty or clayey gravel and sand. This method has been used in soils with a wide range of plastic index and liquid limits. Retaining structures have also been used in slopes with a variety of drainage conditions (poor to good). Results show that typically professional contractors perform slope repair projects using retaining structures.

3.2.4.2. Out-of-State Survey Results

Retaining structures have also been adopted in other states, such as Colorado and West Virginia. Long-term service life is the key reason for selecting this method. No recurring slope failures using this method were reported in the survey responses.

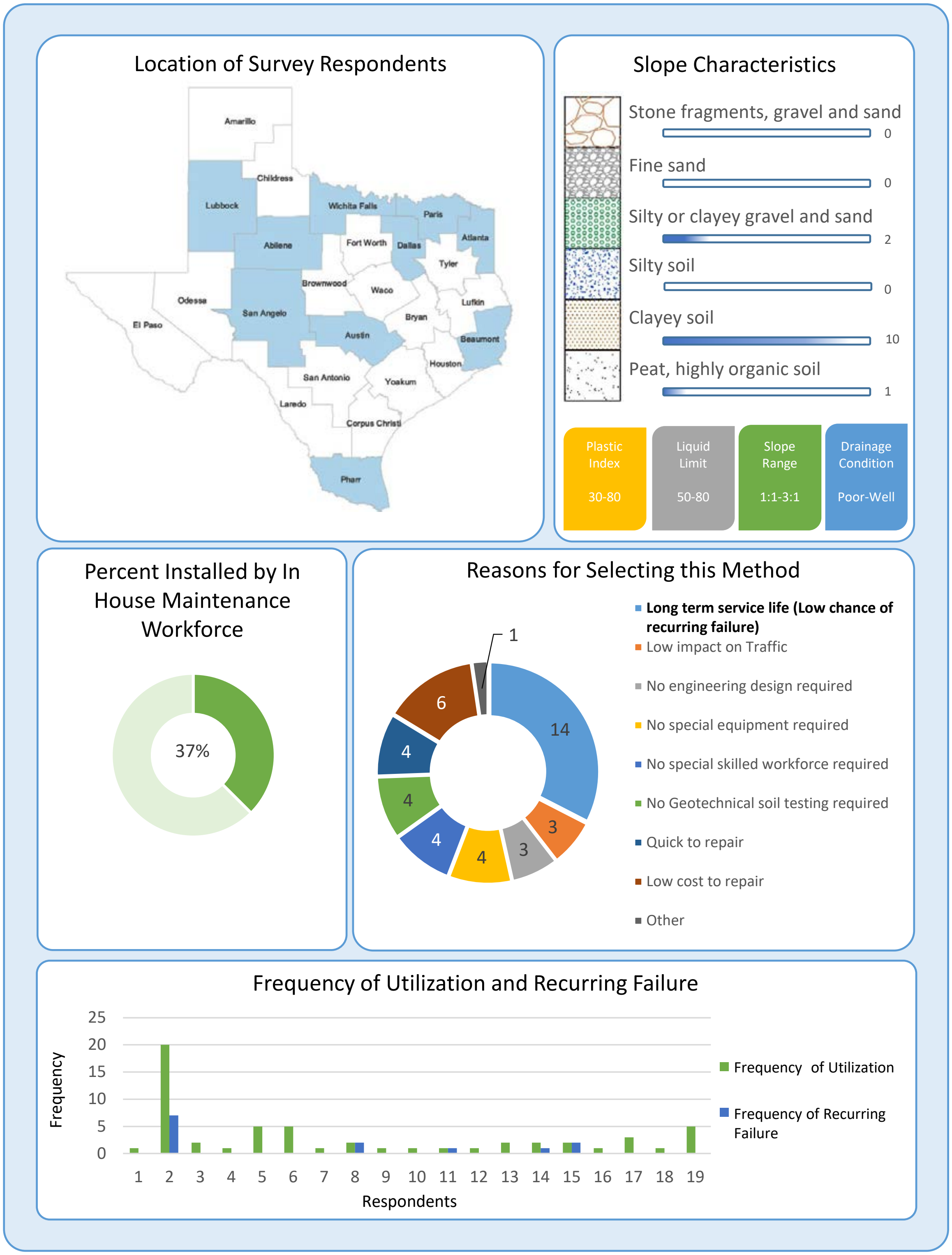

Figure 3-6 Summary of survey results for retaining structure method

3.2.5. Recycled Plastic Pins

3.2.5.1. In-State Survey Results

Survey results on the evaluation of the recycled plastic pin method are summarized in Figure 3-7. Three respondents had used this method for repairing embankment slope failures in Texas. One of the respondents had experienced failure for a few slopes repaired using this method. Rapidity is selected as the main reason for using this method. Long-term performance, low impact on traffic, and low cost are among the other reasons for selecting this method. Recycled plastic pins have been used to repair slopes with angles as steep as 2:1. This method has been used to repair slopes in various soil types including clayey soils and silty soils. Recycled plastic pins have also been used in slopes with a poor drainage condition. Results show that this method is typically implemented by professional contractors.

3.2.5.2. Out-of-State Survey Results

No survey respondents from other states reported using this method.

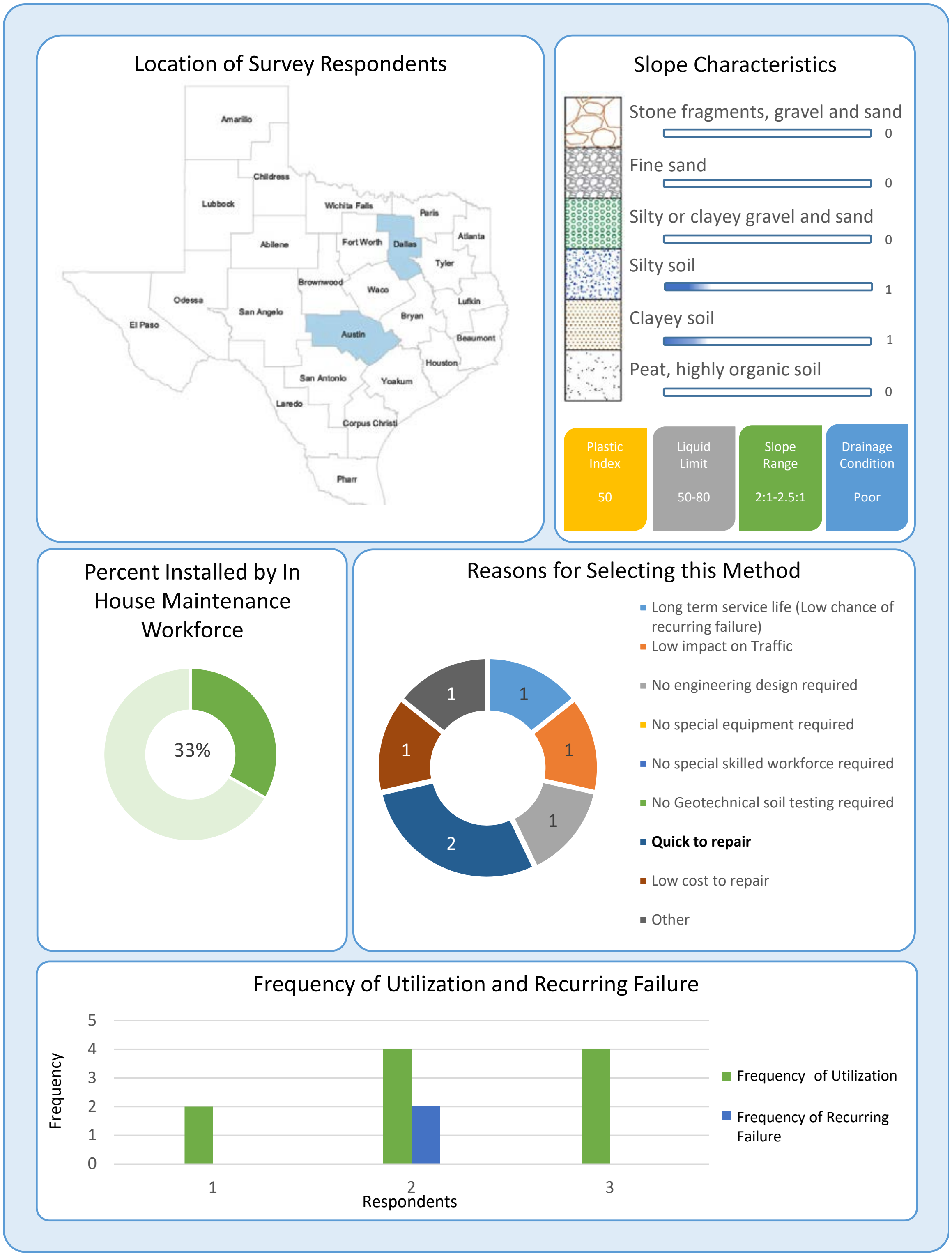

Figure 3-7 Summary of survey results for the recycled plastic pin method

3.2.6. Earth Anchors

3.2.6.1. In-State Survey Results

Survey results on the evaluation of the earth anchor method are summarized in Figure 3-8. Five respondents have used this method for repairing embankment slope failures. Two respondents had experienced recurrent slope failure where the earth anchor method was used. Nevertheless, long-term service life and low impact on traffic are the key reasons for selecting this method. Earth anchors have been used to repair steep slopes and even vertical walls. This method has been used to repair slopes in various soil types including clayey soil, fine sand, silty soil, and silty or clayey gravel and sand. Earth anchors have also been used in slopes with poor drainage conditions. Results show that 75 percent of the time, earth anchors are installed by professional contractors.

3.2.6.2. Out-of-State Survey Results

Earth anchors had also been used in other states, such as Wyoming and West Virginia. Long-term service life is the key reason for selecting this method. No recurring failure was reported for slopes repaired using this method. Moreover, earth anchors were used in silty or clayey gravel and sandy soils.

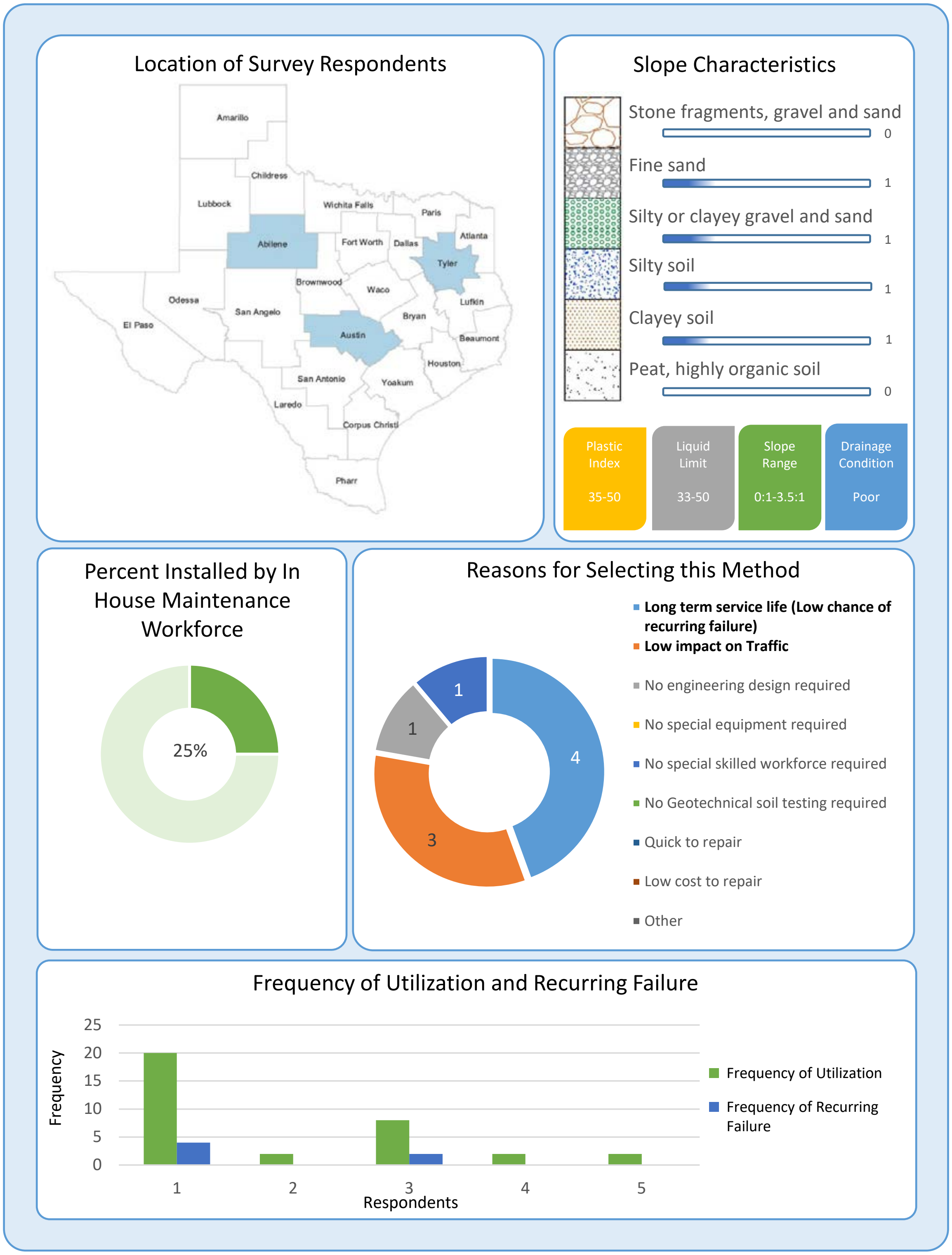

Figure 3-8 Summary of survey results for earth anchor method

3.2.7. Piles

3.2.7.1. In-State Survey Results

Survey results on the evaluation of the pile method are summarized in Figure 3-9. Five respondents had used this method for repairing embankment slope failures. Three respondents had experienced failure for a slope repaired using the pile method. Long-term service life is the key reason for selecting this method. Piles have been used to repair slopes with angles up to 3:1. This method has been used in clayey and silty soils with a wide range of plastic indexes and liquid limits. Piles have been used in slopes with various drainage conditions (poor-good). All the reported slope repair projects using piles had been performed by the TxDOT maintenance workforces.

3.2.7.2. Out-of-State Survey Results

Piles had also been used in other states, such as Wyoming and West Virginia. Similar to in-state survey results on this method, long-term service life is the key reason for selecting this method.

No recurring slope failures using this method were reported in the survey responses.

Moreover, piles had been used for repairing slopes with silty or clayey gravel and sandy soils.

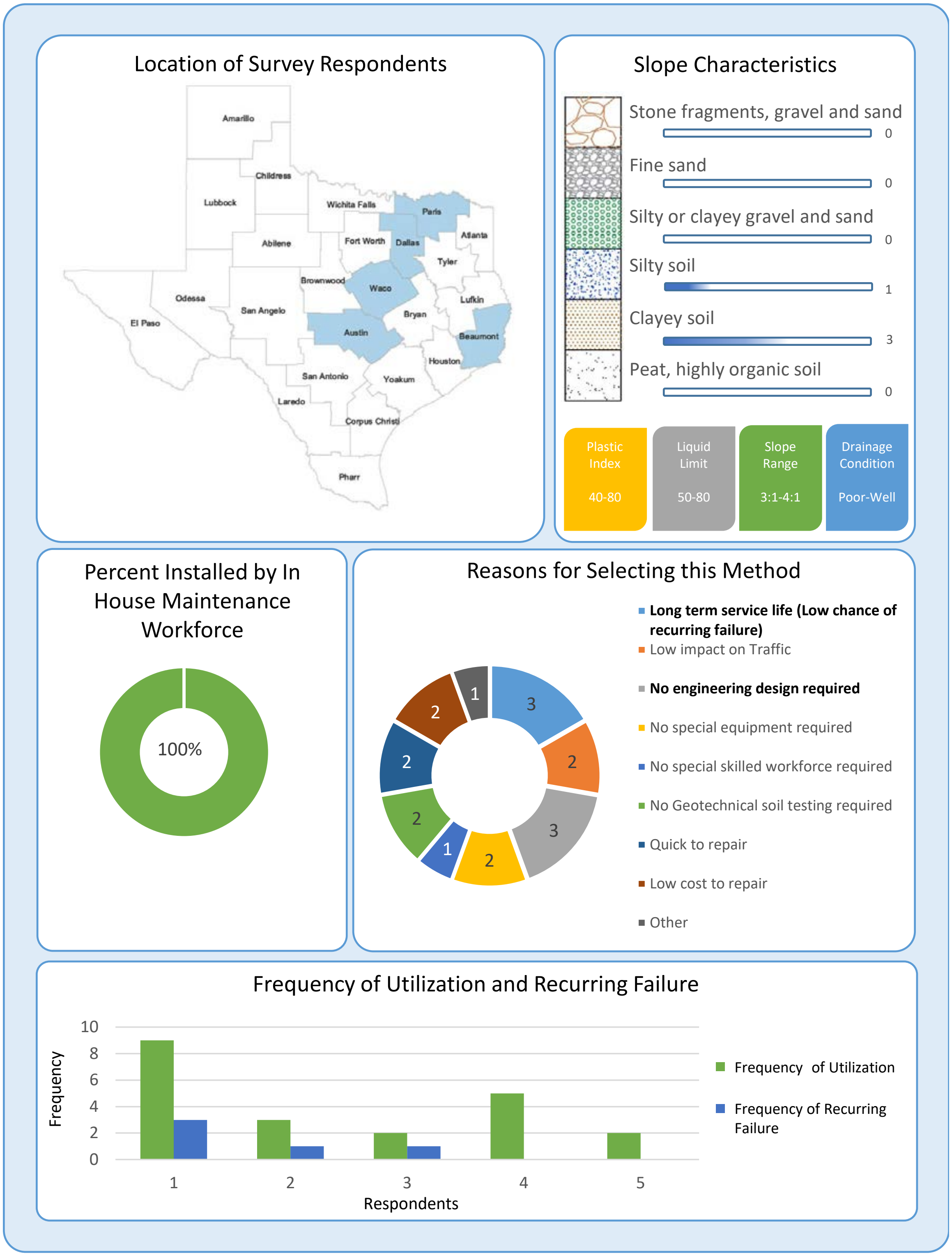

Figure 3-9 Summary of survey results for pile method

3.2.8. Sheet Piles

3.2.8.1. In-State Survey Results

Survey results on the evaluation of the sheet pile method are summarized in Figure 3-10. This method is popular mostly in the eastern and northern parts of Texas for repairing embankment slope failures. Ten respondents specified using sheet piles method. Although the main reason for the selection of the sheet pile method is its long-term performance, six respondents had experienced failure for a few slopes repaired using this method. Low impact on traffic, rapidity, and low costs are the other key reasons for selection of this method. Sheet piles have been used to repair slopes with angles as steep as 2:1. This method has been used to repair slopes in various soil types including clayey soils and fine sand. Sheet piles have also been used in slopes with a variety of drainage conditions (poor to good). Results show that typically professional contractors perform slope repair projects using sheet piles.

3.2.8.2. Out-of-State Survey Results

Sheet piles have also been used in other states, such as Wyoming and West Virginia. Long-term service life, low impact on traffic and rapidity were the key reasons for selecting this method by professionals. No recurring slope failures using this method were reported in the survey responses. Sheet piles were used to repair slopes with silty or clayey gravel and sandy soils.

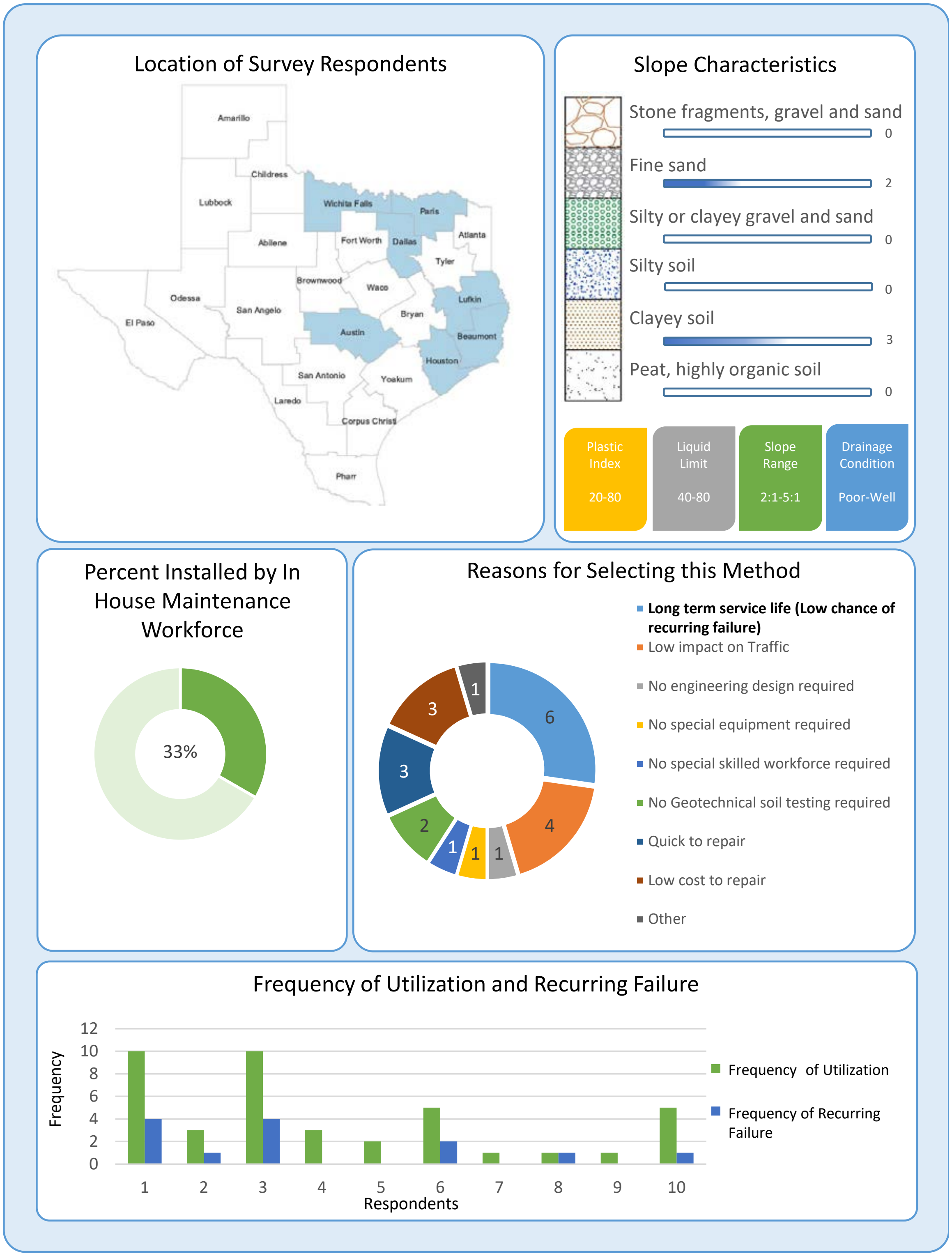

Figure 3-10 Summary of survey results for sheet pile method

3.2.9. Soldier Piles and Lagging

3.2.9.1. In-State Survey Results

Survey results on the evaluation of soldier pile and lagging method are summarized in Figure 3-11. Out of 33 in-state survey respondents, only one respondent specified using this method to repair embankment slope failures. This result indicates that the soldier pile and lagging method is not a popular method for slope repair projects in Texas. No recurring slope failure using this method is reported in the survey responses. Rapidity, long-term performance, and no special skilled workforces were specified as the key reasons for selecting this method. Results show that typically professional contractors perform slope repair projects using soldier piles and lagging.

3.2.9.2. Out-of-State Survey Results

The soldier pile and lagging method was also reported as having been used in other states. A survey respondent from Wyoming specified this method as a popular method in this state. Long-term service life was specified as the main reason for selecting this method. A 10 percent recurring slope failure using this method was reported in the survey responses.

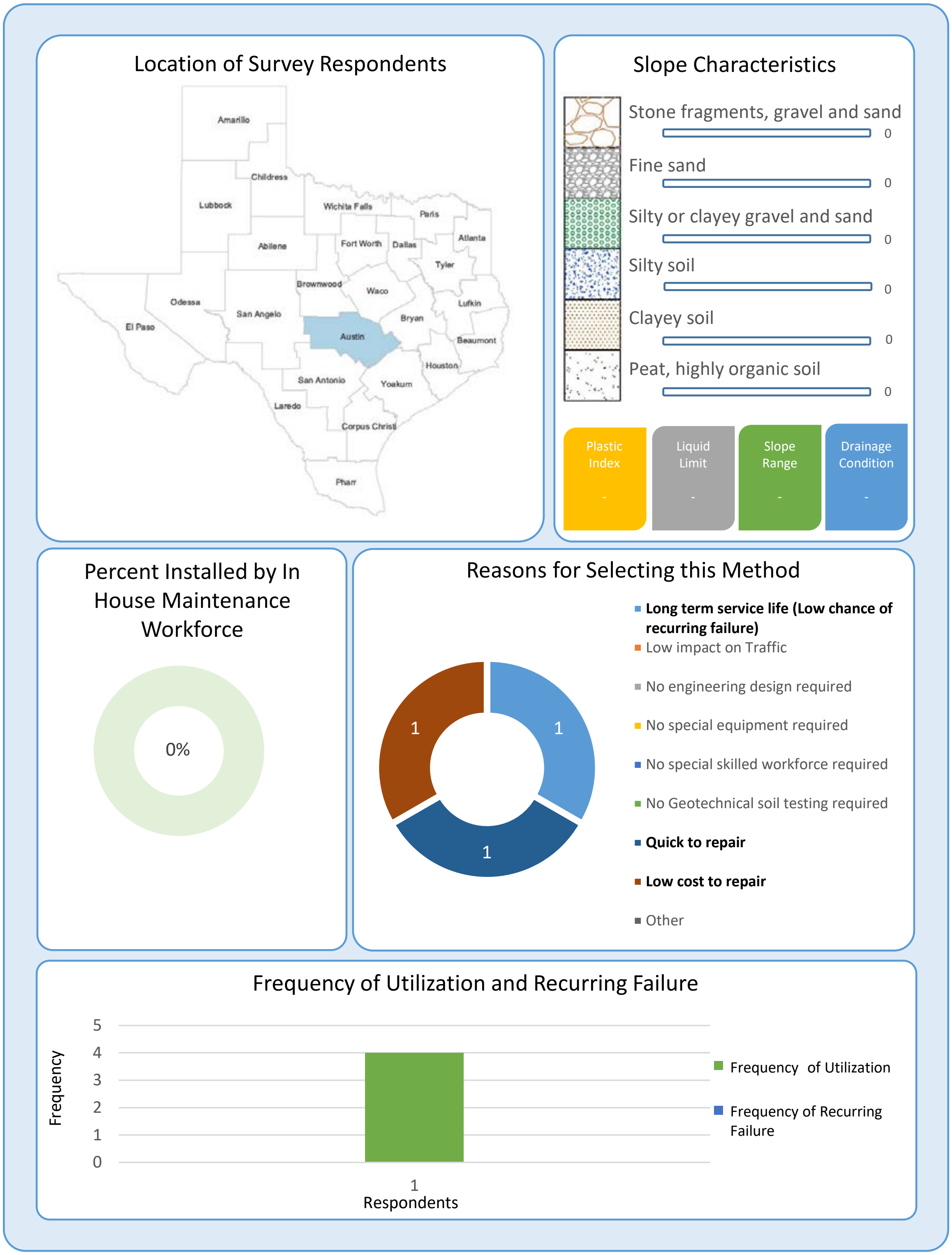

Figure 3-11 Summary of survey results for soldier pile and lagging method

3.2.10. Gabions

3.2.10.1. In-State Survey Results

Survey results on the evaluation of the gabion method are summarized in Figure 3-12. This method has been used in many parts of Texas to repair embankment slope failures. Fifteen respondents have specified using gabions. Although the main reason for selecting gabions is their long-term performance, six respondents had experienced recurring failures where this method was used. No specialized workforce requirements and rapidity were among the other key reasons for selecting this method. Other reasons stated by survey respondents focused on the appropriateness of this method near streams and its popularity. Gabions have been used to repair slopes with various angles and even vertical walls. This method has also been used to repair slopes with various soil types including clayey soil, fine sand, and silty soil. Gabions have been used in slopes with a variety of drainage conditions (poor to good). Results show that typically professional contractors perform slope repair projects using retaining structures.

3.2.10.2. Out-of-State Survey Results

Gabions have also been used in other states, such as Wyoming and West Virginia. Long-term service life, low cost, and rapidity were the key reasons for selecting this method by professionals. Gabions were used to repair slopes with angles up to 1.5:1. Furthermore, survey results indicate a high percentage (more than 50 percent) of recurring failure for this repair method.

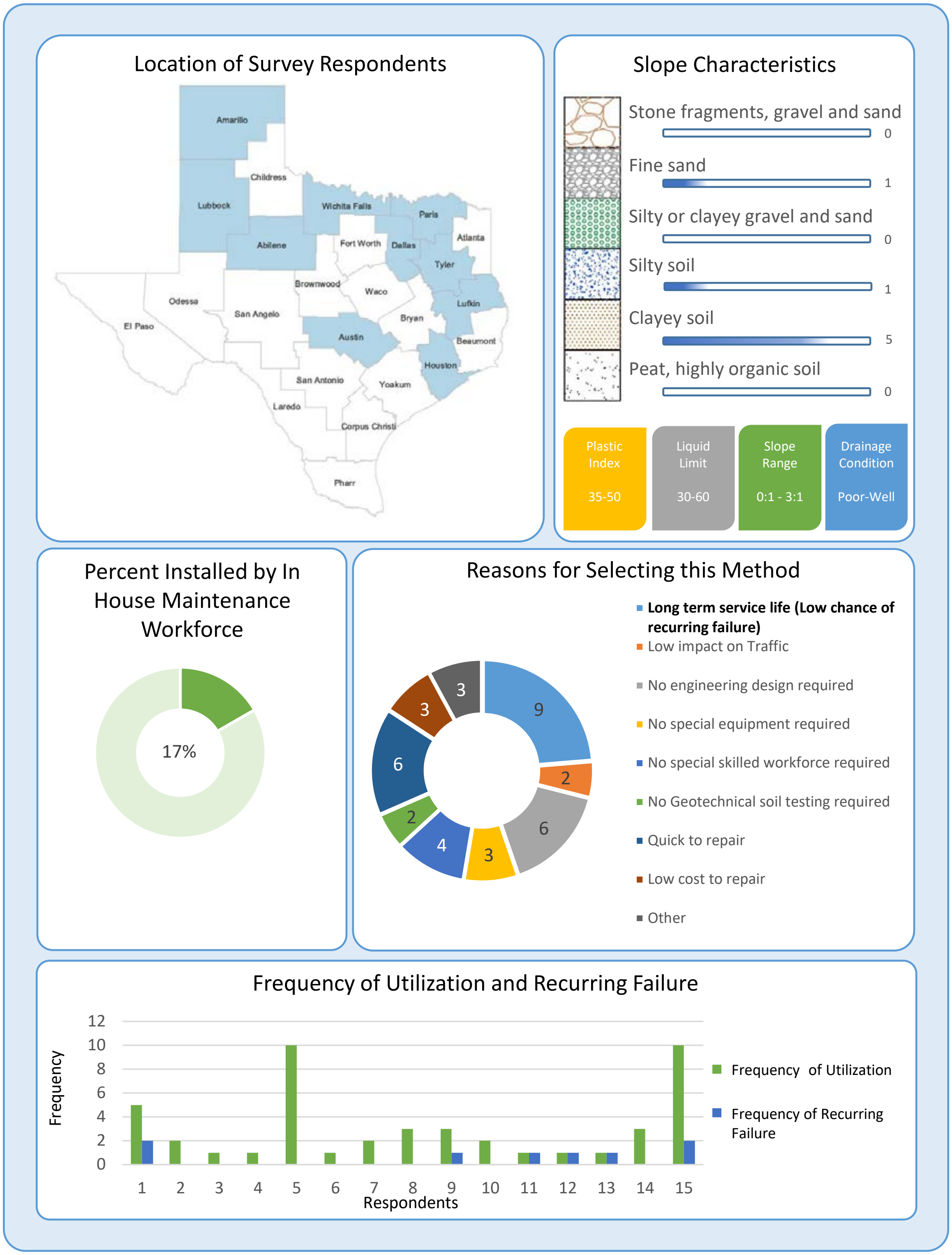

Figure 3-12 Summary of survey results for gabion method

3.2.11. Rebuilding and Compaction

3.2.11.1. In-State Survey Results

Survey results on the evaluation of the rebuilding and compaction method are summarized in Figure 3-13. Results show that this is the most general method to repair embankment slope failures in Texas. Out of 33 in-state survey respondents, 31 respondents (94 percent) specified using the rebuilding and compaction method. Despite the popularity of rebuilding and compaction, many recurring failures were reported after this method was used to repair slopes. Low cost and rapidity were specified as the key reasons for selecting this method. The rebuilding and compaction method is well-known between maintenance workforces; thus, the ease of working with the familiar was another reason for selection, which was reported by many survey respondents. This method has been used to repair slopes with slopes up to 2:1. Moreover, this method has been used to repair slopes with various soil types, including stone fragments, gravel and sand, clayey soil, silty soil, and silty or clayey gravel and sand. Rebuilding and compaction have also been used in slopes with a variety of drainage conditions (poor to good). Results show that slope repairs using rebuilding and compaction were typically performed by TxDOT in-house workforces.

3.2.11.2. Out-of-State Survey Results

Two respondents from Wyoming and West Virginia specified having had the experience of using rebuilding and compaction to repair embankment slope failures. Long-term service life and low impact on traffic were reported as the key reasons for selecting this method by professionals. This method has been used in clayey soils. These survey respondents reported a few recurring failures occurring after this method was used to repair slopes.

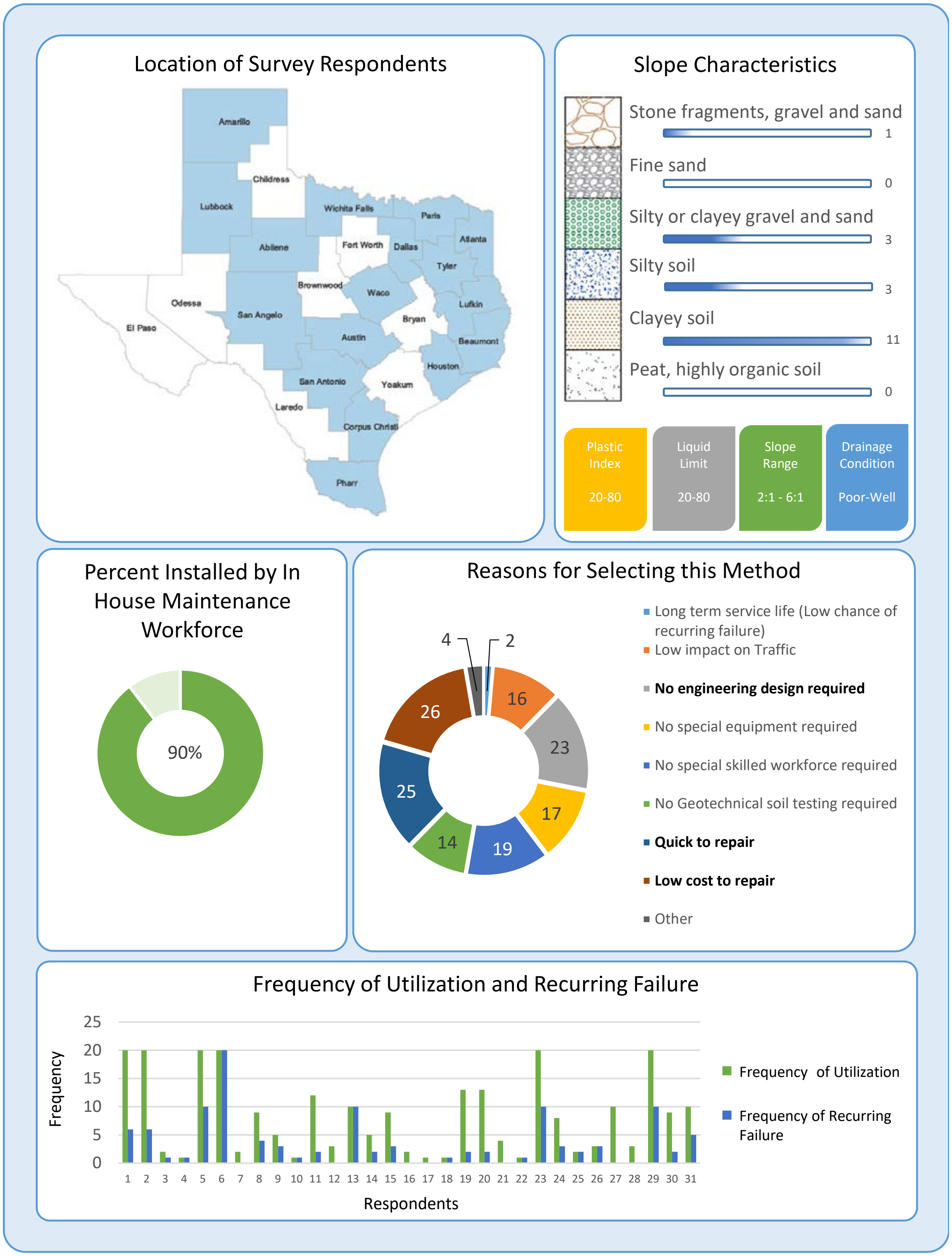

Figure 3-13 Summary of survey results for the rebuilding and compaction method

3.2.12. Benching and Stepping

3.2.12.1. In-State Survey Results

Survey results on the evaluation of the benching and stepping method are summarized in Figure 3-14. Four respondents had used the benching and stepping method to repair embankment slope failures. Two of the respondents experienced failure for a few slopes repaired using this method. Low cost and rapidity were among the main reasons for selecting this method by professionals. The benching and stepping method had only been used in clayey soil with high plasticity. This method had also been used in slopes with angles up to 2.5:1. The benching and stepping method had usually been implemented by professional contractors in slope repair projects.

3.2.12.2. Out-of-State Survey Results

A survey respondent from West Virginia had used the benching and stepping method to repair embankment slope failures. This respondent had identified long-term service life and low cost as the key reasons for selecting this method. The benching and stepping method had been used to repair slopes with angles up to 1.5:1. No recurring slope failures using this method were reported in the survey responses.

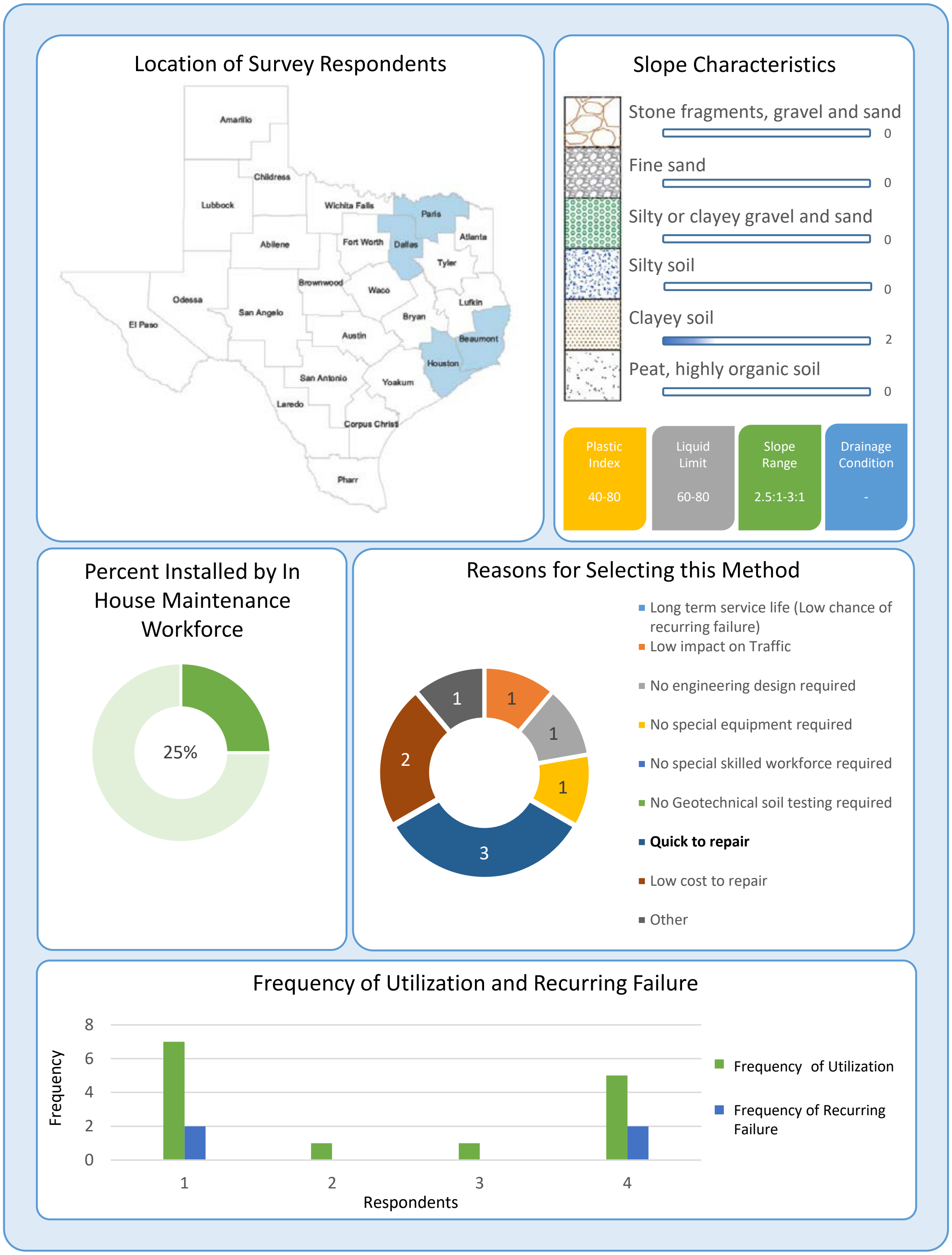

Figure 3-14 Summary of survey results for the benching and stepping method

3.2.13. Slope Flattening

3.2.13.1. In-State Survey Results

Survey results evaluating the slope flattening method are summarized in Figure 3-15. Ten respondents had used this method for repairing embankment slope failures. Four of the respondents had experienced failure for slopes repaired using this method. Low cost of repair and rapidity were identified as the main reasons for selecting this method. Survey respondents also stated that this method could be a part of other slope repair methods. The slope flattening method had been used to repair slopes with angles up to 2.5:1. This method had been used to repair slopes with various soil types including fine sand, silty soil, and clayey soil. The slope flattening method had also been used in slopes with a variety of drainage conditions (poor to good). Results showed that typically in-house maintenance workforces perform slope repair projects using the slope flattening method.

3.2.13.2. Out-of-state Survey Results

A survey respondent from Wyoming had used the slope flattening method to repair embankment slope failures. Long-term service life and low cost were the key reasons for selecting this method by this respondent. No recurring failures using slope flattening were reported by the respondent, which explains the long-term service life of this method.

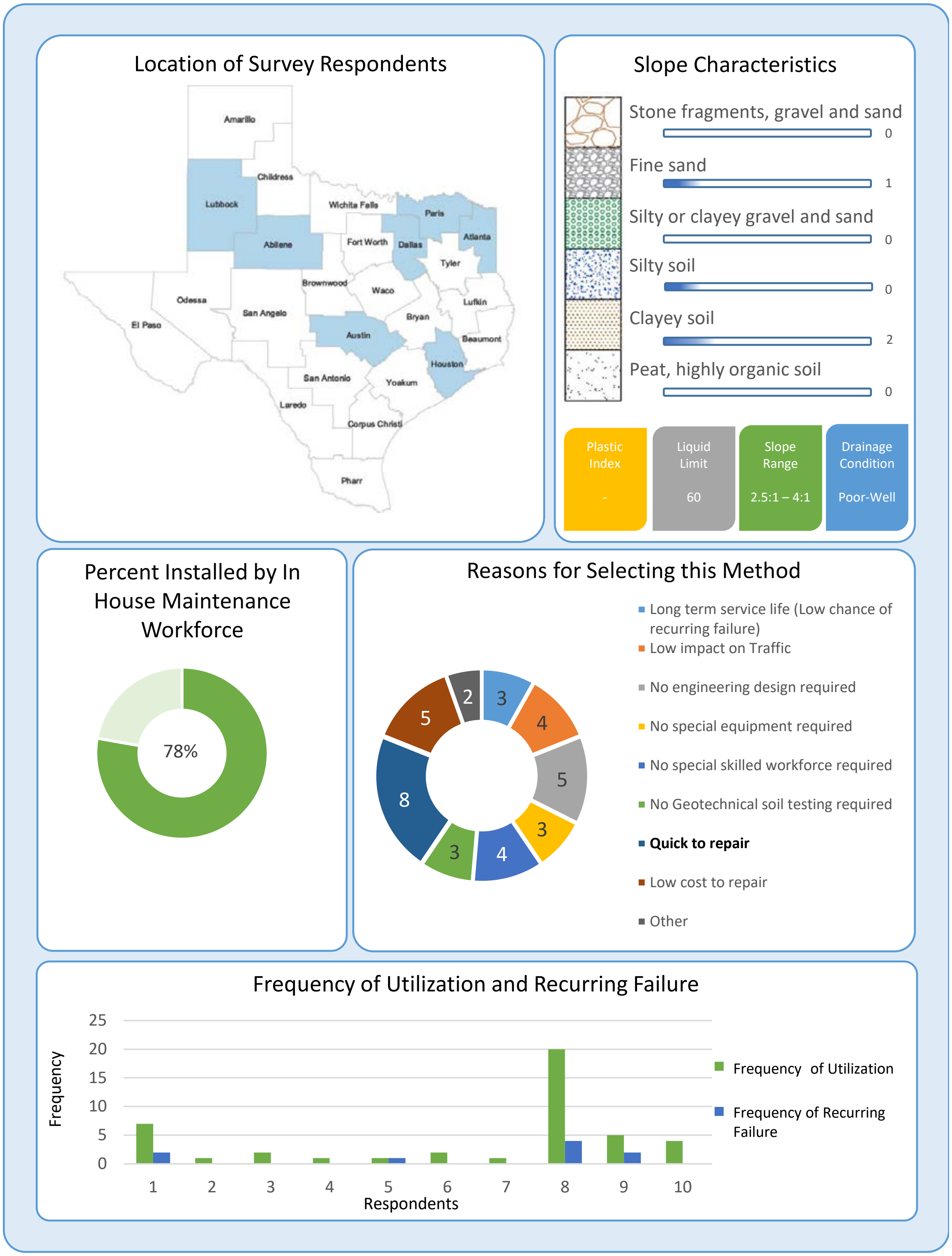

Figure 3-15 Summary of survey results for the slope flattening method

3.2.14. Soil Substitution

3.2.14.1. In-State Survey Results

Survey results on the evaluation of the soil substitution method are summarized in Figure 3-16. Eleven respondents had used soil substitution method to repair embankment slope failures. Five respondents had experienced failure for a few slopes repaired using this method. Rapidity was the main reason for selecting this method by professionals. Long-term performance, low impact on traffic, and no specialized equipment or engineering design requirements were among the other key reasons for selecting this method. The soil substitution method has been used to repair slopes with angles up to 2:1. This method has been used in clayey and silty soils. Soil substitution has also been used in slopes with a variety of drainage conditions (poor to good). This method had been implemented by in-house maintenance crews or professional contractors.

3.2.14.2. Out-of-State Survey Results

Soil substitution had also been used in other states, such as Wyoming and West Virginia. Long-term service life and low cost of repair were specified as the key reasons for selecting this method by professionals. Soil substitution had been used to repair slopes with angles up to 1.5:1. This method has been implemented in slopes with silty or clayey gravel and sandy soil. A few recurring slope failures (less than 50 percent) using this method were reported by survey respondents.

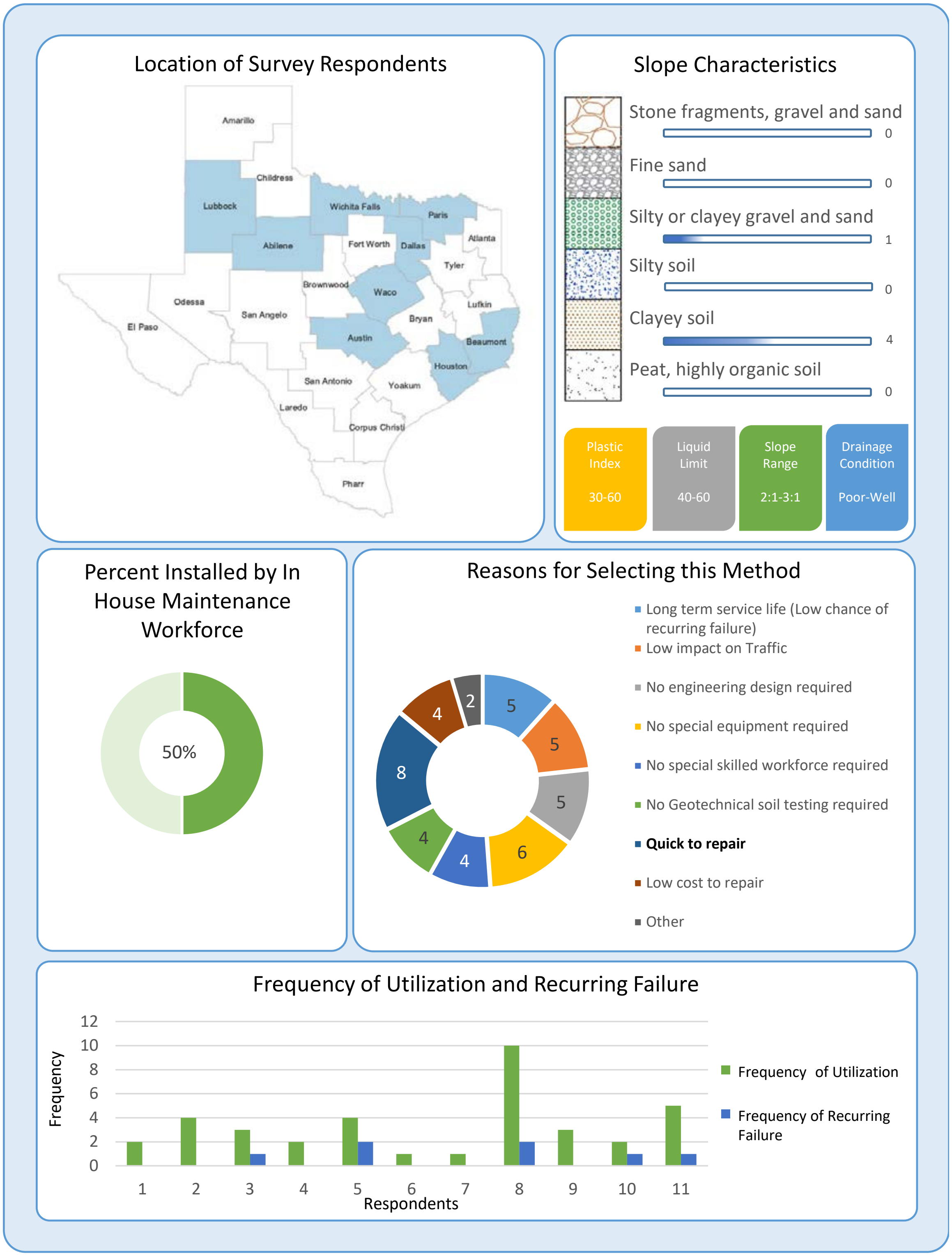

Figure 3-16 Summary of survey results for the soil substitution method

3.2.15. Buttressing

3.2.15.1. In-State Survey Results

Survey results on the evaluation of the buttressing method are summarized in Figure 3-17. Two respondents had used the buttressing method to repair embankment slope failures. One of the respondents had experienced failure for a few slopes repaired using this method. Long-term performance, no specialized equipment and geotechnical soil testing requirements, plus low costs were the key reasons for selecting this method. The buttressing method had been used to repair slopes with angles up to 1:1. This method had been used in less cohesive soils including silty or clayey gravel and sand and silty soils. Buttressing had also been used in slopes with good drainage conditions. This method had been implemented by in-house maintenance crews or professional contractors.

3.2.15.2. Out-of-State Survey Results

Buttressing had also been used in other states, such as Wyoming and West Virginia. Long-term service life and low cost of repair were specified as the key reasons for selecting this method by professionals. Similar to in-state survey results, buttressing had been used to repair slopes with angles up to 1.5:1. Buttressing had also been used to repair slopes with clayey soil. A few recurring slope failures using this method were reported by survey respondents.

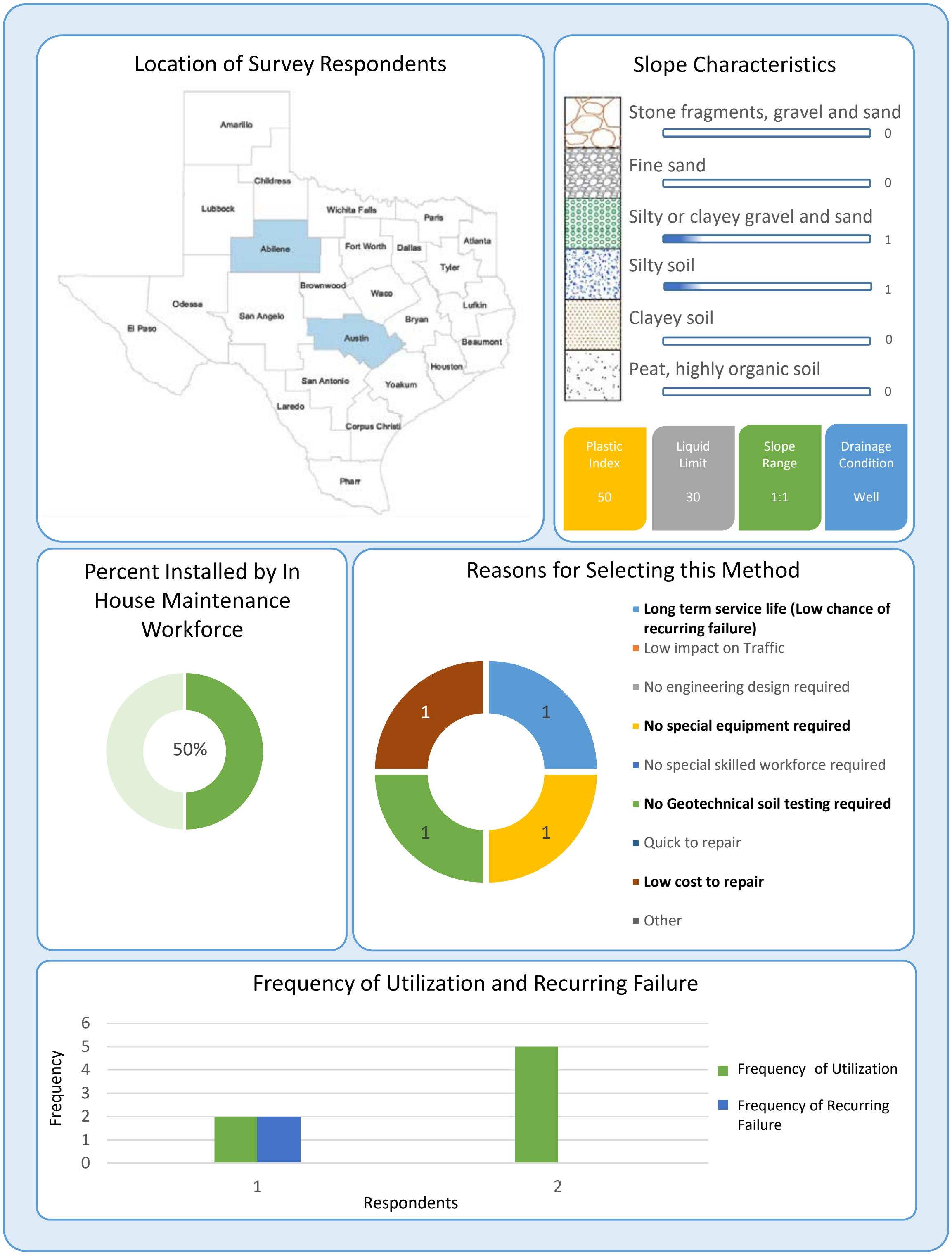

Figure 3-17 Summary of survey results for the buttressing method

3.2.16. Biotechnical Methods

3.2.16.1. In-State Survey Results

Survey results on the evaluation of biotechnical methods are summarized in Figure 3-18. Two respondents had used this method to repair embankment slope failures. One of the respondents had experienced failure for a few slopes repaired using this method. Long-term service-life, no specialized equipment or skilled workforce, no geotechnical soil testing and engineering design requirements, and low costs were the reasons for selecting these methods. Biotechnical methods had been used to repair slopes with good drainage conditions. These methods had been implemented by in-house maintenance crews or professional contractors.

3.2.16.2. Out-of-State Survey Results

No survey respondents from other states reported using biotechnical methods to repair embankment slope failures.

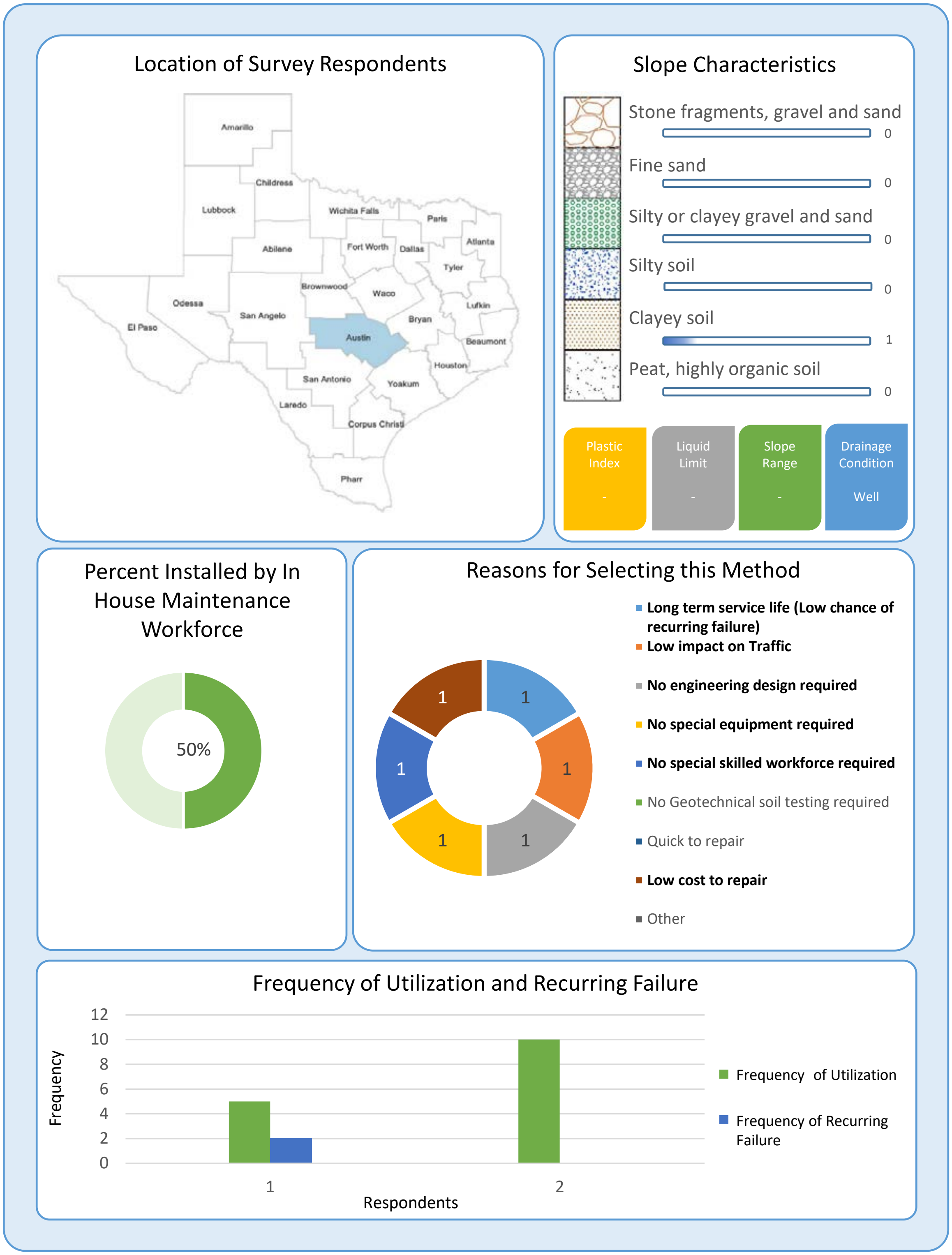

Figure 3-18 Summary of survey results for the biotechnical method

3.2.17. Additives

3.2.17.1. In-State Survey Results

Survey results on the evaluation of the additive method are summarized in Figure 3-19. Five respondents had used this method to repair embankment slope failures. Survey responses showed that lime and cement was more popular in slope repair projects than fly ash. Three respondents had experienced failure for a few slopes repaired using this method. Low cost of repair, no requirements for specialized equipment, and engineering design were the key reasons for selecting this method by professionals. Additives had been used to repair slopes with various angles up to 1:1. This repair method had been used for stone fragments, gravel and sandy soils, as well as clayey soils. Additives had also been used in slopes with good drainage conditions. This method had been implemented by in-house maintenance crews or professional contractors.

3.2.17.2. Out-of-State Survey Results

No survey respondents from other states reported using additives to repair embankment slope failures.

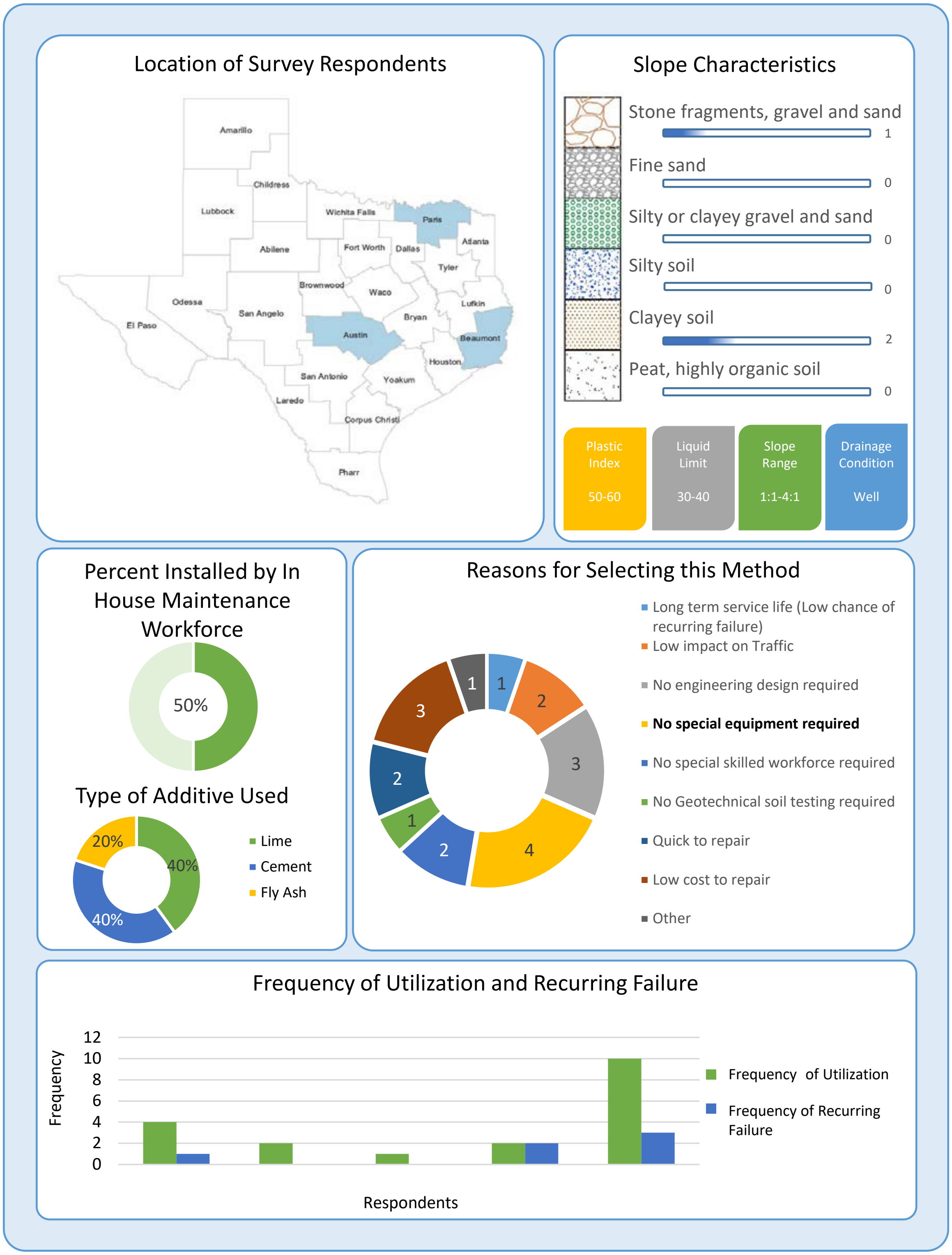

Figure 3-19 Summary of survey results for the additives method

3.2.18. Water Management Methods

3.2.18.1. In-State Survey Results

The results of the survey on the evaluation of water management methods are summarized in Figure 3-20. Sixteen respondents had used these methods to repair embankment slope failures. All the respondents had used surface water management methods and none of them had reported using subsurface water management methods. Four of the respondents had experienced failure for some slopes repaired using this method. Low cost of repair, rapidity, and long-term performance were the key reasons for selecting these methods by professionals. These methods had been used to repair slopes with angles up to 2.5:1. Water management methods were only used in clayey soils. These methods had been used in slopes with poor drainage conditions. Typically, water management methods were implemented by in-house maintenance workforces to repair embankment slope failures.

3.2.18.2. Out-of-State Survey Results

Water management methods have also been used in other states, such as Wyoming and West Virginia. Similar to in-state survey responses, out-of-state responses indicated utilization of only surface water management methods to repair embankment slope failures. Long-term service life, low impact on traffic and low cost were the key reasons for selecting this method by professionals. Some recurring slope failures (less than 50 percent) using this method were reported by survey respondents. Surface water management methods had also been used to repair slopes with poor drainage conditions and angles up to 1.5:1.

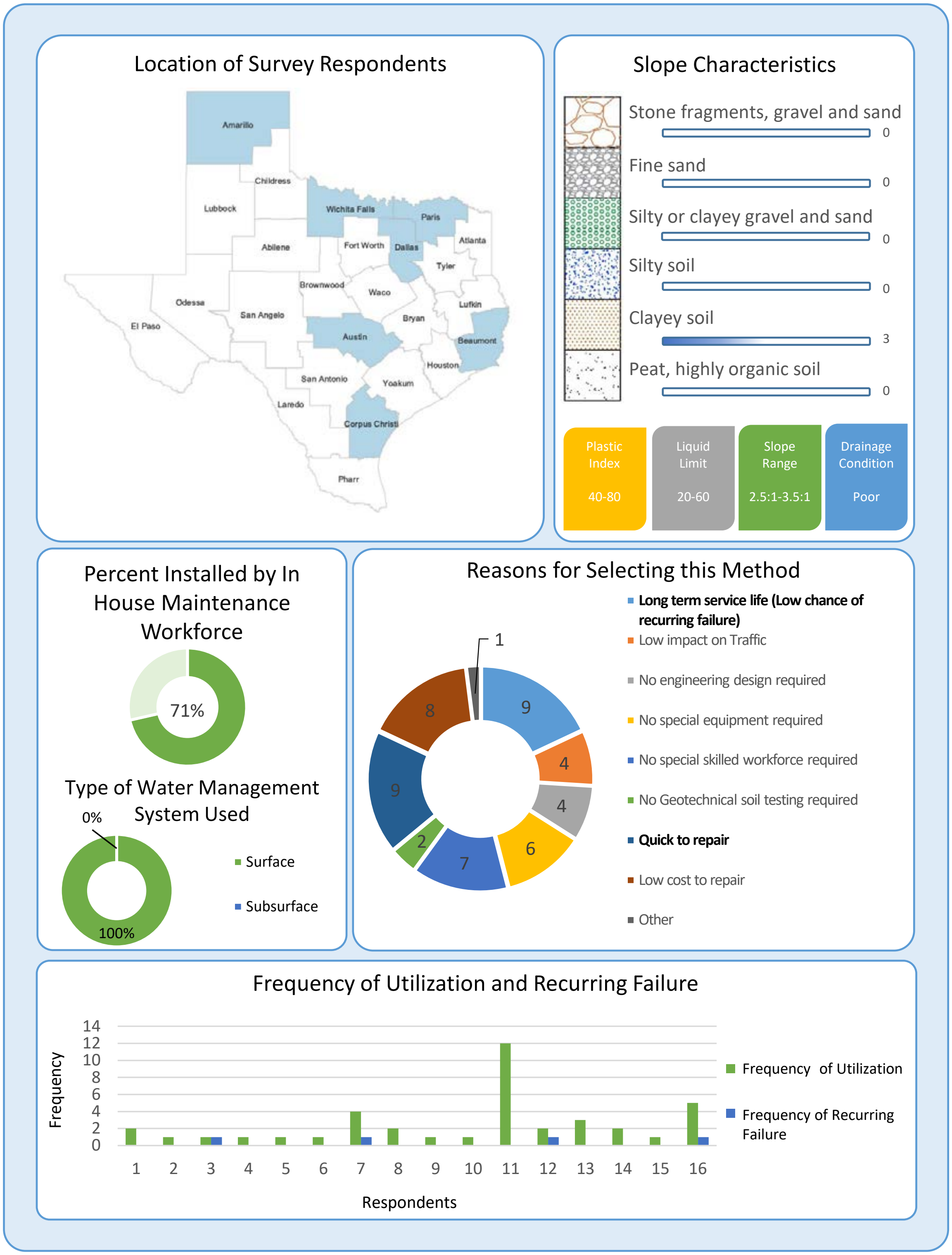

Figure 3-20 Summary of survey results for water management method

Chapter 4. INTERVIEWS

After collecting and analyzing survey responses, the research team conducted follow-up interviews to identify recommendations for successful implementation of slope repairs. These interviews were aimed to identify interviewee's best practices and lessons learned from real projects. Selection of interviewees, interview instructions, and interview results are presented in the following sections.

4.1. SELECTION OF INTERVIEWEES

The research team analyzed the survey results to select individuals for conducting follow-up interviews. The research team considered the following criteria to choose interviewees:

- Covering TxDOT districts with diverse geographical characteristics (e.g., soil type, weather condition);
- Selecting respondents that provided the most detailed information in their survey responses;
- Selecting individuals that are willing to participate in the follow-up interviews;
- Selecting individuals from TxDOT districts experienced with the highest number of repair methods; and
- Selecting individuals from TxDOT districts experienced with innovative and advanced repair methods.

Based on these criteria and survey responses, the research team selected eight interviewees from the Dallas, Corpus Christi, Paris, Lubbock, and Beaumont districts. The research team also selected two interviewees from the TxDOT Maintenance division. The interviewees hold different positions, such as district bridge engineer, district maintenance engineer, director of construction, and district area engineer.

4.2. INSTRUCTIONS FOR CONDUCTING FOLLOW-UP INTERVIEWS

To conduct follow-up interviews with selected interviewees, the interview sessions were structured based on the four following tasks:

1. Reviewing contact information;
2. Reviewing survey responses and asking whether interviewees would like to further explain their responses;
3. Acquiring more detailed information on the utilized methods (e.g., current practices that prevent successful implementation of slope repair methods and strategies to overcome these barriers, current challenges that appear when repairing slope failures, current practices that resulted in successful implementation of the methods); and

4. Asking interviews to provide detailed information on actual recent repair projects that could be presented as case studies.

4.3. INTERVIEW RESULTS

In total, the research team conducted 10 follow-up interviews. The results of these interviews are presented in the following subsections.

4.3.1. Interview Number 1 (Maintenance Division, TxDOT)

4.3.1.1. General Comments for Successful Slope Repairs

- One of the common reasons for slope failures is the lack of water management system to divert water from slopes.
- Another common reason for slope failures could be the mowers that move over vegetation, tear up the slope, and remove the vegetation.
- Water management (especially surface water management) is the most essential and critical step in the repair and stabilization of roadside slopes. One of the effective ways of implementing this method is to divert the water from entering the slope from the top of the slope by constructing curbs and ditches.
- The simplest and cheapest method that helps to protect the slopes from shallow failures is mass planting. Mass planting of Yaupon or Pampas grass is suggested. Nevertheless, these species may not grow in some areas, so it is recommended to use native plants that grow quickly in the desired area.
- It is recommended to salvage the topsoil during construction, protect the salvaged soil, and replace it on the slopes after construction. This will help avoid slope failures across newly developed corridors. Construction contracts should demand that the contractors use the topsoil (not just dirt) to protect slopes along the newly developed corridors.

4.3.1.2. Method Specific Comments for Successful Slope Repairs

Biotechnical Methods

Vegetation is a long-term solution for stabilizing and protecting roadside slopes. This method has a low impact on traffic. There is no engineering design required for this method. Also, no specialized equipment or workforces are required for implementing this method. This method is also a very economical slope repair method.

Vegetation requires time to get established. During this period, it is essential to take care of newly vegetated plants or seeds by frequent irrigation, diverting excessive water (e.g., heavy rainfall or storm) from the slope, and surface protection in case of wind. Biotechnical methods are not suitable for high acidic soils.

Common barriers and challenges

- Biotechnical methods are not suitable for acidic soils (common in east Texas) where the soil pH is low around 4.5.
- Sometimes vegetation does not establish or grow because of dry soil and hot weather.
- Although Yaupon or Pampas grass are two recommended plants for mass vegetation, they are not applicable for every location.
- Commonly, vegetation on slopes are damaged by mowing machines.

How to overcome barriers and challenges

- Conduct soil testing if the soil is not clayey (especially when it includes sand).
- Add lime to the soil prior to vegetation by increasing the soil pH to at least 5.5 and lowers the soil acidity. Lime also helps to stabilize the soil as a cementation agent.
- Use irrigation at the early stages of vegetation for the growth and establishment of plants.
- Not all plant species are suitable for every area or region. Thus, 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.

Tire Bails

Tire bales could be considered as a permanent method for repairing slope failures. They can stand a lot of water. No specialized equipment or skilled workforce are needed for installing tire bails. We can simply use a loader for installation. Moreover, the implementation of this method is relatively quick. However, Tire bales are not aesthetically pleasing and need to be covered by topsoil. The covering topsoil should be protected from failure itself. Compared to gabions, tire bales are less aesthetic.

Common barriers and challenges

- Absence of a proper water management system is the most common barrier to the success of this repair method.

How to overcome barriers and challenges

- Collect and divert water from the top of the slope using ditches and curbs to prevent the slope from getting saturated.

Geosynthetics

Geosynthetics are long lasting methods if they are implemented correctly. These methods require technical engineering design and specialized equipment for installation. They are costly compared to many other repair methods, such as gabions and vegetation.

Common barriers and challenges

- Some of the repaired slopes fail because of inappropriate design or installation.
- In some cases, repaired slopes fail because of heavy rainfall or the existence of excessive water.

How to overcome barriers and challenges

- 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.
- Using roadside curbs and ditches will help divert water from entering the slope area.

Gabions

Repairing slopes with gabions is a common method especially around stream banks. Gabions do not usually require geotechnical soil testing or engineering design. This method is a long-lasting solution if gabions are installed appropriately and maintained frequently.

Common barriers and challenges

- Some of the repaired slopes continue to fail because of inappropriate design or installation.
- In some cases, repaired slopes fail because of heavy rainfall or excessive water flow (especially if gabions get submerged).

How to overcome barriers and challenges

- Gabion cages should be tied together tightly and fixed to the ground. A careful construction procedure is necessary for their long-term performance.
- Using roadside curbs and ditches will help to divert excess water from entering the repaired slope area.

Rebuilding and Compaction

This method is the cheapest and the most common method for repairing slope failures. It does not need any specialized equipment, skilled workforce, or engineering design. On the other hand, this method showed the highest number of recurring failures.

Common barriers and challenges

- The most common problem with this method is the lack of proper water management.

How to overcome barriers and challenges

- Prevent the slope from getting saturated using roadside curbs and ditches. These surface water management techniques (roadside curbs and ditches) will help to divert excess water from entering the slope area.

Soil Substitution

Soil substitution is a simple method that is occasionally used to repair roadside slope failures. Similar to the rebuilding and compaction method, the existence of excessive water leads to recurring slope failure even after soil substitution.

Common barriers and challenges

- The existence of excessive water is the primary reason for recurring slope failure after soil substitution.

How to overcome barriers and challenges

- Preventing the slope from getting saturated using roadside curbs and ditches. These techniques will help divert excess water from entering the slope area.

Additives

Using additives for repairing slope failures is a long-term solution, especially for “fill slopes.” However, there are some challenges when it comes to “cut slopes”. Using additives improves the stability of the slope by reducing both the shrinkage and swelling nature of the soil. It also helps control the acidity of the soil.

Common barriers and challenges

- Inadequate use of additives especially in case of “cut slopes”.

How to overcome barriers and challenges

- Soil tests and engineering design will ensure the use of a sufficient amount of additives, which guarantees success in using this method (especially for “cut slopes”).

4.3.2. Interview Number 2 (Maintenance Division, TxDOT)

4.3.2.1. General Comments for Successful Slope Repairs

Southeast Texas has a highly expansive soil with high swelling and shrinkage characteristics. When this type of soil on a slope gets dry (after being exposed to water), it swells and creates a “skid line” (slip surface) that leads to slope failure. The key point to repairing these failures is to excavate deeper to break the skid line and remove the unstable soil completely.

4.3.2.2. Method Specific Comments for Successful Slope Repairs

Rebuilding and Compaction

Rebuilding and compaction is the simplest and most common method for repairing slope failures. No engineering design is needed for this method. This method is performed using typical construction equipment such as a loader.

Common barriers and challenges

- Recurring slope failure happens in many cases if rebuilding and compaction is not done properly.

How to overcome barriers and challenges

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 putting it back, (3) The removed soil should be placed back and compacted properly in a stepwise manner, and (4) The embankment should be vegetated to assure a long-term performance.

4.3.3. Interviewee Number 3 (District Bridge Engineer, Corpus Christi District, TxDOT)

4.3.3.1. General Comments for Successful Slope Repairs

- Most of the slope failures are around highway structures, especially bridge abutments.
- "Rebuilding and compaction" along with "water management" is the most common and successful approach for repairing slope failures. The key point for having a successful slope repair project is to pair these two methods together.

4.3.3.2. Method Specific Comments for Successful Slope Repairs

Rebuilding and Compaction

Rebuilding and compaction are the most common method for repairing slope failures in the area. No specialized equipment or skilled workforce is required for this method. This method usually does not require engineering design. This method has a fairly low cost. One of the reasons behind successful implementation of this method is the formal assessment of the failures by an experienced area engineer or maintenance supervisor before implementing a repair method.

Common barriers and challenges

- Existence of excessive water.

How to overcome barriers and challenges

- This method will be a successful slope repair method with long-term service life if it is accompanied by controlling surface water away from the repaired slope.

- Use curbs and concrete flumes that direct the water from the top of the slope to the bottom of the slope.

Water Management

The soil in the Corpus Christi area is well drained. Thus, surface water management is more popular in this region. Surface water management along with a simple rebuilding of the failed slope could be successful. This method is quick to implement compared to many other slope repair methods. For instance, it could take less than two weeks to repair a failed slope around bridge abutments (both sides). This method is usually implemented based on experience and does not require engineering design in case of small-scale slope failure projects. This method has a low impact on traffic and relatively low cost.

Common barriers and challenges

- The only barrier that might threaten the success of this method is improper water diversion from the slope.

How to overcome barriers and challenges

- Direct the water (using curbs, flumes, and riprap) far from the slope and highway structures (i.e., do not discharge water close to the slope).

4.3.4. Interviewee Number 4 (Dallas District, TxDOT)

4.3.4.1. General Comments for Successful Slope Repairs

- Redirecting water from the top of the slope to the toe using pipes or concrete flumes is one of the essential techniques in the repair and protection of embankment slopes.
- Mechanically stabilized earth (MSE) walls are the most permanent solution for repairing the slope failures based on this interviewee's experience. Increasing the embedment height from 1 foot to 2 feet is the key factor in the success of MSE walls.

4.3.4.2. Method Specific Comments for Successful Slope Repairs

Rebuilding and Compaction

Rebuilding and compaction are usually used by an in-house maintenance crew to repair shallow slope failures. However, large slope failures (deep-seated) are typically contracted out. In the case of shallow slope failure, the rebuilding and compaction method is a rapid repair method with low cost. On the other hand, for large slope failures, this method is usually not efficient. Typically, in the latter type of failure, we will lose some soil mass, and the repair will need extra soil. Hauling the additional soil increases the cost of repair and makes the repair more time-consuming. In addition, repairing deep-seated slope failures using rebuilding and compaction requires engineering design. Slopes repaired using this method have shown a high percentage of recurring failures.

Common barriers and challenges

- Rebuilding and compaction did not show promising performance for large slope failures (deep-seated).

How to overcome barriers and challenges

- MSE walls are recommended for repairing deep-seated slope failures. Rebuild the slope behind the wall at angles flatter than 4:1. Vegetation is recommended.

Retaining Structures

Retaining structures (especially MSE walls) have been successfully implemented for repairing embankment slope failures. This method requires technical engineering design and a special workforce. Although this method is usually implemented by professional contractors, it does not require specialized equipment. In case of recurring failure of tall slopes, this method is highly recommended as a permanent solution. MSE walls are the most cost-effective in comparison with other retaining wall.

Common barriers and challenges

- MSE walls often fail due to inappropriate design.

How to overcome barriers and challenges

- Use proper procedure for design and implementation.
- Increase the embedment height at the toe of the wall (at least 2 feet).
- Rebuild the slope behind the wall with at least a 4:1 slope.

Geosynthetics

Use of geosynthetics is quite widespread in north Texas. Geogrids are the most popular type of geosynthetics, especially in constructing embankment slopes. The rapidity of implementing this method depends on the existence of geogrids in the failed slope. If the failed slope contains a geogrid (repaired or constructed), then the repair would take a significant amount of time. On the other hand, if there is no geogrid in the ground from the past, rebuilding the failed slope is relatively rapid. This method needs special engineering design and a skilled workforce.

Common barriers and challenges

- Re-failure of slopes that were built or repaired using geogrids.

How to overcome barriers and challenges

- It is necessary to overlap the new geogrid with the already existing one to avoid future failures.
- Cut the failed slope beyond the failure surface.
- Remove the damaged geogrids and replace with new ones.
- Use vegetation after rebuilding the slope and take good care of that until the vegetation is fully established.

Lunched Soil Nail

This method requires specialized equipment, engineering design, and experienced workforce. This method is relatively quick and showed a long-term service life.

Gabions

This interviewee usually used gabions for repairing and protecting slopes near bridge abutments. This method has shown long-term performance. This method is typically implemented using experienced contractors. Gabions are also aesthetically pleasing.

Common barriers and challenges

- In some cases, the stream water penetrates beneath or covers the gabions or riprap around bridge abutments and leads to their failure (washes them away).

How to overcome barriers and challenges

- Extend the length of thrie beam curb beyond the bridge abutment for least 10 to 15 feet. Beyond this length, filters and protection for gabion or riprap should be installed. This length should be enough to protect bridge piers and abutments from the stream. This practice lowers the chance of gabion or riprap failure.

Benching and Stepping

This method has been used to repair slope failures near streams. It is usually combined with gabions for improving stability. Benching and stepping have shown a good performance.

Soil Substitution

Soil substitution is an effective slope repair method with long-term service life. It helps in situations where soil with lower Plasticity Index (PI) is needed. The interviewee had used this method around bridge abutments to increase the soil stability. This method is recommended when a source of appropriate substitution material is available nearby.

Common barriers and challenges

- One of the major limitations of this method is the hauling of new material and disposal of the existing soil.
- In some parts of Texas, providing proper substitution material is challenging.
- The extra cost of hauling may affect the selection of this method.

How to overcome barriers and challenges

- Use this method if appropriate substitution material is available nearby.

4.3.5. Interviewee Number 5 (Dallas District, TxDOT)

4.3.5.1. General Comments for Successful Slope Repairs

- One repair method may be used for various purposes with different design, implementation, and target performance. For instance, while soil nails are used permanently to support the steep slopes behind retaining walls or steep slopes, they may temporarily be used for supporting excavation shoring. These two applications are entirely different in design, implementation, and performance.
- Frequent dry and wet cycles of soil in one area can cause lots of cracks on the slopes that will lead to failure.
- Controlling surface water from entering the slope is critical for repair and protection of slopes. For tall slopes, concrete flumes parallel to slope are required to control and transfer surface water.
- One of the common methods for repairing shallow slope failures is replacing back the failed soil mass after lime treatment.
- Retaining structures such as MSE walls and drilled shaft walls are often the last option for repairing recurring slope failures in the area considering their high initial cost.

4.3.5.2. Method-Specific Comments for Successful Slope Repairs

Retaining Structures

Retaining structures (especially MSE walls and drilled shaft walls) are a long-term solution to repair tall slopes. Retaining structures could be cost-effective if the lifecycle costs of slope repairs are considered. Drilled shaft walls are costlier compared to other types of retaining structures. Using retaining structures is a rapid method for repairing slope failures. At least one lane closure is required to implement this method. If the retaining structures are to be built on highway ramps, the ramp would be completely closed to traffic. Retaining structures do not require specialized equipment, engineering design, and a skilled workforce when low height is needed. However, construction of tall retaining structures requires engineering design and experienced contractors.

MSE walls are the most popular retaining structures in north Texas. Nevertheless, a few limitations are attributed to this method, which resulted in further failures.

Common barriers and challenges

- A few MSE walls fail due to the inappropriate design of toe embedment.

How to overcome barriers and challenges

- The Dallas district overcame this problem by modifying the design of the embedment. These changes are:
    - Increase the embedment depth at the toe of the wall from 1 foot to at least 2 feet.
    - Flatten the slope behind and in front of the wall from 3:1 to at least 4:1.

Lunched Soil Nails

This method is usually used for two purposes: (1) to establish temporary retaining of soil in construction projects (shoring), or (2) to permanently stabilize slopes and support the steep slopes behind the retaining walls. In the latter case, this method requires specialized equipment to install, along with engineering design and an experienced workforce. In the case of temporary use, launched soil nails are used without engineering design. Recurring failures are reported more often for temporary utilization of launched soil nails, while this method is very successful when it is used for permanent purposes.

Common barriers and challenges

- Sulfur drainage affects soil nail durability.

How to overcome barriers and challenges

- Use of proper subsurface drainage is recommended.
- Use of material that is not vulnerable to sulfur.
- Soil nails are not recommended for use in soils containing high levels of sulfur.

Geosynthetics

Geosynthetics, such as geogrids, could have a long service life if they are correctly implemented in the first place. It is essential to install geogrids horizontally into the slope. To take the most advantage of geogrids, excavation beyond the skid line is recommended.

Common barriers and challenges

- Failure due to inappropriate installation.
- Failure due to heavy rainfall right after the repair process.

How to overcome barriers and challenges

- Careful installation (not to damage the material and follow the correct procedure) of geogrids is important.
- Inspection during installation is recommended.
- Maintain the vegetation cover until plant root system has had time to completely stabilize.
- Use pipe or flumes to remove water from entering the repaired slope area.

Recycled Plastic Pins

Recycled plastic pins (RPPs) have been used recently for repairing slope failures in North Texas. This method is rapid and has a low implementation cost. So far, recycle plastic pins have shown a good performance in stabilizing failed slopes.

Common barriers and challenges

- Recycled plastic pins are not appropriate for stiff soils. They will buckle and break while driving in such soils.

How to overcome barriers and challenges

- Two solutions are recommended for this issue:
    - Pre-drill a smaller diameter hole compared to RPPs, and then insert the pins.
    - Drive steel nails first and then, insert RPPs.

Gabions

Gabions are usually used near streams, canals, and creeks. This slope repair method is quick and shows a long-term performance. However, failures have been reported in some cases. Gabions usually fail (are washed away) with frequent overflows of an adjacent stream. This method has also been used around bridge abutments.

Common barriers and challenges

- In many cases, gabions placed near bridge abutments are washed away due to insufficient protection (embedment and protected channel under the bridge).

How to overcome barriers and challenges

- It is recommended to use concrete curbs or walls to redirect stream water far from the bridge abutment. In this case, the velocity of water would decrease enough not to wash away the gabions.

4.3.6. Interviewee Number 6 (Dallas District, TxDOT)

4.3.6.1. General Comments for Successful Slope Repairs

- MSE or other retaining structure could be permanent solution for frequent slope failure along the roadside with high traffic. Plastic pins are recommended for localized slope repairs.

4.3.6.2. Method-Specific Comments for Successful Slope Repairs

Piles

W shape guardrail driven as pile could be used as an emergency solution for slope repair, especially around bridge abutments and wing wall on stream crossing. However, they should be replaced with a permanent solution. This method is cheap and can be done in house, usually perform well as a temporary soil repair solution.

Common barriers and challenges

- Hammering guardrail piles in a stiff soil is hard and may cause the piles to bend.

How to overcome barriers and challenges

- Use stronger piles for stiff soils.

Gabions

Gabions are mainly used to protect the toes of slopes adjacent to streams. They last longer if they are appropriately designed. High streamflow and heavy rainfalls are the main reasons for their failure.

Common barriers and challenges

- Gabions usually fail when subjected to frequent stream overflows.

How to overcome barriers and challenges

- It is recommended to excavate the intended gabion location deeper to install the gabions on a deeper level.

4.3.7. Interviewee Number 7 (Beaumont District, TxDOT)

4.3.7.1. General Comments for Successful Slope Repairs

- Following engineering procedures lead to successful implementation of retaining structures. These procedures can include a detailed site investigation, geotechnical soil testing, surveying, and engineering design.

- The repair methods can be combined to enhance the performance. For instance, the rebuilding and compaction method for repairing a slope could be enhanced by adding additives to modify the characteristics of the soil, benching for better stabilization, and using geotextiles to improve resistance in the failure-prone surface.
- The impact of slope repair methods on traffic depends on the distance between the road and the toe of the slope and the location of the slope failure on the slope (at the top, middle, or toe of the slope).

4.3.7.2. Method-Specific Comments for Successful Slope Repairs

Tire Bales

Tire bales are easy to install. However, they have been subject to failure, especially when they get supersaturated. Therefore, tire bales cannot be considered a long-term solution for slope repair projects. This method has a low-impact on traffic.

Common barriers and challenges

- Tire bales can become very heavy due to retainage of water. Their excessive weight leads to recurring slope failures.
- Tire bales cannot be drained entirely, and there is almost no way to empty the retained water.

How to overcome barriers and challenges

- It is recommended to put temporary soil nail walls behind tire bales.
- Geogrids could be laid in the soil under tire bails.
- 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.

Geosynthetics

Geotextiles could be used for repairing slope failures and building MSE retaining walls. In the case of a slope repair project, first, the slope is excavated a little bit further than the failure plane; then the geotextile is laid on the ground, and the soil is put back (at a 3-ft depth) and is compacted. In the case of MSE walls, geotextiles are used to improve the stability of the ground beneath and behind the wall. This method is straightforward, quick, and it doesn’t require specialized equipment or workforces.

Retaining Structures

Retaining structures are a long-term solution if they are engineered well. The engineering procedure includes conducting site investigation, surveying the project site, and performing geotechnical soil testing. Then, an accurate engineering design is developed. Finally, the slope is repaired using experienced contractors.

Common barriers and challenges

- Retaining walls could fail due to improper drainage systems.

How to overcome barriers and challenges

- A detailed engineering procedure should be followed to design and implement this method.
- Use surface (a combination of curbs, concrete flumes, and riprap) and subsurface (pipes) drainage systems to collect and transfer the water from the top of the wall to the bottom.

Sheet Piles

Sheet piles are commonly used to repair slope failures and stabilize embankment slopes in East Texas. Sheet piles are one of the best solutions for retaining road or railroad embankments in location with many flat swamp areas. Sheet piles can absorb the vibration from the road or railroad, and they do not break! This system may need specialized equipment especially when the length of the sheet pile is too long. Sheet piles are quite expensive and require engineering design. Proper installation and correct technical design are necessary for sheet piles to provide long-term service life. The height of the sheet piles should not be reduced just to match the available installation equipment.

Common barriers and challenges

- Inadequate design and improper installation.

How to overcome barriers and challenges

- Design sheet piles properly; select the correct cross-section (e.g., a Z or PZ shape)
- Use surface and subsurface drainage systems to reduce the driving forces on the sheet pile wall.

Soil Substitution

It is recommended to excavate beyond the failure plane (3 to 5 feet beyond the failure plane) and use geotextile layer at the failure envelope. Stepping also helps to improve the performance of this method. This method does not require specialized workforce or equipment.

Rebuild and compaction

The application of the rebuilding and compaction method is popular because implementation is easier than most methods and is feasible for in-house maintenance workforces. However, slopes repaired using this method are subject to recurring failures. It is vital to enhance the drainage to make this method more durable.

Common barriers and challenges

- This method fails due to lack of appropriate drainage system.

How to overcome barriers and challenges

- Use curbs to collect surface water from the top of the slope and under the guard rails.
- Every 100 to 150 feet, use concrete flumes and a riprap system to transfer water from the top curb to a ditch at the bottom of the slope.
- Use an adequate amount of riprap where there is a chance that water can go over and under the concrete flume.
- Prevent the water from entering the slope with high PI.

Additives

The interviewee had an experience of using additives to improve the characteristics of the existing soil in one of the slope repair projects. The innovation used by this interviewee was to treat the existing soil in two phases. The slope repair project was located at the intersection of US69 and the BNSF railroad on the I-10 Highway. The repair team used an available vacant land near the slope failure site to spread the excavated soil from the slope. They spread the soil on the flat space with a thickness of 12 inches. They lime treated the soil with 6% lime to improve the characteristics of the soil. Further, they treated the soil with 4% cement and hauled it back to the slope area in a day. Cement treatment helped to increase the shear strength of the soil, reduced the water content of the soil and helped to reduce the setting time. This practice significantly improved the characteristics and workability of the existing soil.

Water management

Surface water drainage systems are essential to the durability and performance of embankment slopes. Experience shows that many slope failures are due to the absence of a surface drainage system. A combination of curbs, concrete flumes, and riprap could be used for surface water management.

Unfortunately, the subsurface water management systems are usually an afterthought or designed incorrectly, especially in the case of retaining walls and sheet piles. Many design errors reveal themselves during the construction (e.g., wrong location of the pipes considering the site topography).

Common barriers and challenges

- Improper design of subsurface drainage systems

How to overcome barriers and challenges

- The designers need to consider the topography of the site and design the drainage system accordingly.

- The drainage system can be designed a little bit higher to ensure it is not buried behind or beneath the wall after construction.
- Consider a proper location for the discharge of subsurface drained water.

4.3.8. Interviewee Number 8 (Paris District, TxDOT)

4.3.8.1. General Comments for Successful Slope Repairs

- Extreme wetting and drying cycles are the main reasons for most of the slope failures in in North Texas.
- It is better to use geogrids instead of additives (especially polyethylene fibers) for non-homogenous soils incorporating large particles such as stones and boulders. Also, geogrids could be more cost-effective in comparison to additives. A geogrid layer runs all the way to the failure plane and locks the slope together.
- Concrete ripraps are more popular than stone ripraps in urban areas because unwanted vegetation can grow between stone ripraps, which is not acceptable in urban areas. Also, stone ripraps collect more trash and waste material along the roadside.

4.3.8.2. Method-Specific Comments for Successful Slope Repairs

Rebuilding and compaction

The rebuilding and compaction method is one of the most popular methods for repairing slope failures since it is quick and inexpensive. It does not require engineering design. However, the slopes repaired with this method fail more often than the slopes repaired with other methods.

Common barriers and challenges

- Absence of vegetation and damage made by mowing machines are among the reasons for the recurring failure of slopes repaired using this method. The main challenge of vegetation is irrigation, especially at the early stages.
- This method could fail if an appropriate drainage system does not exist.

How to overcome barriers and challenges

- 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 sprinklers connected to watering trucks, and pumps.
- Mowers should be careful not to damage the vegetation cover. If damage happens, the vegetation should be fixed.
- It is recommended to include vegetation in slope repair contracts.
- Surface water drainage systems including roadside curbs, ditches, and riprap could be used.

Retaining Structures

This interviewee and his crew used a retaining structure as an immediate solution to repair a slope failure blocking its adjacent road. The maintenance crew utilized some salvaged I-beams from old bridges. They staked the salvage beams up, strapped them together, and fixed them to the ground. Although this method was used as an emergency and temporary fix, it has been working well and left in place. This retaining structure is not aesthetically pleasing, but it works. The interviewee believes such retaining structures are quick-to-install, low cost, and could also be a long-term solution for repairing slope failures when aesthetic criterion is not a concern.

Water management

Common barriers and challenges

- Damaged roadside edges (or damaged curbs) could create a water pathway along the edge and eventually result in slope runoff. Undesired vegetation along the roadside edge could damage edges.
- Inadequate water management design around bridge abutments and overpasses (i.e., not carrying water far enough from the slopes).
- A high pore water pressure under the concrete riprap creates buckling on the concrete cover, causing it to eventually collapse.

How to overcome barriers and challenges

- Frequent maintenance of roadside edges is necessary.
- Design surface drainage systems around bridges to carry water far enough from the slope to an area where there is no slide issue.
- 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.

Additives

Common barriers and challenges

- Lime usually leaches out from the soil with frequent heavy rainfalls.
- Additives such as polyethylene fibers do not perform well in non-homogenous soils.

How to overcome barriers and challenges

- Use cementation in combination with lime treatment to stabilize soil on slopes (e.g., 12–14% cement and 6–8% lime)
- Use geogrids instead of additives such as polyethylene fibers to provide an interlock for embankment slopes in non-homogenous soils.

4.3.9. Interviewee Number 9 (Paris District, TxDOT)

4.3.9.1. General Comments for Successful Slope Repairs

- Cracks could appear where the riprap intersects with pavement or a structure, especially in dry seasons. These gaps should be filled with grout.
- Retaining walls are the last option to solve slope-failure problems permanently due to their high initial cost. This method has a long-term service life but requires engineering design, and construction of retaining walls is usually contracted out.

4.3.9.2. Method-Specific Comments for Successful Slope Repairs

Soil Substitution

Common barriers and challenges

- Use of improper substitutes for existing soil
- Steep slopes could cause failure even if soil is substituted
- Poor drainage

How to overcome barriers and challenges

- Use appropriate material (e.g., crushed stone) for substitution.
- Use suitable drainage system such as roadside curbs and flumes to divert the water from entering the slope area.
- Flatten the slope to an angle of 4:1 or flatter.
- A 6-inch cover of topsoil and vegetation is also suggested for the success of this method.

4.3.10. Interviewee Number 10 (Lubbock District, TxDOT)

4.3.10.1. Method-Specific Comments for Successful Slope Repairs

Geosynthetics

Geosynthetics such as geotextiles are suitable for stabilizing slopes in arid areas. One of the reasons for the success of geotextiles is their ability to band softer and more erodible materials together. Moreover, they function as an artificial rooting system in more arid places where natural vegetation rooting systems do not exist. (In arid areas, vegetation may die in a dry season, which means a heavy rain in spring could cause failures where no rooting system exists to hold the soil together.)

Geotextiles could be considered as a long-term solution for slope repair projects. There are several types of geotextiles on the market; a proper type of geotextile should be selected based on the application. For instance, geotextiles that are proper for landscaping may not be appropriate for the highway infrastructure. It is recommended to install geotextiles deeper to incorporate topsoil and natural vegetation to create a stronger network of the rooting system. This method requires engineering design or at least standards where engineers can use and select the best type of geotextile based on their purpose and condition. This method can be implemented using standard equipment.

Biotechnical Methods

Mass vegetation using native species could be very effective in places where enough moisture exists. Some of the local species grow seed and fill out abundantly when the moisture is sufficient. However, they will die in a drought situation. There are a few species that tend to hold better than the others. One of the methods that are used to enhance vegetation growth is to utilize hydro mulches and early stage watering. However, experience showed that these methods might not be effective when drought happens.

Common barriers and challenges

- Existing vegetation dies back in arid areas or when drought happens.
- Planted vegetation may not be able to germinate or does germinate but withers and dies because of drought or insufficient watering.

How to overcome barriers and challenges

- Re-seed uncovered slopes with species more resistant to drought.

Soil Substitution

This method can be a long-term solution for repairing slope failures if appropriate fill material is used. For instance, the interviewee had experience with slope repairs using this method that had lasted 10 to 20 years. The repair used fill materials from dredging the bottom of a lake near the failure site. Unfortunately, these materials are not ideal for slope repair due to being highly plastic and subject to swell when water is presence and cracking during drought.

This method could fail especially after a severe drought. Using additives, such as lime and cement is one of the methods used by the interviewee to alleviate this problem. Lime treatment could be protected from leaching out by seal coating on the surface of the slope and paving the road shoulders.

Common barriers and challenges

- The occurrence of large cracks after a severe drought.

How to overcome barriers and challenges

- Along with soil substitution, lime stabilization is recommended for clayey soils.
- Along with soil substitution, cementation is recommended for sandy soils.

Retaining Structures

Retaining structures are often used in situations when the right of way is limited. Retaining structures are a very long-lasting piece of infrastructures that should be maintained for a long time. Therefore, the interviewee suggests buying the right of way if it is possible and building a low-grade slope.

Retaining walls require drainage that works properly. Precast retaining walls are very durable, but when it comes to bridges, the capital cost of retaining wall construction is substantial. Despite all the advantages of retaining structures, this interviewee recommends avoiding them when ROW is available to put in gentle slopes or purchase additional ROW when economics allow.

Gabions

Gabions are appropriate stabilization structures especially for repairing ditches and stream banks. Although expectations from the use of gabions are low compared to retaining walls, they provide multiple benefits at the same time. They are used for channel linings to slow down the velocity of the water by causing a natural turbulence. They are used to naturally control the stream silt load, which cleans the water. Gabions are also utilized as erosion proof fillers for channels. Since gabions are segmented and detachable, they are much simpler to repair and maintain. The damaged parts can be detached and replaced with new ones while the undamaged ones can be remained fixed. The interviewee has not experienced a big failure with gabions.

Common barriers and challenges

- The only concern with gabions is when the galvanized mesh system is covered with silt and damaged, leaving the rocks unsecured.

How to overcome barriers and challenges

- Routine maintenance of gabions, such as repairing the gabion mesh or replacing damaged segments could be solutions to this issue.

Chapter 5. CASE STUDIES

After conducting follow-up interviews, the interview participants were asked to provide detailed information on actual recent slope repair projects that could be presented as case studies. Eight slope repair projects are presented as case studies in the following sections. The application of one or a combination of several slope repair methods have been illustrated in the case studies.

5.1. SLOPE REPAIR USING RETAINING STRUCTURES, SOIL NAILS, AND A DRAINAGE SYSTEM

In 2015, a slope repair project was contracted out by TxDOT for reconstructing failed slopes with retaining structures and soil nails.

5.1.1. Location

The failed slopes were located on Highway US 69 at the TX-93 Spur overpass. The locations of slope repairs are shown in Figure 5-1.

Figure 5-1 Slope failures in Jefferson County on US 69 at TX-93 Spur

5.1.2. Soil Characteristics

The soil testing results show that the slope soil is clayey soil (CL and CH). The moisture content varies from 17.1 percent to 42.8 percent. The soil liquid limit is between 69 and 83, and plasticity index ranges from 45 to 55.

5.1.3. Procedure

The reconstruction of the failed slopes included: (a) removal of failed slope materials, *i.e.*, existing sheet piles (old metal beam guards), existing tire bales, existing failed embankment, and riprap materials; (b) excavating the outside shoulder and front slope in coordination with the retaining wall installation; (c) installing flowable fill material and a drainage system (weep hole) behind the retaining structure, and soil nails installation. Figure 5-2 illustrates the schematic design of this proposed retaining structure with soil nails. Soil nails used in this project were #6 epoxy coated reinforcement bars with various lengths between 21 and 32 feet. In total, 1001 nails (27190 linear feet) were used to support the 8780-square-feet retaining wall. Figure 5-3 shows the street view of the repaired slope after construction.

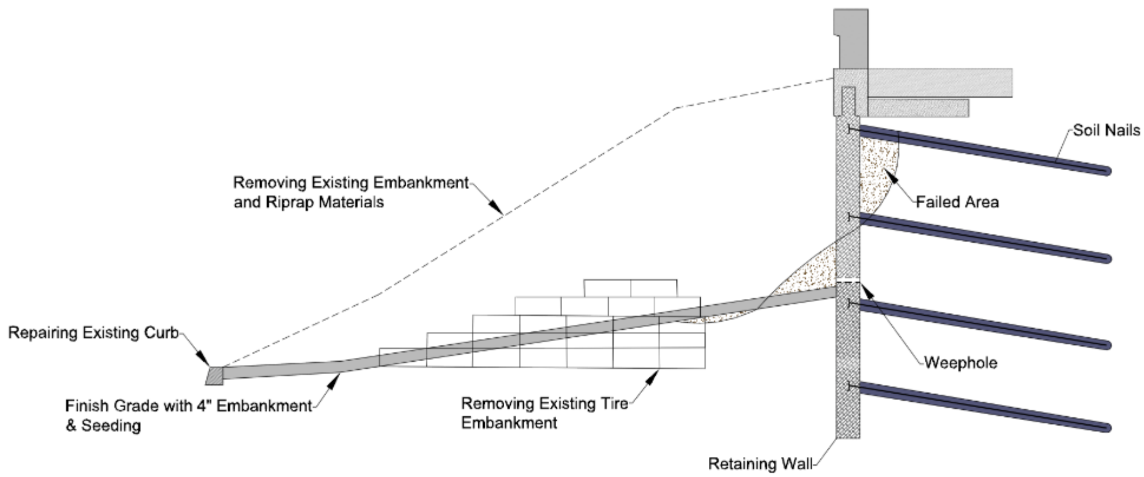

Figure 5-2 Schematic design of proposed retaining wall supported with soil nails

Figure 5-3 Reconstructed slope on North US 69 at TX-93 Spur

5.2. SLOPE REPAIR PROJECTS FOLLOWING HURRICANE HARVEY

Several slope failures happened after Hurricane Harvey (2017) in southeast Texas due to excessive raining. Figure 5-4 shows two example of slope failures in two locations in Beaumont district. Several slope repair projects were contracted in Jefferson and Hardin Counties as emergency maintenance contracts.

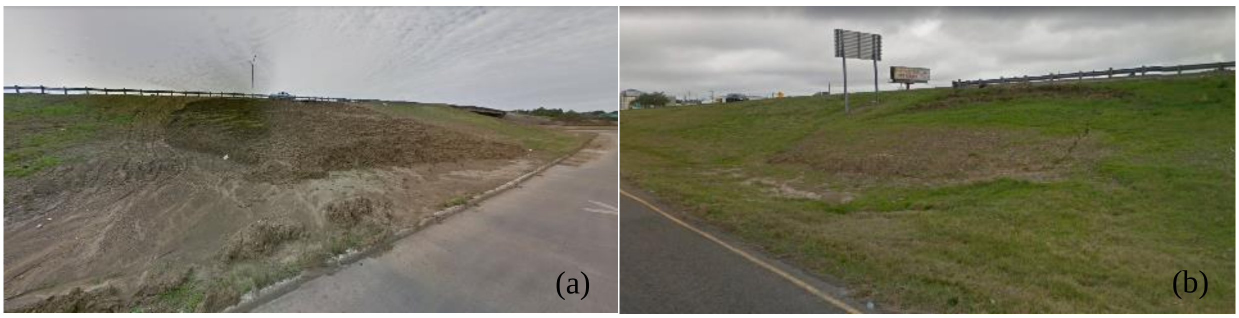

Figure 5-4 Slope failures in Beaumont, TX, after Hurricane Harvey: (a) North US 69 at Fannet Road Junction and (b) South US 69 at Lower Neches Valley Authority

Five slope stabilization methods were used for repairing the slope failures. These methods were a combination of repairing methods including temporary shoring, benching, filter fabric, cement stabilization, cellular fiber mulch seeding, soil retention blankets, and an underdrain pipe system. Depending on the characteristics of the slope, a proper slope repair method was selected for each slope. Figure 5-5 shows the location of the slope repair projects and the selected method for each project.

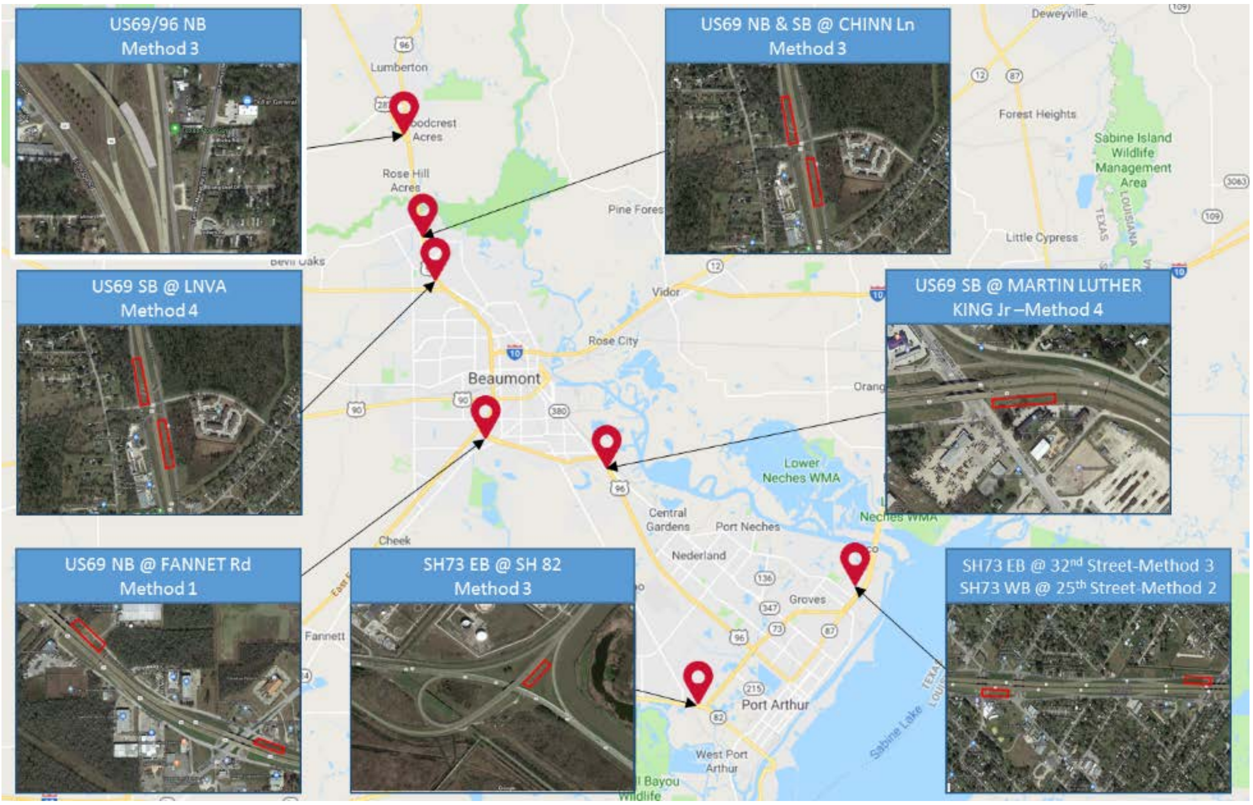

Figure 5-5 Slope failure locations in Jefferson and Hardin Counties after Hurricane Harvey

5.2.1. Slope Repair Using Rebuilding and Compaction, Cellular Fiber Mulch Seeding, and Soil Retention Blankets

This method was used for repairing two failed slopes in Jefferson County.

5.2.1.1. Location

The failed slopes were located on North US 69 at Fannet Rd. The failures were surficial slope failures on embankment slopes (Figure 5-6).

Figure 5-6 Slope failure on North US 69 at TX-93 Spur

5.2.1.2. Soil Characteristics

The soil testing results show that the slope soil is clayey and acidic.

5.2.1.3. Slope Geometry

The average depth of the slope was about 5 feet with a slope angle of 2H:1V.

5.2.1.4. Procedure

Figure 5-7 shows the schematic design of the method used for repairing the failed slopes in a cross-section view. In this project, the failed mass was removed from the failed slopes. The slopes were filled with the embankment soil and compacted. The cellular fiber mulch seeds were distributed on the slopes and then covered by soil retention blankets. A concrete curb and flume were installed to collect rain water.

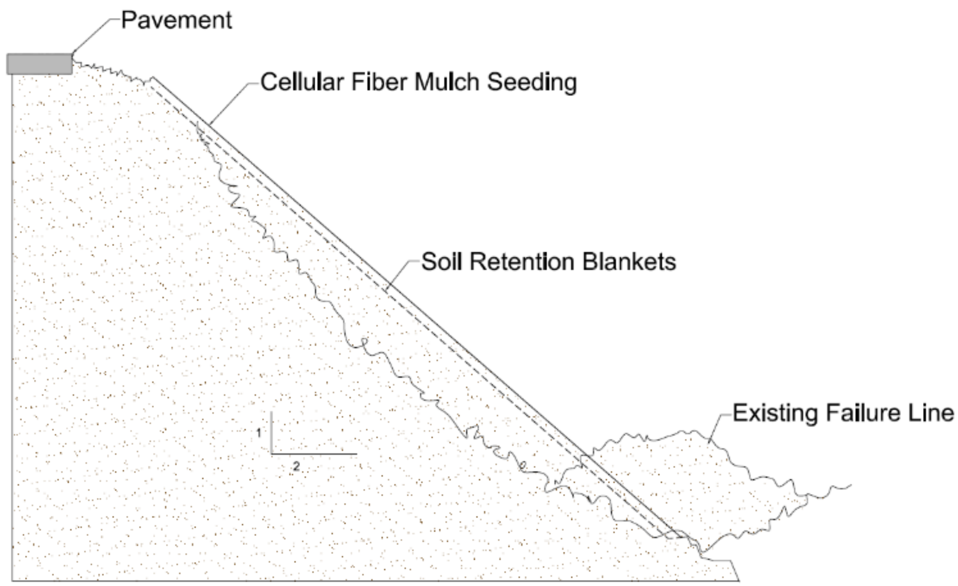

Figure 5-7 Slope repair using rebuilding and compaction, cellular fiber mulch seeding, and soil retention blankets

5.2.2. Slope Repair Using Benching, Filter Fabric, Cement Stabilization, Cellular Fiber Mulch Seeding, and Soil Retention Blankets

This method is a combinational method including benching, cellular fiber mulch seeding, soil retention blankets, and filter fabric.

5.2.2.1. Location

The failed slope was on West SH 73 at the intersection of 25th Street. The failure was a surficial slope failure on the fill embankment slope. This location is just a couple of miles away from Sabine Lake.

5.2.2.2. Soil Characteristics

The soil testing results show that the slope soil is clayey and poorly drained.

5.2.2.3. Slope Geometry

The average depth of the slope was about 3 feet with a slope angle of 2H:1V.

5.2.2.4. Procedure

Figure 5-8 shows the schematic design of this method in a cross-section view. The failed soil mass was removed, and the slope was excavated beyond the failure plane (670 CY). The slope was benched and covered using filter fabric to provide drainage. The embankment was rebuilt to the original slope with sandy clay soil. The cellular fiber mulch seeds were distributed on the slope and covered by soil retention blankets (940 SY). A curb and flume were installed using 1 CY concrete to collect rain water.

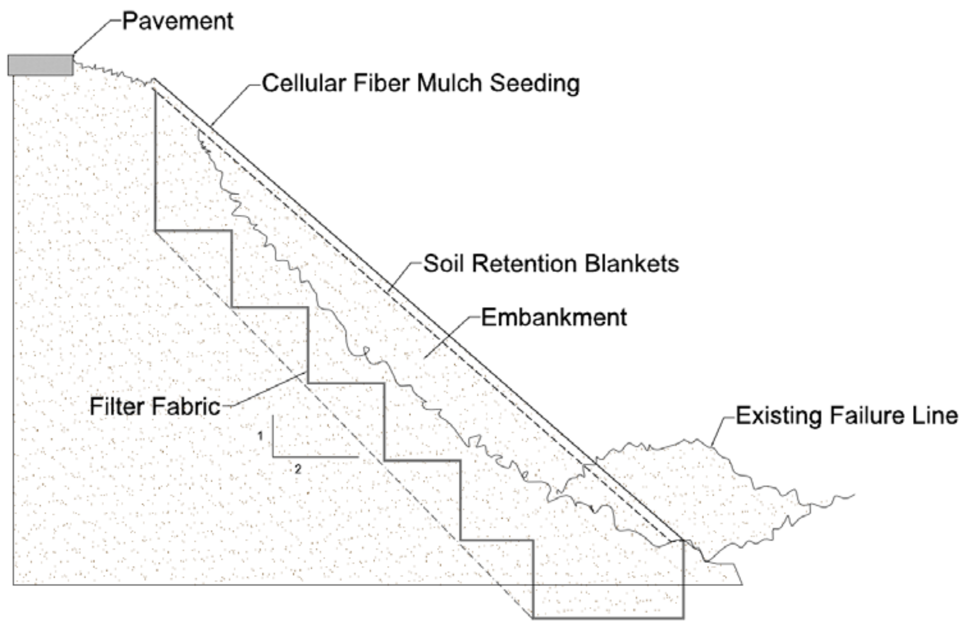

Figure 5-8 Slope repair using benching, filter fabric, cellular fiber mulch seeding, and soil retention blankets

5.2.3. Slope Repair Using Benching, Filter Fabric, Cement Stabilization, Cellular Fiber Mulch Seeding, Soil Retention Blankets, and an Underdrain Pipe System

This method is a combinational method including benching, filter fabric, mulching, soil retention blankets, and an extra underdrain system.

5.2.3.1. Location

The location of the failed slopes was on both North and South US 69 at Chinn Lane. Figure 5-9 shows the surficial slope failure on South US 69 at Chinn Lane.

Figure 5-9 Slope failure on South US 69 at Chinn Lane

5.2.3.2. Soil Characteristics

The soil testing results show that the slope soil is clayey and acidic.

5.2.3.3. Slope Geometry

The average depth of the slope was about 5 feet with a slope angle of 2H:1V.

5.2.3.4. Procedure

Figure 5-10 shows the schematic design of the method used for repairing the failed slopes in a cross-section view. The failed soil mass was removed, and the slope was excavated beyond the failure plane (1650 CY). The slope was benched and covered using filter fabric to provide drainage. The embankment was rebuilt to the original slope with cement stabilized sand. The cellular fiber mulch seed were distributed to cover the slope, which was then covered again by soil retention blankets (2310 SY). An underdrain system was used for collecting excessive water from the slopes. Each 4" diameter pipe used for the underdrain system was 10 feet long. In total, 660 linear feet of underdrain pipe were installed in the slopes. A curb and flume were also installed to collect rain water.

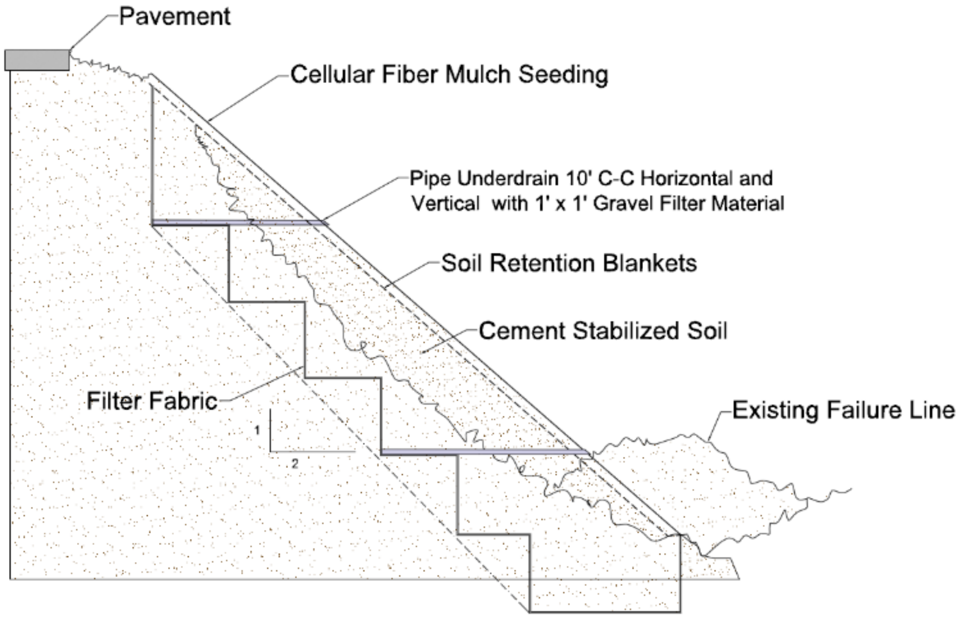

Figure 5-10 Slope repair using benching, filter fabric, cement stabilization, cellular fiber mulch seeding, soil retention blankets, and an underdrain pipe system

5.2.4. Slope Repair Using Temporary Shoring, Benching, Filter Fabric, Cement Stabilization, Cellular Fiber Mulch Seeding, Soil Retention Blankets, and an Underdrain Pipe System

This method is a combination of temporary shoring, benching, filter fabric, embankment reconstruction, cellular fiber mulch seeding, soil retention blankets, and an underdrain pipe system.

5.2.4.1. Location

The slope failure occurred on South US 69 at Martin Luther King Jr Rd.

5.2.4.2. Soil Characteristics

The soil testing results show that the slope soil is clayey and acidic.

5.2.4.3. Slope Geometry

The average depth of the slope was about 7.5 feet with a slope angle of 2H:1V.

5.2.4.4. Procedure

Figure 5-11 shows the schematic design of the method used for repairing the failed slopes in a cross-section view. Temporary shoring was provided before removing failed soil mass using sheet piles; then, the failed soil mass was removed, and the slope was excavated beyond the failure plane

(1345 CY). The slope was benched and covered using filter fabric to provide drainage. The embankment was rebuilt to the original slope with cement stabilized sand (1492 CY). The cellular fiber mulch seed were distributed on the slope and covered by soil retention blankets (1100 SY). An underdrain system was used for collecting excessive water from the slopes. The 4" pipe used for the underdrain system was 10 feet long. In total, 720 linear feet of underdrain pipe were installed in the slope. A curb and flume were installed to collect the rain water. After removing the temporary sheet piles, flowable backfill was used to fill the void.

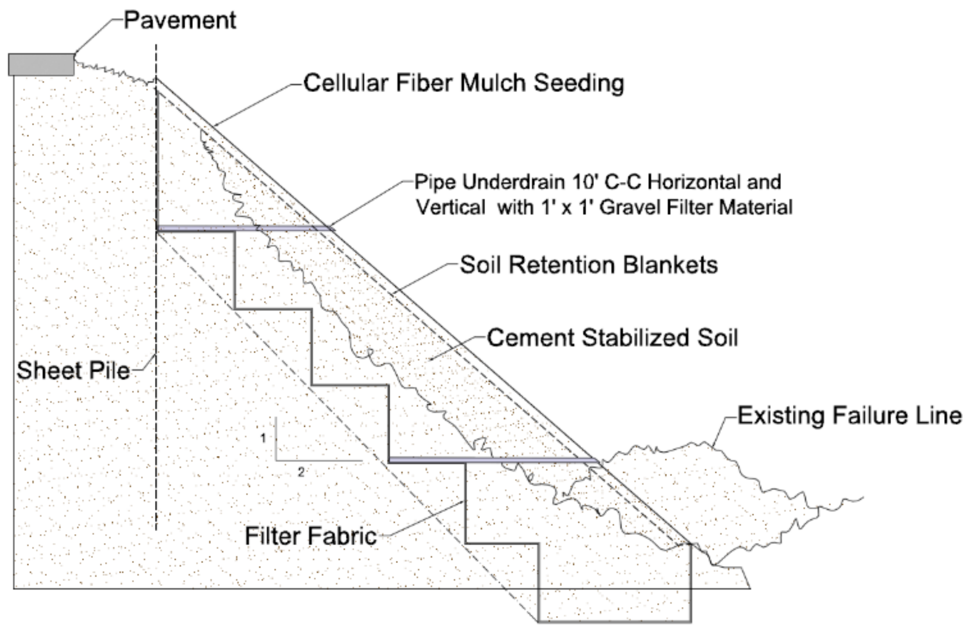

Figure 5-11 Slope repair using temporary shoring, benching, filter fabric, cement stabilization, cellular fiber mulch seeding, soil retention blankets, and an underdrain pipe system

5.3. SLOPE REPAIR USING RECYCLED PLASTIC PINS

Recycled plastic pins (RPPs) were used for stabilizing some slopes in the North Texas area. In this section, two slope repair projects using RPPs are provided as case studies.

5.3.1. Slope Repair on Interstate 35E Using Recycled Plastic Pins

A slope failure happened at Dallas County on the shoulder of Interstate 35 East. A crack approximately 42 feet long was reported along the pavement on the shoulder of Highway I35 East due to the surficial movement of soil at the slope (Figure 5-12). The depth of failure was reported at about 7 feet.

Figure 5-12 Crack and surficial movement of the slope (Hossain et al. 2017)

5.3.1.1. Location

The slope failure occurred on the northbound of Interstate 35E near Mockingbird Lane, Dallas, Texas. Figure 5-13 shows the location of the failure on the map.

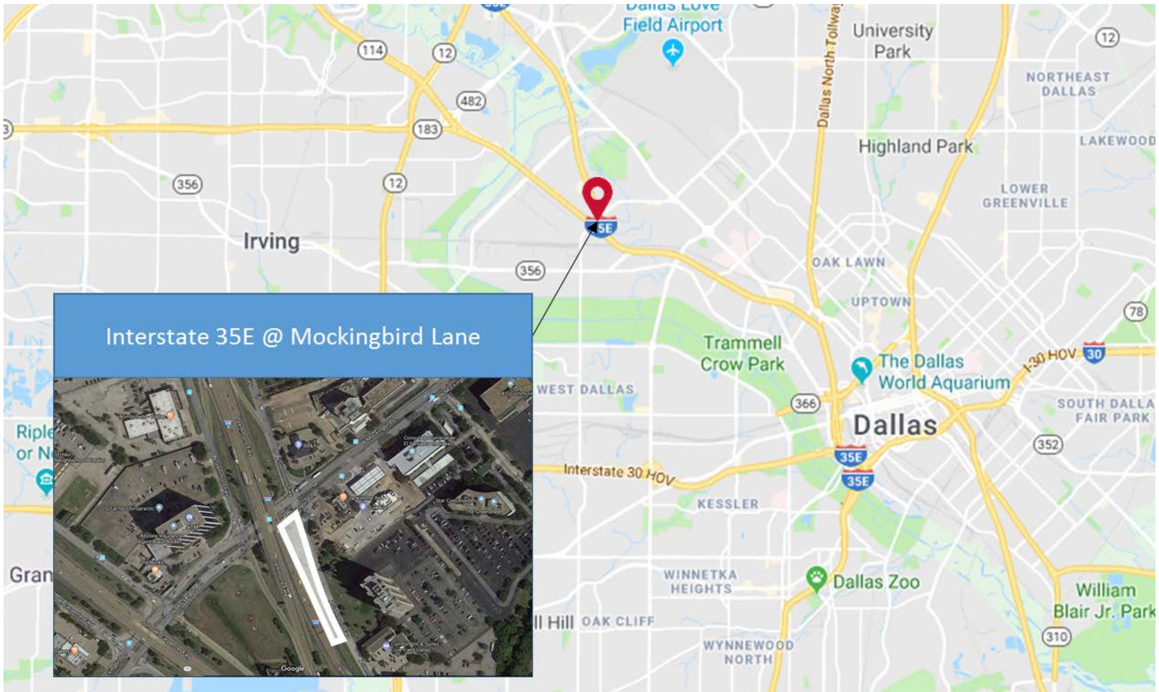

Figure 5-13 Slope failure on the northbound of Interstate 35E at Mockingbird Lane, Dallas, Texas

5.3.1.2. Soil Characteristics

The soil testing results showed that the soil type was high-plasticity clayey soil. The moisture content varied from 6.1 percent to 32.8 percent. The soil liquid limit is between 48 and 70, and the plasticity index ranges from 26 to 45.

5.3.1.3. Slope Geometry

The average depth of the slope was about 10 feet with a slope angle of 3H:1V.

5.3.1.4. Procedure

The installation of RPPs was performed in two phases. The first phase began in May 2014 by installing 130 pins using a Deere 200D excavator equipped with an FRD F22 hydraulic hammer) (Figure 5-14). In the second phase, which began in Octobre 2014, 121 pins were installed. In total, 251 pins were installed to stabilized the Mockingbird slope on I35 E. Figure 5-15 illustrates the field installation layout of RPPs on the Mockingbird slope. Figure 5-16 shows the Mockingbird slope three years after construction. Inclinometers were installed at the crest and toe of the Mockingbird slope to evaluate the performance of the RPPs. Moreover, a topographic survey was performed on a monthly basis. The results of both investigations showed no sign of failure on the Mockingbird slope.

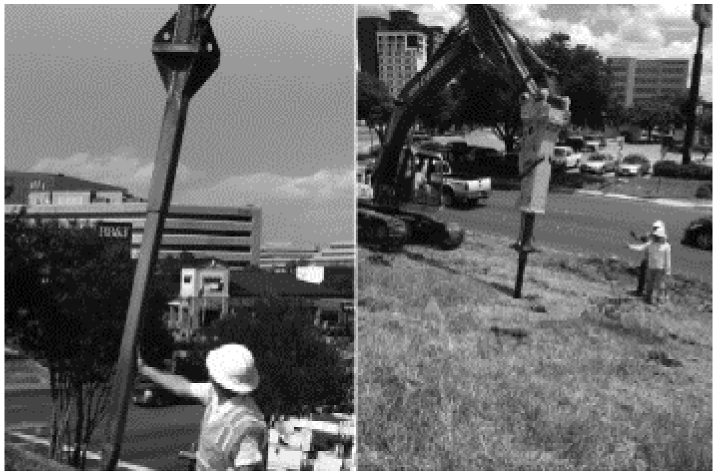

Figure 5-14 Installation of recycled plastic pins on Mockingbird slope (Hossain et al. 2017)

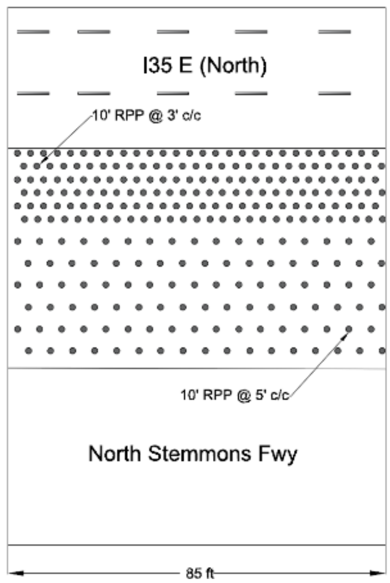

Figure 5-15 Field installation layout of recycled plastic pins on Mockingbird slope (Hossain et al. 2017)

Figure 5-16 Mockingbird slope three years after stabilization with recycled plastic pins

5.3.2. Slope Repair on US Highway 287 Using Recycled Plastic Pins

In this case study, RPPs were used for stabilizing a fill slope on US Highway 287. The slope was constructed during 2003 and 2004. Almost six years after the construction, several cracks appeared on the shoulder of the pavement (Figure 5-17) due to soil movements (shallow failure) at two sections of the embankment. After investigating the site, embankment slope repair using the RPP method was decided. Figure 5-18 illustrates these slope failures.

Figure 5-17 Crack and surficial movement of slope (Tamrakar 2015)

Figure 5-18 Failure of fill slope on US Highway 287 North near the St. Paul overpass in Midlothian

5.3.2.1. Location

The slope failure occurred on US Highway 287 North near the St. Paul overpass in Midlothian, Ellis County, TX. Figure 5-19 shows the location of the failures on the map.

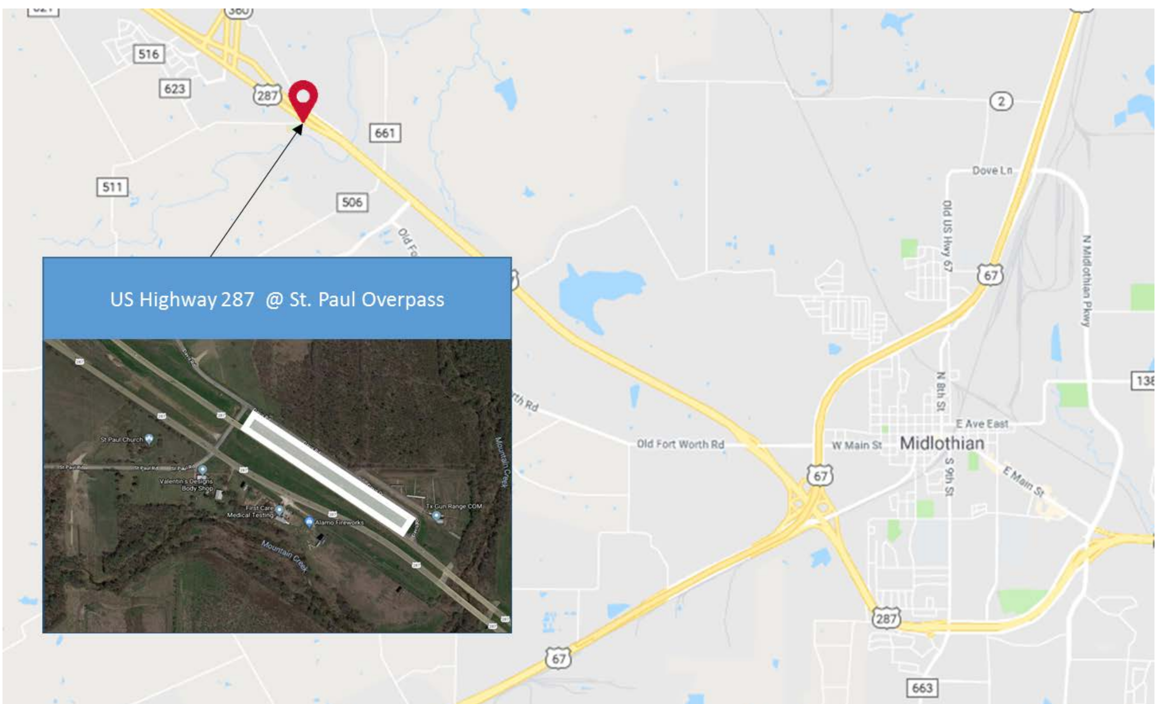

Figure 5-19 Slope failure on US 287 North at the St. Paul overpass

5.3.2.2. Soil Characteristics

The soil testing results showed that the slope was constructed using high-plasticity clay, and the topsoil may have been softened due to shrinkage and swelling behavior, which led to the initiation of slope movement, resulting in the crack over the shoulder. The moisture content varied from 17 percent to 34 percent. The soil liquid limit is between 48 and 79, and plasticity index ranging from 25 to 51.

5.3.2.3. Slope Geometry

The average depth of the slope was about 12 feet with a slope angle of 3H:1V.

5.3.2.4. Procedure

The RPPs were installed to resist the movement of the slope and provide additional support. The, 10 ft. long recycled plastic pins were launched at a center-to-center spacing of 3 feet near the crest of the slopes. Figure 5-20 illustrates the installation of recycled plastic pins on the slope using a hydraulic hammer.

Figure 5-20 Installation of recycled plastic pins (Khan et al., 2016)

5.4. SLOPE REPAIR USING TEMPORARY SHORING, SOIL NAILS, CONCRETE RETAINING WALL, AND SURFACE WATER MANAGEMENT

In 2010, a slope failure happened at Dallas County on the service road of West Texas Loop 12. The total length of the failed slope was 460 feet. The existing retaining wall was failed due to soil movement. Figure 5-21 illustrates the slope failure on the Texas Loop 12.

Figure 5-21 Slope failure on the West Texas Loop 12 (photo courtesy of Nicasio Lozano)

5.4.1. Location

The slope failure located on the service road of the West Texas Loop 12 at the Union Pacific Railroad. Figure 5-22 shows the location of the slope failure on the map.

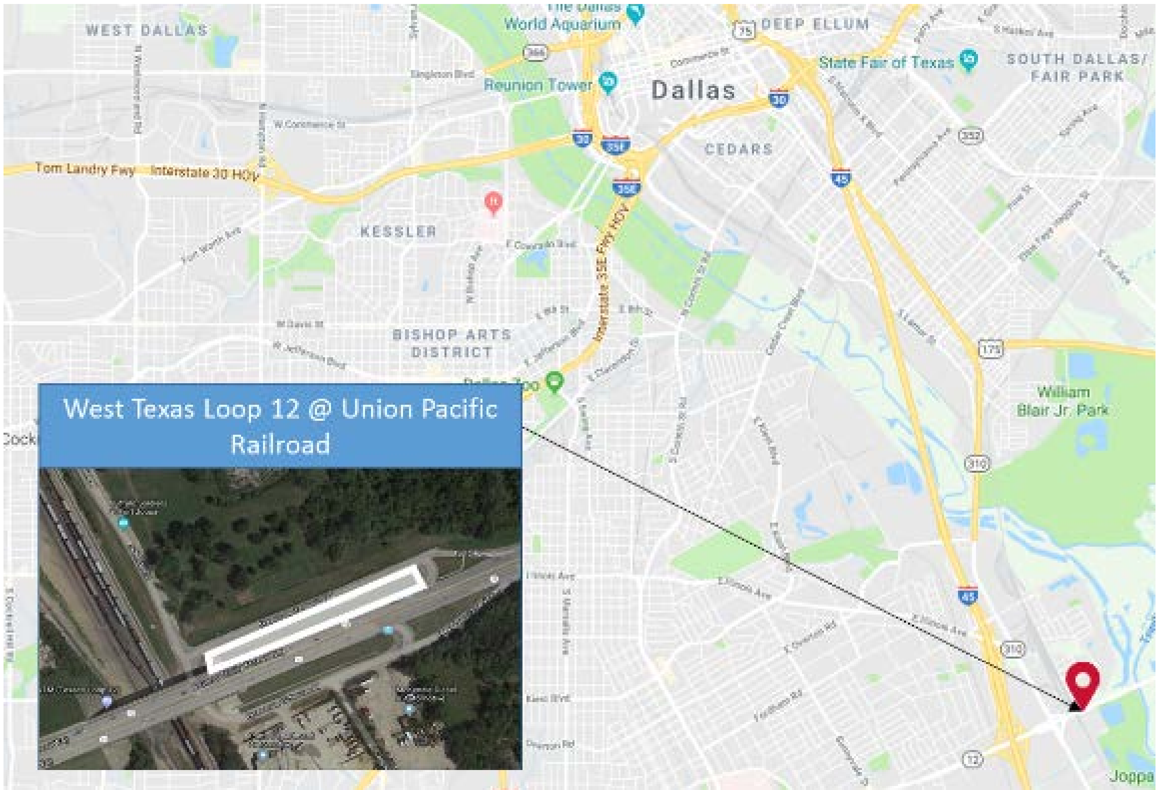

Figure 5-22 Location of the slope failure on the West Texas Loop 12, Dallas, Texas

5.4.2. Soil Characteristics

The soil testing results showed that the soil (0 to 20 feet depth) is moist, and soft clayey with limestone fragments. The soil is moist, stiff clayey sand beyond the 20 feet depth.

5.4.3. Slope Geometry

The average depth of the slope was about 10 feet with a slope angle of 4H:1V.

5.4.4. Procedure

Figure 5-23 shows the schematic design of the method used for repairing the failed slope in a cross-section view. The reconstruction of the failed slope was started by removing the failed materials including failed retaining wall, failed soil mass, concrete riprap, and flume. The face of the failed wall was protected by temporary shoring and soil nails. Then, the concrete retaining wall (5627 SF) was installed. The bottom of the excavation was benched before backfilling. The backfill material was Type A (behind the wall) and Type C2. Figure 5-24 shows the backfilling and compaction of the slope using heavy equipment. After compaction of the backfill material, a concrete flume installed to collect runoff water. Figure 5-25 shows the slope after reconstruction.

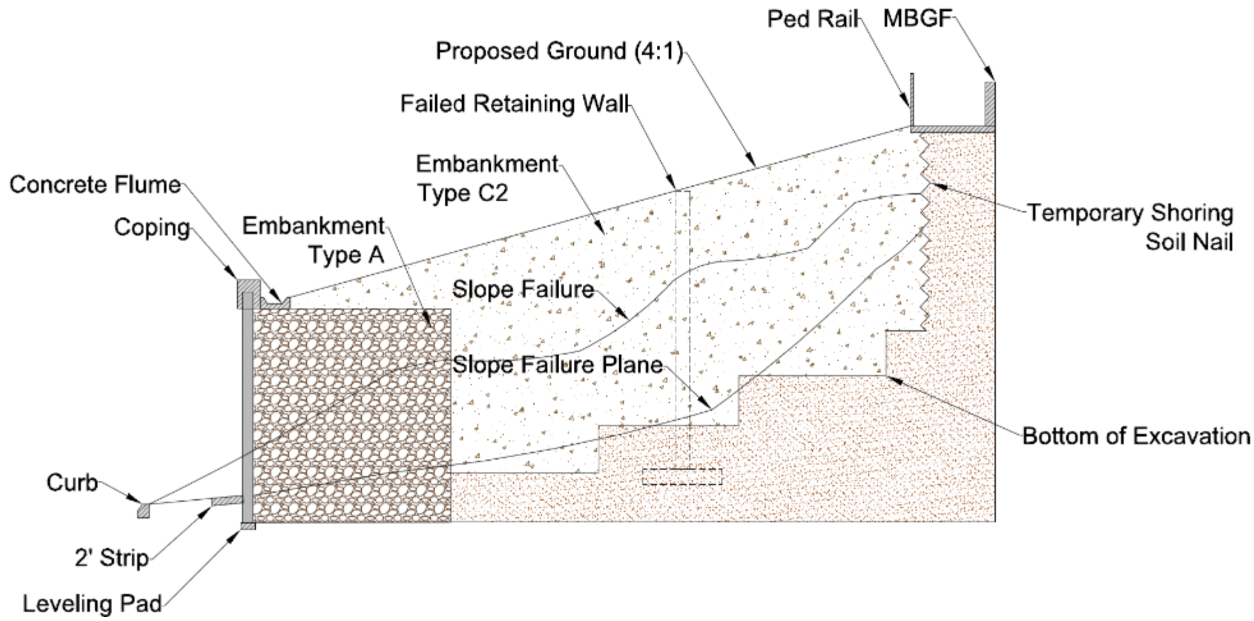

Figure 5-23 Slope repair using temporary shoring, soil nails, benching, concrete retaining wall, and water management

Figure 5-24 Installation of concrete retaining wall, backfilling and compaction (photo courtesy of Nicasio Lozano)

Figure 5-25 Reconstructed slope (photo courtesy of Nicasio Lozano)

Chapter 6. CONCLUSION

The data collected from literature, survey questionnaire, interviews, and case studies were critically analyzed and synthesized in this chapter. Table 6-1 to 6-5 present the advantages and disadvantages of various slope repair methods (mechanical slope repair and stabilization methods, earthwork slope repair and stabilization methods, biotechnical slope repair and stabilization methods, slope repair and stabilization with additives, and water management slope repair and stabilization methods) along with recommended practices to avoid recurring failures. The recommendations are suggested in addition to the standard specification of each method and does not replace them (standard specifications). Future research is recommended to determine a detailed cost breakdown of the slope repair methods compared to a base line.

Table 6-1 Evaluation of mechanical slope repair and stabilization methods

Repair and Stabilization Methods	***Type of Slope Failure***	***Advantage***	***Disadvantage***	***Recommendation for Successful Implementation***
Tire Bales	Deep	Quick to repair Applicable for structural and non-structural fill material Applicable for clay with high plasticity soil Cost-effective compared to conventional methods* (especially when rebate programs exist) Does not require special skilled workforce Does not require special equipment except for bailing Environmentally friendly (utilization of material with difficult disposal)	Not suitable for shallow slope failures Vulnerable to fire Requires large excavation and earth work Usually requires detailed engineering design	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 if needed to improve long-term performance.

* Conventional slope repair methods refer to traditional methods such as, retaining earth structures (concrete and masonry walls).

Repair and Stabilization Methods	Type of Slope Failure	Advantage	Disadvantage	Recommendation for Successful Implementation
Geosynthetics *(Geotextiles, Geogrids, and Geofoams)*	Shallow to deep	Quick to repair Applicable for most types of soil Cost-effective (in comparison with conventional methods) Flexible and lightweight materials with high tensile and compression strength Applicable in combination with other repair methods Resilient under seismic conditions Provides high quality drainage Provides long-term performance (Low chance of recurring failure) Environmentally friendly Does not require special equipment	Not applicable when high unit weight is required Vulnerable to chemical degradation mechanisms Usually requires detailed engineering design Requires special skilled workforce Requires large excavation and earth work (especially for Geofoams)	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 and inspection (not to damage the material and follow the correct procedure) of geogrids is important.
Launched Soil Nails	Shallow to deep	Quick to repair Low impact on traffic Applicable in most types of soil (sand, gravel, silt, clay) Suitable for steep slopes and vertical wall facing Cost-effective for repairing shallow slopes Does not require a large working space Provides drainage Provides long-term performance (Low chance of recurring failure) Creates minimum ground disturbance	Not applicable for slopes with excessive amount of cobbles or boulders Requires detailed engineering design (in the case of temporary use, launched soil nails may be used without engineering design.) Requires special installation equipment Requires skilled workforce and experienced contractors Vulnerable to corrosion (steel nails)	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).

Repair and Stabilization Methods	Type of Slope Failure	Advantage	Disadvantage	Recommendation for Successful Implementation
Retaining Structures	Shallow to deep	Suitable for slopes with limited space Applicable for short to high slope heights Applicable for all types of soil Applicable to various situations (different drainage requirements, different heights, different borrow materials) Provides extra space for road shoulders Provides long-term performance (Low chance of recurring failure) Improves the aesthetic quality of road side Does not require special equipment Does not require special skilled workforce	High initial and life-cycle-cost (depending on the type of the retaining structure) May require ground improvement in fine-grained soil Requires engineering design to repair deep slope failures (tall retaining structures); Does not necessarily require engineering design for temporary use or to repair shallow slope failures (short retaining structures) Requires drainage system (especially brick, masonry, and concrete types)	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: • Ensure the embedment depth at the toe of the wall is at least 2 feet. • Flatten the slope behind the wall from 3:1 to at least 4:1 if possible. Use surface and subsurface drainage systems.
Recycled Plastic Pins (RPPs)	Shallow	Quick to repair Cost-effective compared to conventional methods Does not require a large working space or major earthwork Resistant to chemical and biological degradation Environmentally friendly (utilization of materials that are difficult to dispose)	Requires detailed engineering design (The design could be conducted using simple charts.) Requires special installation equipment	In case of stiff soils: • Derive steel nails first and follow with inserting RPPs, or • Pre-drill a smaller diameter hole compared to RPPs, and then insert the pins (Costly approach).

Repair and Stabilization Methods	***Type of Slope Failure***	***Advantage***	***Disadvantage***	***Recommendation for Successful Implementation***
Earth Anchors	Shallow	Quick to repair Low impact on traffic Cost-effective compared to conventional methods Applicable in combination with other repair methods Applicable for temporary and permanent earth supporting purposes Provides extra stability for retaining structures Provides long-term performance	Requires detailed engineering design Requires experienced contractors Requires special equipment Requires pre-production load testing before installment	
Plate Piles	Shallow	Provides long-term performance (Low chance of recurring failure) Applicable for silty and clayey soil Suitable in regions with frequent wetting-drying cycles Creates minimum ground disturbance Cost-effective (in comparison with conventional methods)	Requires detailed engineering design Requires experienced contractors Requires special installation equipment	

Repair and Stabilization Methods	***Type of Slope Failure***	***Advantage***	***Disadvantage***	***Recommendation for Successful Implementation***
Pin Piles	Shallow to Deep	Provides long-term performance (Low chance of recurring failure) Does not necessarily require engineering design Suitable for slopes with higher water table Flexible applications (applicable for different slope angles) Ideal for foundation stabilization on slopes Creates minimum ground disturbance Cost-effective for deep-seated slope failures	Expensive compared to conventional methods Requires detailed engineering design Requires experienced contractors Requires special installation equipment More challenging installation than launched soil nails	
Sheet Piles	Shallow to deep	Quick to repair Applicable for slopes with high water table Provides long-term performance	More costly compared to conventional methods Not recommended for soil including excessive amount of cobbles or boulders Requires detailed engineering design Requires experienced contractors Requires special installation equipment	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!)
Soldier Piles and Lagging	Shallow to deep	Quick to repair Provides long-term performance (Low chance of recurring failure) Easy to construct Does not require skilled workforce	Not applicable for slopes with high water table Requires detailed engineering design Requires additional drainage system Provides temporary slope repair solution May require special equipment	

Repair and Stabilization Methods	***Type of Slope Failure***	***Advantage***	***Disadvantage***	***Recommendation for Successful Implementation***
Gabions	Shallow to deep	Provides long-term performance (Low chance of recurring failure) Cost-effective (in comparison with concrete retaining walls) Suitable for protecting river embankments Suitable for slopes with limited space Applicable to slopes with different angles Applicable to silty and clayey soil Applicable in combination with other repair methods Provides high quality drainage Does not require skilled workforce Does not require special equipment Does not necessarily require engineering design	It requires routine maintenance to ensure long-term performance. Provides temporary slope repair solution Does not improve the aesthetic quality of road side	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 of gabions, 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 6-2 Evaluation of earthwork slope repair and stabilization methods

Repair and Stabilization Method	*Type of Slope Failure*	*Advantage*	*Disadvantage*	*Recommendation for Successful Implementation*
Rebuilding and Compaction	Shallow to deep	Quick to repair Cost-effective Easy to implement (for small shallow slope failures) Most common method for repairing the surficial slope failures used by maintenance workforces Applicable in combination with other repair methods Does not necessarily require engineering design	High chance of recurring failure Requires skilled workforce and experienced contractors to achieve best performance Requires drainage system Requires surface protection	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	Quick to repair Applicable for steep slopes Applicable for slopes with weathered rock Applicable in combination with other repair methods Controls run-off and minimizes erosion	Not applicable in sandy, non-cohesive, or highly erodible soils May requires large excavation and earth work Requires drainage system for each bench Not suitable for slopes with high water table	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	Quick to repair Easy to implement Applicable in small slopes Applicable to most soil types Does not requires special skilled workforce Dose not necessarily require engineering design	Not suitable for large slopes Requires large excavation and earth work Requires acquisition of additional right-of-way Requires procurement of fill material and disposal of extra material	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.

Repair and Stabilization Method	***Type of Slope Failure***	***Advantage***	***Disadvantage***	***Recommendation for Successful Implementation***
Soil Substitution	Shallow to deep	Quick to repair Does not require special skilled workforce Does not necessarily require engineering design Cost-effective when a convenient source of fill material be available close to the project Applicable in small slopes Applicable to most soil types	Not cost-effective for large slopes Requires large excavation and earth work Requires procurement of fill material and disposal of extra material	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.
Buttress	Shallow to deep	Cost effective for small slopes Does not require special equipment Does not necessarily require geotechnical soil testing Applicable for small- to medium- size slope failures Applicable for slope failures occurred at the toe of the slope Applicable in most soil types Provides drainage	Not applicable in shallow slope failures at top of the slope Not cost-effective method for large slopes Requires detailed engineering design Requires acquisition of additional right-of-way Requires procurement of buttressing material	

Table 6-3 Evaluation of biotechnical slope repair and stabilization methods

Repair and Stabilization Method	***Type of Slope Failure***	***Advantage***	***Disadvantage***	***Recommendation for Successful Implementation***
Vegetation	Shallow	Quick to repair Low impact on traffic Applicable in small and shallow slope failures Applicable in combination with other repair methods Provides drainage Provides visually pleasing landscape Provides long-term performance (Low chance of recurring failure) Does not require engineering design Does not require special equipment Does not require special skilled workforce Cost-effective (in comparison with mechanical repair methods such as, retaining walls) Controls run-off and minimize erosion Creates minimum ground disturbance Environmentally friendly	Not suitable for steep slopes Requires specific installation season (Spring and Fall) Requires monitoring and maintaining after installation Not a short-term solution (with immediate impact) for slope stabilization and erosion control	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 6-4 Evaluation of slope repair and stabilization with additives

Repair and Stabilization Method	***Type of Slope Failure***	***Advantage***	***Disadvantage***	***Recommendation for Successful Implementation***
Lime	Shallow to deep	Cost-effective (in comparison with mechanical repair methods) Applicable in clay with high plasticity, clayey silt, and dry clayey sand Does not require special equipment	Not applicable to frozen soil High chance of leaching without appropriate surface water management system Requires detailed engineering design Requires heavy construction equipment Requires high quality mixing procedure Requires work space to properly mix soil and lime Requires special construction process and condition (temperature, sun, wind)	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	Applicable in regions with heavy rains Applicable in slopes with cohesive or granular soils Reduces the permeability of the slope Does not require special equipment	Not applicable in frozen soil Not applicable in soils with pH less than 5.3 Not applicable in soils with organic content over than 2% Requires detailed engineering design Requires heavy construction equipment Requires high quality mixing procedure Requires work space to properly mix soil and lime Expensive compared to lime stabilization method	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.

Repair and Stabilization Method	*Type of Slope Failure*	*Advantage*	*Disadvantage*	*Recommendation for Successful Implementation*
Fly ash	Shallow to deep	Applicable in silt and clay with high plasticity Suitable for soil drying Controls excessive soil shrinkage and swell Does not require special equipment	Not applicable for soils with sulfate content greater than 10% Certain sources of fly ash are corrosive to metal pipes Requires detailed engineering design Requires heavy construction equipment Requires high quality mixing procedure Requires work space to properly mix soil and lime Requires special construction process (compaction) and working condition (temperature, sun, wind)	

Table 6-5 Evaluation of water management slope repair and stabilization methods

Repair and Stabilization Method	***Type of Slope Failure***	***Advantage***	***Disadvantage***	***Recommendation for Successful Implementation***
Surface Water Management	Shallow to deep	Quick to repair Provides high quality and long-term performance (Low chance of recurring failure) Does not require special equipment Applicable in regions with heavy rains Diverts water from top and toe of slopes Controls run-off and minimize erosion Controls excessive water infiltration	Requires monitoring and maintenance after installation Requires engineering design	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	Applicable in regions with heavy rains Suitable for soil drying Controls underground water level	Requires monitoring and maintenance after installation Requires detailed engineering design Requires experienced contractors May require special equipment 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).	Detailed engineering design is essential Drainage system for retaining structures is necessary 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.

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APPENDIX A – VALUE OF SYNTHESIS ON RAPID REPAIR METHODS FOR EMBANKMENT SLOPE FAILURES

A-1 INTRODUCTION

Table A-1 presents the summary of the value of research (VoR) estimation for Project 0-6957 based on the functional areas selected by the Texas Department of Transportation (TxDOT). In this table, the benefit areas are associated with qualitative and economic (quantitative) benefits. Qualitative benefits of transportation research are those benefits that are not directly quantifiable, such as safety (Ellis et al. 2003). On the other hand, the quantitative benefits are those that can be quantified as savings after implementation, such as reduction in construction operations and maintenance costs (Ellis et al. 2003). In the following sections, the qualitative and economic benefits of this research across various areas are discussed.

Table A-1 The Project's Value of Research (VoR)

Benefit Area	***Qual***	***Econ***	***Both***	***TxDOT***	***State***	***Both***
Reduced Construction Operations and Maintenance Cost		×		×		
Environmental Sustainability	×					×
Level of Knowledge	×			×		
Safety	×					×
Infrastructure Condition	×					×
Material and Pavements	×			×		
System Reliability	×			×		
Increase Service Life	×			×		
Management and Policy	×			×		
Reduced Administrative Costs	×			×		
Traffic and Congestion Reduction	×					×
Customer Satisfaction	×					×

Notes: Qual: Qualitative; Econ: Economic; TxDOT: Texas Department of Transportation; State: State of Texas.

A-2 REDUCED CONSTRUCTION OPERATIONS AND MAINTENANCE COST

The Texas Department of Transportation (TxDOT) is projecting to spend approximately $28.5 million in slope repair projects[1] for fiscal year 2018 (TxDOT 2018). This amount is not atypical considering the Texas soil conditions. Considering the 2018 fiscal year's approved slope repair projects and Texas soil condition, most slope failures in Texas have occurred in districts underlain by highly plastic clay soil with a moderate-to-high swelling potential. Results of our survey on slope repair projects in Texas showed that most TxDOT districts which are to some extent prone to clays with high swelling potential have the most number of slope failures. In essence, highway slope failure is an ongoing concern all over Texas.

Survey analysis showed that approximately 55% of the slope failures in Texas are recurring failures. If we assume that TxDOT spends $28.5 million annually for repairing slopes, 55% reduction in slope repair costs is around $15.67 million annual cost-savings. This 55% reduction can be attributed not only to the long-performance (preventing failure reoccurrence) but also to the rapidity and cost-effectiveness of the best practices proposed in this research project. In a 10-year horizon, if we assume that the discount rate is 5%, the net present value of this research project (with $59,596 capital cost) will be over $130 million. Figure 1 shows how this presented value is calculated.

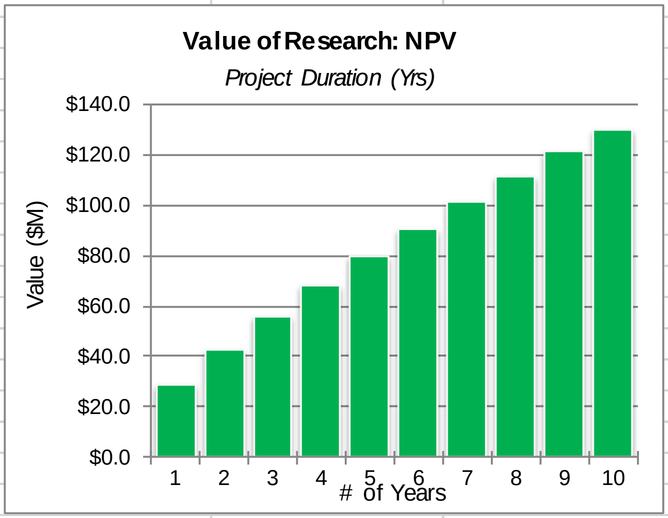
[1]Projects are grouped into 4 categories: projects that are currently let (Construction Scheduled); projects in the construct authority (Finalizing for Construction); projects in the develop authority (Under Development); and projects in the initial phases of project development (Long Term Planning). The dataset excludes non-letting projects. It is updated daily and used in the Project Tracker application (http://apps.dot.state.tx.us/apps-cq/project_tracker/) on TxDOT.gov.

Texas Department of Transportation	Project #	0-6957			
	Project Name:	Synthesis on Rapid Repair Methods for Embankment Slope Failure			
	Agency:	UTA	Project Budget	$	59,596
	Project Duration (Yrs)	1.0	Exp. Value (per Yr)	$	15,675,000
Expected Value Duration (Yrs)		10	Discount Rate		5%

Economic Value

Total Savings:	$ 156,690,404	Net Present Value (NPV):	$	130,146,285
Payback Period (Yrs):	0.003802	Cost Benefit Ratio (CBR, $1 : $___):	$	2,184

Years	Expected Value
0	$15,615,404
1	$15,675,000
2	$15,675,000
3	$15,675,000
4	$15,675,000
5	$15,675,000
6	$15,675,000
7	$15,675,000
8	$15,675,000
9	$15,675,000
10	$15,675,000



Years	Expected Value	Expected Value	Expected Value	NPV
0	$15,615,404	$15,615,404	$15.62	$14.87
1	$15,675,000	$31,290,404	$31.29	$29.09
2	$15,675,000	$46,965,404	$46.97	$42.63
3	$15,675,000	$62,640,404	$62.64	$55.53
4	$15,675,000	$78,315,404	$78.32	$67.81
5	$15,675,000	$93,990,404	$93.99	$79.50
6	$15,675,000	$109,665,404	$109.67	$90.64
7	$15,675,000	$125,340,404	$125.34	$101.25
8	$15,675,000	$141,015,404	$141.02	$111.36
9	$15,675,000	$156,690,404	$156.69	$120.98
10	$15,675,000	$172,365,404	$172.37	$130.15

Notes:

Amounts on Value of Research are estimates.

Project cost should be expensed at a rate of no more than the expected value per year.

This electronic form contains formulas that may be corrupted when adding or deleting rows, by variables within the spreadsheet, or by conversion of the spreadsheet. The university is responsible for the accuracy of the Value of Research submitted.

Figure A-1 Value of Synthesis on Rapid Repair Methods for Embankment Slope Failure

A-3 ENVIRONMENTAL SUSTAINABILITY

This research project provides value by identifying and evaluating existing environmentally sustainable slope repair methods. This is in line with TxDOT mission to reduce the environmental impacts of the maintenance programs (TxDOT 2011). Examples of environmentally sustainable slope repair methods are biotechnical slope repair methods, tire bales, recycled plastic pins, and geosynthetics. Slope repair using tire bales, recycled plastic pins, and geosynthetics has significant environmental benefits not only by providing durable and long-lasting embankments but also by reusing waste materials that are difficult to dispose of. Biotechnical methods are environmentally sustainable since they use natural construction materials and blend well with the surrounding landscape that makes them visually appealing.

A-4 LEVEL OF KNOWLEDGE

The information on slope failure mechanisms and slope repair methods are extensive but not concentrated. First and foremost, this study collected the most important and recent information on slope repair knowledge and practice from various sources. By synthesizing all the gathered information, this information provides best condition-based slope repair practices focusing on long-term performance, constructability, and ease of implementation by TxDOT workforces. This study improves the level of knowledge by providing guidelines and suggestions for successful implementation of each slope repair method based on information gathered from technical literature and professional experiences.

A-5 SAFETY

According to Spiker and Gori (2000), the United States is experiencing about 50 deaths annually due to slope failures. Although shallow slope failures do not usually cause danger to human life directly, they affect the performance and structural stability of the adjacent infrastructure systems and disturb the regular traffic flow if the resulting debris flows into the highway pavement (Titi and Helwany 2007). Additionally, the process of repairing these slope failures requires work zones that jeopardize the safety of drivers. TxDOT reported 25,814 crashes with 181 fatalities due to work zones (TxDOT 2017b). This research project indirectly contributes to highway safety by identifying best slope repair methods that reduce the number of recurring highway slope failures and subsequently, decrease the number of work zones related to slope failures.

A-6 INFRASTRUCTURE CONDITION

Shallow slope failures could affect the performance and structural stability of adjacent infrastructure systems; they could also disturb the regular traffic flow if the resulting debris flows into the highway pavement (Titi and Helwany 2007). For example, they can damage guardrails, shoulders, and even roadways (Loehr et al. 2007). This research project provides value by identifying and evaluating slope repair methods that prevent recurring failures that affect adjacent infrastructure systems.

A-7 MATERIALS AND PAVEMENTS

Every year, TxDOT spends millions of dollars on repairing pavements damaged by slope failures (Hossain et al. 2017). Shallow embankment slope failures are one of the main causes of damages to pavements, especially throughout central Texas (Jouben 2014). This research provides value by synthesizing and evaluating slope repair methods that insure the long-term performance of repaired embankments and adjacent pavements.

A-8 SYSTEM RELIABILITY AND INCREASED SERVICE LIFE

Although many slope repairs using common repair approaches show satisfactory performance, some repair attempts have shown recurring failures after a period. Recurring slope failures frequently happen (35% of total slope failures) in Texas, due to the extreme weather and soil conditions. This research project provides value by identifying and evaluating reliable slope repair methods with long-term service life. It also provides guidelines and suggestions for successful implementation of each slope repair method. For instance, our research showed the use of a simple roadside curb could increase the service life of rebuilding and compaction slope repair method-as the most frequent method used with a high chance of failure- significantly.

A-9 MANAGEMENT AND POLICY

This research project provides value by synthesizing critical information in a single repository for (1) making effective decisions, (2) meeting strategic goals, and (3) avoiding the consequences of not knowing (Dresley and Lacombe 1998). The results of synthesis research can potentially provide the opportunity for managers and policy makers to improve the state of practice. For example, a synthesis study by Transportation Report Board (TRB) for New York resulted in an innovative slope stabilization technique that saved $20,000 to $50,000 per project (Dresley and Lacombe 1998).

A-10 REDUCED ADMINISTRATIVE COSTS

Repairing recurring slope failures requires administrative tasks, such as project management and paperwork. Reducing recurring slope failures results in a decrease in the costs associated with these administrative tasks. This research provides value with respect to this benefit area by synthesizing and evaluating slope repair methods preventing recurring failures.

This research project also creates value by providing freely available educational materials, such as video presentations that can be accessed by TxDOT managers and decision makers. TxDOT expenditure on the training programs was approximately $600 per employee in 2015 (TxDOT

2016). This research project provides opportunity to reduce the annual educational expenditures by providing freely available educational materials.

A-11 TRAFFIC AND CONGESTION REDUCTION

In 2015, Americans spent 6.9 billion hours in traffic and consumed 3.1 billion gallons of fuel that is equivalent to $160 billion in time and fuel loss (Schrank et al. 2015). According to the U.S. Department of Transportation (USDOT), about 10% of total delay attributes to the work zones (U.S. Department of transportation 2017). Therefore, the congestion cost due to work zones is about $16 billion. Most conventional slope repair methods (e.g., earthwork slope repair methods and additives) require work zones (Bromhead et al. 2012; Abrams and Wright 1972). This research project contributes to congestion reduction by identifying the slope repair methods with minimum work zone requirements.

A-12 CUSTOMER SATISFACTION

Congestion is one of the significant factors affecting the transportation customer satisfaction (Ye et al. 2013). This research project contributes to congestion reduction by identifying the slope repair methods with minimum work zone requirements. It also identifies and assesses slope repair methods that do not disturb the aesthetic and visual quality of drivers.

APPENDIX B – SURVEY QUESTIONNAIRE

Survey on Rapid Repair Methods for Embankment Shallow Slope Failure

Project Description

The University of Texas at Arlington invites you to participate in a short survey pertaining to rapid repair methods for embankment slope failure. This survey is an integral part of the TxDOT Research and Technology Implementation (RTI) Project #0-6957, titled: "Synthesis on Rapid Repair Methods for Embankment Slope Failure." This survey aims to capture the state of practice in repairing embankment shallow slope failures performed by TxDOT and other state DOTs maintenance staff. We expect this survey to take approximately 15 minutes. TxDOT and our research team highly appreciate your contribution to this unique effort. If results of this study are published or presented, your name will remain confidential. Please continue if you voluntarily agree to participate in this research.

If you have any questions about this research study, please contact Dr. Mohsen Shahandashti, P.E. at mohsen@uta.edu or directly at 817-271-0440.

Section 1 – Contact Information

Please provide the following contact information:

- Name: ______________________________
- Position: ______________________________
- District: ______________________________
- Address: ______________________________
- City/Town: ______________________________
- State: ______________________________
- E-mail: ______________________________

Section 2 - Shallow Slope Repair Methods

1. How many shallow slope failures do you repair every year?

   "**Shallow Slope Failure**" refers to the downslope movement of a thin layer of soil approximately parallel to the slope face. Shallow slope failure depth does not usually exceed four to six feet.

   Write a number between 0-20

2. How many of these repairs are due to recurring failures?

   "**Recurring Failure**" refers to the failure of a slope that was at least repaired once before.

   Write a number between 0-20

3. When would you institute a formal analysis to select a repair method?
   - ☐ All slope failures are formally reviewed
   - ☐ None of the slopes are formally reviewed
   - ☐ When slope has failed more than once
   - ☐ When slope has failed more than twice
   - ☐ When the paved roadway surface is impacted on a fill section
   - ☐ When the slide leaves a vertical face greater than a pre-determined height
   - ☐ When a Structure such as a Bridge is involved
   - ☐ Other

   Please specify

Section 3 – Evaluation

This section provides a list of 18 slope repair methods. Please evaluate each slope repair method that you have experience utilizing. If you have not used the method, simply check "No" to move to the next method.

1-18 Tire Bales

Tire bales: Excavation of the failed existing soils and replacement with interlocking stacks of recycled tire bales, then capping the area with topsoil.

1. Has your area ever utilized Tire Bales as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Tire Bales

1. How many times has your area utilized Tire Bales as a shallow slope failure repair method?

   [Write a number between 0-20]

2. How many slopes repaired utilizing Tire Bales have failed?

   [Write a number between 0-20]

3. Were the Tire Bales installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown

4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?

- ☐ 0.5:1
- ☐ 1:1
- ☐ 1.5:1
- ☐ 2:1
- ☐ 2.5:1
- ☐ 3:1
- ☐ 3.5:1
- ☐ 4:1
- ☐ 4.5:1
- ☐ 5:1
- ☐ 5.5:1
- ☐ 6:1
- ☐ 6.5:1
- ☐ 7:1
- ☐ Vertical
- ☐ Unknown
- ☐ Other

Please specify

2-18 Geosynthetics

Geosynthetic is a generic term that encompasses flexible polymeric materials used in geotechnical engineering. Geosynthetics significantly increase the strength of the soil by improving tensile strength (e.g., Geogrid) or bearing capacity (e.g., Geofoam). 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.

1. Has your area ever utilized Geosynthetics as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Geosynthetics

1. How many times has your area utilized Geosynthetics as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Geosynthetics have failed?

   Write a number between 0-20

3. Were the Geosynthetics installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No

☐ Unknown

4. What type of Geosynthetics was used?
   ☐ Geotextile
   "**Geotextiles** are a planar, permeable, polymeric textile material, which is utilized to repair slopes in at least one of four following forms: separation, reinforcement, filtration, and drainage."
   ☐ Geogrid
   "**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."
   ☐ Geofoam
   "**Geofoam** blocks are primarily expanded polystyrene (EPS) or extruded polystyrene (XPS). Geofoams are a perfect substitute to traditional earth fills in highway embankment construction, especially where small unit weight and high bearing capacity is needed."
   ☐ Other

   Please specify

5. Check all the reasons that apply to selecting this method:
   ☐ Long term service life (Low chance of recurring failure)
   ☐ Low impact on Traffic
   ☐ No engineering design required
   ☐ No special equipment required
   ☐ No special skilled workforce required
   ☐ No Geotechnical soil testing required
   ☐ Quick to repair
   ☐ Low cost to repair
   ☐ Other (Please write any other reasons that support your selection):

6. If known, select the soil type of failed slope:
   ☐ Stone fragments, gravel and sand
   ☐ Fine sand
   ☐ Silty or clayey gravel and sand
   ☐ Silty soil
   ☐ Clayey soil

- ☐ Peat, highly organic soil
- ☐ Unknown

7. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

Write a number or range between 0 and 70

8. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

Write a number or range between 0 and 100

9. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

10. If known, what was the typical slope (xH:1V) of failed slopes?
    - ☐ 0.5:1
    - ☐ 1.5:1
    - ☐ 2.5:1
    - ☐ 3.5:1
    - ☐ 4.5:1
    - ☐ 5.5:1
    - ☐ 6.5:1
    - ☐ Vertical
    - ☐ Other
    - ☐ 1:1
    - ☐ 2:1
    - ☐ 3:1
    - ☐ 4:1
    - ☐ 5:1
    - ☐ 6:1
    - ☐ 7:1
    - ☐ Unknown

Please specify

3-18 Launched Soil Nails

Launched soil nail (LSN) is a steel nail or rod that is inserted in the face of the slope to penetrate into a stable region using compressed air force. These nails reinforce the soil mass by transferring the tensile and shear resistance of nails to the sliding soil.

1. Has your area ever utilized Launched soil nail as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Launched Soil Nails

1. How many times has your area utilized Launched soil nail as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Launched soil nail have failed?

   Write a number between 0-20

3. Were the Launched soil nail installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown

4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?
   - ☐ 0.5:1
   - ☐ 1:1
   - ☐ 1.5:1
   - ☐ 2:1
   - ☐ 2.5:1
   - ☐ 3:1
   - ☐ 3.5:1
   - ☐ 4:1
   - ☐ 4.5:1
   - ☐ 5:1
   - ☐ 5.5:1
   - ☐ 6:1
   - ☐ 6.5:1
   - ☐ 7:1
   - ☐ Vertical
   - ☐ Unknown
   - ☐ Other

   Please specify

4-18 Retaining Structures

Retaining structures are used to stabilize slope failures by holding back the material and increasing the resisting forces (shear stress) of the soil mass. 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. These structures may also be used at the top portion of the slope to provide extra space for expanding roadside width.

1. Has your area ever utilized Retaining Structures as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Retaining Structures

1. How many times has your area utilized Retaining Structures as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Retaining Structures have failed?

   Write a number between 0-20

3. Were the Retaining Structures installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown

4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?

☐ 0.5:1	☐ 1:1
☐ 1.5:1	☐ 2:1
☐ 2.5:1	☐ 3:1
☐ 3.5:1	☐ 4:1
☐ 4.5:1	☐ 5:1
☐ 5.5:1	☐ 6:1
☐ 6.5:1	☐ 7:1
☐ Vertical	☐ Unknown
☐ Other	

Please specify

5-18 Recycled Plastic Pins

Recycled Plastic Pins (RPPs) are fabricated from recycled plastics and waste materials (polymers, sawdust, and fly ash). These pins are inserted (driven) in the face of the slope and reinforce the soil mass by transferring the tensile and shear resistance of nails to the sliding soil.

1. Has your area ever utilized Recycled Plastic Pins as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Recycled Plastic Pins

1. How many times has your area utilized Recycled Plastic Pins as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Recycled Plastic Pins have failed?

   Write a number between 0-20

3. Were the Recycled Plastic Pins installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown

4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?

☐ 0.5:1	☐ 1:1
☐ 1.5:1	☐ 2:1
☐ 2.5:1	☐ 3:1
☐ 3.5:1	☐ 4:1
☐ 4.5:1	☐ 5:1
☐ 5.5:1	☐ 6:1
☐ 6.5:1	☐ 7:1
☐ Vertical	☐ Unknown
☐ Other	

   Please specify

6-18 Earth Anchors

Earth or ground anchors are structural elements installed in soil or rock to transmit an applied tensile load into the ground. Earth anchors are typically installed in grout filled drill holes. Earth anchors have been used as a temporary and permanent earth-supporting method.

1. Has your area ever utilized Earth Anchors as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Earth Anchors

1. How many times has your area utilized Earth Anchors as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Earth Anchors have failed?

   Write a number between 0-20

3. Were the Earth Anchors installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown
4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?

☐ 0.5:1	☐ 1:1
☐ 1.5:1	☐ 2:1
☐ 2.5:1	☐ 3:1
☐ 3.5:1	☐ 4:1
☐ 4.5:1	☐ 5:1
☐ 5.5:1	☐ 6:1
☐ 6.5:1	☐ 7:1
☐ Vertical	☐ Unknown
☐ Other	

   Please specify

7-18 Piles

Piles are vertically inserted into slopes using hydraulic hammers. There are several types of piles with different shapes (pipe, cylindrical, rectangular, and H-pile.) and materials (steel, wood, and concrete). Although piles are mostly used for foundation stabilization, they have been proven as an effective solution for slope stabilization. Piles provide passive resistance against lateral forces from the surrounding soil.

1. Has your area ever utilized Piles as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Piles

1. How many times has your area utilized Piles as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Piles have failed?

   Write a number between 0-20

3. Were the Piles installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown

4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   [Write a number or range between 0 and 70]

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   [Write a number or range between 0 and 100]

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?

☐ 0.5:1	☐ 1:1
☐ 1.5:1	☐ 2:1
☐ 2.5:1	☐ 3:1
☐ 3.5:1	☐ 4:1
☐ 4.5:1	☐ 5:1
☐ 5.5:1	☐ 6:1
☐ 6.5:1	☐ 7:1
☐ Vertical	☐ Unknown
☐ Other	

   [Please specify]

8-18 Sheet Piles

Sheet piles are continuous walls, created by interlocking long structural sections together to resist horizontal water or soil pressures. 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.

1. Has your area ever utilized Sheet Piles as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Sheet Piles

1. How many times has your area utilized Sheet Piles as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Sheet Piles have failed?

   Write a number between 0-20

3. Were the Sheet Piles installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown
4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?

☐ 0.5:1	☐ 1:1
☐ 1.5:1	☐ 2:1
☐ 2.5:1	☐ 3:1
☐ 3.5:1	☐ 4:1
☐ 4.5:1	☐ 5:1
☐ 5.5:1	☐ 6:1
☐ 6.5:1	☐ 7:1
☐ Vertical	☐ Unknown
☐ Other	

   Please specify

9-18 Soldier Piles and Lagging

Soldier piles and lagging is an earth retention technique that retains soil using vertical steel piles and a horizontal lagging system. This system provides resistance alongside the failed slope.

1. Has your area ever utilized Soldier Piles and Lagging as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Soldier Piles and Lagging

1. How many times has your area utilized Soldier Piles and Lagging as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Soldier Piles and Lagging have failed?

   Write a number between 0-20

3. Were the Soldier Piles and Lagging installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown

4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?

☐ 0.5:1	☐ 1:1
☐ 1.5:1	☐ 2:1
☐ 2.5:1	☐ 3:1
☐ 3.5:1	☐ 4:1
☐ 4.5:1	☐ 5:1
☐ 5.5:1	☐ 6:1
☐ 6.5:1	☐ 7:1
☐ Vertical	☐ Unknown
☐ Other	

   Please specify

10-18 Gabions

Gabions are rectangular baskets made of heavy wires, filled with selected rocks and stones, such as cobbles or crushed rock. These baskets are connected to form a retaining wall. The primary goal of using gabion baskets is to utilize smaller and cheaper stones that are not stable by themselves to build retaining walls.

1. Has your area ever utilized Gabions as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Gabions

1. How many times has your area utilized Gabions as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Gabions have failed?

   Write a number between 0-20

3. Were the Gabions installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown
4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
    - ☐ Stone fragments, gravel and sand
    - ☐ Fine sand
    - ☐ Silty or clayey gravel and sand
    - ☐ Silty soil
    - ☐ Clayey soil
    - ☐ Peat, highly organic soil
    - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

    Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

    Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
    - ☐ Well drained
    - ☐ Poorly drained
    - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?

☐ 0.5:1	☐ 1:1
☐ 1.5:1	☐ 2:1
☐ 2.5:1	☐ 3:1
☐ 3.5:1	☐ 4:1
☐ 4.5:1	☐ 5:1
☐ 5.5:1	☐ 6:1
☐ 6.5:1	☐ 7:1
☐ Vertical	☐ Unknown
☐ Other	

    Please specify

11-18 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.

1. Has your area ever utilized Rebuilding and Compaction as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Rebuilding and Compaction

1. How many times has your area utilized Rebuilding and Compaction as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Rebuilding and Compaction have failed?

   Write a number between 0-20

3. Were the Rebuilding and Compaction installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown

4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   [Write a number or range between 0 and 70]

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   [Write a number or range between 0 and 100]

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?

☐ 0.5:1	☐ 1:1
☐ 1.5:1	☐ 2:1
☐ 2.5:1	☐ 3:1
☐ 3.5:1	☐ 4:1
☐ 4.5:1	☐ 5:1
☐ 5.5:1	☐ 6:1
☐ 6.5:1	☐ 7:1
☐ Vertical	☐ Unknown
☐ Other	

   [Please specify]

12-18 Benching and Stepping

Benching and stepping is the transformation of a high slope to several lower ones by excavating horizontal cutouts periodically along the slope.

1. Has your area ever utilized Benching and Stepping as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Benching and Stepping

1. How many times has your area utilized Benching and Stepping as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Benching and Stepping have failed?

   Write a number between 0-20

3. Were the Benching and Stepping installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown
4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?
   - ☐ 0.5:1
   - ☐ 1:1
   - ☐ 1.5:1
   - ☐ 2:1
   - ☐ 2.5:1
   - ☐ 3:1
   - ☐ 3.5:1
   - ☐ 4:1
   - ☐ 4.5:1
   - ☐ 5:1
   - ☐ 5.5:1
   - ☐ 6:1
   - ☐ 6.5:1
   - ☐ 7:1
   - ☐ Vertical
   - ☐ Unknown
   - ☐ Other

   Please specify

13-18 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.

1. Has your area ever utilized Slope Flattening as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Slope Flattening

1. How many times has your area utilized Slope Flattening as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Slope Flattening have failed?

   Write a number between 0-20

3. Were the Slope Flattening installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown
4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?
   - ☐ 0.5:1
   - ☐ 1:1
   - ☐ 1.5:1
   - ☐ 2:1
   - ☐ 2.5:1
   - ☐ 3:1
   - ☐ 3.5:1
   - ☐ 4:1
   - ☐ 4.5:1
   - ☐ 5:1
   - ☐ 5.5:1
   - ☐ 6:1
   - ☐ 6.5:1
   - ☐ 7:1
   - ☐ Vertical
   - ☐ Unknown
   - ☐ Other

   Please specify

14-18 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.

1. Has your area ever utilized Soil Substitution as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Soil Substitution

1. How many times has your area utilized Soil Substitution as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Soil Substitution have failed?

   Write a number between 0-20

3. Were the Soil Substitution installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown
4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown
6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown
9. If known, what was the typical slope (xH:1V) of failed slopes?

☐ 0.5:1	☐ 1:1
☐ 1.5:1	☐ 2:1
☐ 2.5:1	☐ 3:1
☐ 3.5:1	☐ 4:1
☐ 4.5:1	☐ 5:1
☐ 5.5:1	☐ 6:1
☐ 6.5:1	☐ 7:1
☐ Vertical	☐ Unknown
☐ Other	

   Please specify

15-18 Buttressing

Building a buttress (buttressing) at the toe of slopes is a commonly used slope repair method that loads the toe of the slope with heavy material to increase stabilizing forces and decrease overall slope height. Buttressing can be implemented with rock fills, earth fills (counter berms), or pneusol (scrap tires and soil).

1. Has your area ever utilized Buttressing as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Buttressing

1. How many times has your area utilized Buttressing as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Buttressing have failed?

   Write a number between 0-20

3. Were the Buttressing installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown
4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown

6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown

9. If known, what was the typical slope (xH:1V) of failed slopes?

☐ 0.5:1	☐ 1:1
☐ 1.5:1	☐ 2:1
☐ 2.5:1	☐ 3:1
☐ 3.5:1	☐ 4:1
☐ 4.5:1	☐ 5:1
☐ 5.5:1	☐ 6:1
☐ 6.5:1	☐ 7:1
☐ Vertical	☐ Unknown
☐ Other	

   Please specify

16-18 Biotechnical 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.

1. Has your area ever utilized Biotechnical Methods as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Biotechnical Methods

1. How many times has your area utilized Biotechnical Methods as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Biotechnical Methods have failed?

   Write a number between 0-20

3. Were the Biotechnical Methods installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown
4. What type of Biotechnical Method was used?
   - ☐ Live Staking

     "**Live Staking** or joint planting is the insertion and tamping of live stakes or rootable cuttings in joints on the slopes. When the stakes grow, they create a living root mat under the structure and bind with the soil that stabilizes the soil mass and prevents soil erosion."
   - ☐ Live fascine

     "**Live fascine** is a bundle of cutting branches bound together to control erosion and stabilize slopes."
   - ☐ Brush Layering

     "In **brush layering**, live branch cuttings are placed in small terraces excavated horizontally along a slope and supported on a small, short log or board."
   - ☐ Log Terracing

"In **log terracing**, the log reinforced earthen terraces are used to decrease the slope length and steepness. Log terracing provides more stable areas for planting and growing plants."

- ☐ Vegetated Geotextile

  "A **vegetated geotextile** is made of successive soil lifts with a mix of live branches, separated and wrapped by synthetic control fabric. These fabrics only last until sufficient rooting is established. Vegetated geotextiles are mostly used to stabilize the loose topsoil layers of slopes."

- ☐ Vegetated Geogrid

  "In **vegetated geogrid**, the failed soil mass is removed, and vegetated geogrids are placed in layers. Then, the branch cuttings are located between layers. Once the live branch cuttings are established, they help to bind geogrids together and stabilize the slope by providing a root structure behind the slope."

- ☐ Branch Packing

  "**Branch packing** is a bioengineering technique consisting of alternating layers of live branches and compacted backfill. The branch packing method is used to repair small slope failures or holes by live branch cuttings and compacted backfills."

- ☐ Live Crib Wall

  "A **Live crib wall** is a boxlike chamber that can be constructed from untreated logs or timbers. It is filled with layers of rock, gravel, soil or other fill materials. In live crib walls, live branches are mixed with local soil to fill the crib wall. After a while, the live branches take roots inside of the box and extend into the slope. This root system helps to bind the crib wall structure to the slope mass."

- ☐ Other

  Please specify

5. Check all the reasons that apply to selecting this method:
    - ☐ Long term service life (Low chance of recurring failure)
    - ☐ Low impact on Traffic
    - ☐ No engineering design required
    - ☐ No special equipment required
    - ☐ No special skilled workforce required
    - ☐ No Geotechnical soil testing required
    - ☐ Quick to repair
    - ☐ Low cost to repair
    - ☐ Other (Please write any other reasons that support your selection):

6. If known, select the soil type of failed slope:
    - ☐ Stone fragments, gravel and sand
    - ☐ Fine sand
    - ☐ Silty or clayey gravel and sand
    - ☐ Silty soil
    - ☐ Clayey soil
    - ☐ Peat, highly organic soil
    - ☐ Unknown
7. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

    Write a number or range between 0 and 70

8. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

    Write a number or range between 0 and 100

9. If known, what was the drainage condition of the failed slope?
    - ☐ Well drained
    - ☐ Poorly drained
    - ☐ Unknown

10. If known, what was the typical slope (xH:1V) of failed slopes?

- ☐ 0.5:1
- ☐ 1:1
- ☐ 1.5:1
- ☐ 2:1
- ☐ 2.5:1
- ☐ 3:1
- ☐ 3.5:1
- ☐ 4:1
- ☐ 4.5:1
- ☐ 5:1
- ☐ 5.5:1
- ☐ 6:1
- ☐ 6.5:1
- ☐ 7:1
- ☐ Vertical
- ☐ Unknown
- ☐ Other

Please specify

17-18 Additives

Soil stabilization using additives (lime, fly ash, etc.) is the process of altering soil properties by adding a certain amount of material such as chemical and biochemical material to the soil. 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.

1. Has your area ever utilized Additives (E.g., lime, cement, fly ash) as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Additives

1. How many times has your area utilized Additives as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing Additives have failed?

   Write a number between 0-20

3. Were this method installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown

4. What type of Additive was used?
   - ☐ Lime
     "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."
   - ☐ Cement
     "Adding **cement** to embankment soil mass increases the stability of the embankment by two means: (1) Fills void spaces and as a result, keeping water out of the embankment section, (2) Adds strength to the soil mass as the cement cures.
   - ☐ Fly Ash
     "**Fly ash** is a byproduct of coal combustion process. Fly ash should be placed in uniform layers no thicker than 12 inches, when loose. Fly ash results in a substantial strength increase by producing a cementitious product."
   - ☐ Other

     Please specify

5. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

6. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil

☐ Unknown

7. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

8. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   Write a number or range between 0 and 100

9. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown
10. If known, what was the typical slope (xH:1V) of failed slopes?

☐ 0.5:1	☐ 1:1
☐ 1.5:1	☐ 2:1
☐ 2.5:1	☐ 3:1
☐ 3.5:1	☐ 4:1
☐ 4.5:1	☐ 5:1
☐ 5.5:1	☐ 6:1
☐ 6.5:1	☐ 7:1
☐ Vertical	☐ Unknown
☐ Other	

   Please specify

18-18 Water Management Methods

Water management techniques are adapted to control the water from entering the slope initially and to drain any water which does enter the slope. Generally, these methods are classified into two categories of Surface and Subsurface water management methods.

1. Has your area ever utilized <u>Water Management</u> as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

Evaluation of Water Management Methods

1. How many times has your area utilized <u>Water Management</u> as a shallow slope failure repair method?

Write a number between 0-20

2. How many slopes repaired utilizing Water Management have failed?

Write a number between 0-20

3. Were this method installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown

4. What type of Water Management was used?
   - ☐ Surface

     "**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."
   - ☐ Subsurface

     "**Subsurface water management** systems often control or reduce groundwater levels, directly. 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."
   - ☐ Other

     Please specify

5. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):

6. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown
7. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

8. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

   Write a number or range between 0 and 100

9. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown
10. If known, what was the typical slope (xH:1V) of failed slopes?
   - ☐ 0.5:1
   - ☐ 1:1
   - ☐ 1.5:1
   - ☐ 2:1
   - ☐ 2.5:1
   - ☐ 3:1
   - ☐ 3.5:1
   - ☐ 4:1
   - ☐ 4.5:1
   - ☐ 5:1
   - ☐ 5.5:1
   - ☐ 6:1
   - ☐ 6.5:1
   - ☐ 7:1
   - ☐ Vertical
   - ☐ Unknown
   - ☐ Other

   Please specify

Other Methods

1. Has your area ever utilized other methods as a shallow slope repair method?
   - ☐ Yes
   - ☐ No

   If yes, please provide the name

Evaluation of Other Methods

1. How many times has your area utilized this method as a shallow slope failure repair method?

   Write a number between 0-20

2. How many slopes repaired utilizing this method have failed?

   Write a number between 0-20

3. Were this method installed by State DOT Maintenance forces?
   - ☐ Yes
   - ☐ No
   - ☐ Unknown
4. Check all the reasons that apply to selecting this method:
   - ☐ Long term service life (Low chance of recurring failure)
   - ☐ Low impact on Traffic
   - ☐ No engineering design required
   - ☐ No special equipment required
   - ☐ No special skilled workforce required
   - ☐ No Geotechnical soil testing required
   - ☐ Quick to repair
   - ☐ Low cost to repair
   - ☐ Other (Please write any other reasons that support your selection):
5. If known, select the soil type of failed slope:
   - ☐ Stone fragments, gravel and sand
   - ☐ Fine sand
   - ☐ Silty or clayey gravel and sand
   - ☐ Silty soil
   - ☐ Clayey soil
   - ☐ Peat, highly organic soil
   - ☐ Unknown
6. If known, what was the typical Plastic Index (PI) of the soil of failed slope?

   Write a number or range between 0 and 70

7. If known, what was the typical Liquid Limit (LL) of the soil of failed slope?

Write a number or range between 0 and 100

8. If known, what was the drainage condition of the failed slope?
   - ☐ Well drained
   - ☐ Poorly drained
   - ☐ Unknown
9. If known, what was the typical slope (xH:1V) of failed slopes?
   - ☐ 0.5:1
   - ☐ 1:1
   - ☐ 1.5:1
   - ☐ 2:1
   - ☐ 2.5:1
   - ☐ 3:1
   - ☐ 3.5:1
   - ☐ 4:1
   - ☐ 4.5:1
   - ☐ 5:1
   - ☐ 5.5:1
   - ☐ 6:1
   - ☐ 6.5:1
   - ☐ 7:1
   - ☐ Vertical
   - ☐ Unknown
   - ☐ Other

Please specify

Section 4 – Further Information

1. Our follow-up interview is designed to acquire practical information about the state of practice on shallow slope repair methods. Are you willing to share your insight in a follow-up interview?
   - ☐ Yes
   - ☐ No

APPENDIX C – SURVEY INVITATION EMAIL

To:

Subject: TxDOT-UTA Survey for Synthesis on Rapid Repair Methods for Embankment Slope Failure.

Dear Colleagues,

The University of Texas at Arlington invites you to participate in a short survey pertaining to rapid repair methods for embankment slope failure. This survey is an integral part of the TxDOT Research and Technology Implementation (RTI) Project #0-6957, titled: "Synthesis on Rapid Repair Methods for Embankment Slope Failure." This survey aims to capture the state of practice in repairing embankment shallow slope failures performed by TxDOT and other state DOTs maintenance staff.

We expect this survey to take approximately 15 minutes. Please fill out the survey before April 15th. TxDOT and our research team highly appreciate your contribution to this unique effort. If results of this study are published or presented, your name will remain confidential. Please continue if you voluntarily agree to participate in this research.

https://www.surveymonkey.com/r/89ZDMHM

If you have any questions about this research study, please contact Dr. Mohsen Shahandashti, P.E. at mohsen@uta.edu or directly at 817-271-0440.

Sincerely,

Darrin Jensen
Research Project Manager
Research & Technology Implementation Division
Office: 512.416.4728