Innovative Solutions for Slope Stability Reinforcement and Characterization: Vol. I

PGA

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Final Report
December 2005

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16. Abstract

Soil slope instability concerning highway infrastructure is an ongoing problem in Iowa, as slope failures endanger public safety and continue to result in costly repair work. Characterization of slope failures is complicated, because the factors affecting slope stability can be difficult to discern and measure, particularly soil shear strength parameters. While in the past extensive research has been conducted on slope stability investigations and analysis, this research consists of field investigations addressing both the characterization and reinforcement of such slope failures.

The current research focuses on applying an infrequently-used testing technique comprised of the Borehole Shear Test (BST). This in-situ test rapidly provides effective (i.e., drained) shear strength parameter values of soil. Using the BST device, fifteen Iowa slopes (fourteen failures and one proposed slope) were investigated and documented. Particular attention was paid to highly weathered shale and glacial till soil deposits, which have both been associated with slope failures in the southern Iowa drift region. Conventional laboratory tests including direct shear tests, triaxial compression tests, and ring shear tests were also performed on undisturbed and reconstituted soil samples to supplement BST results. The shear strength measurements were incorporated into complete evaluations of slope stability using both limit equilibrium and probabilistic analyses.

The research methods and findings of these investigations are summarized in Volume 1 of this report. Research details of the independent characterization and reinforcement investigations are provided in Volumes 2 and 3, respectively. Combined, the field investigations offer guidance on identifying the factors that affect slope stability at a particular location and also on designing slope reinforcement using pile elements for cases where remedial measures are necessary. The research findings are expected to benefit civil and geotechnical engineers of government transportation agencies, consultants, and contractors dealing with slope stability, slope remediation, and geotechnical testing in Iowa.

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EXECUTIVE SUMMARY

Soil slope instability concerning highway infrastructure is an ongoing problem in Iowa, as slope failures endanger public safety and continue to result in costly repair work. This research consists of field investigations addressing both the characterization and reinforcement of such slope failures. The research methods and findings of these investigations are summarized in Volume 1 of this report. Research details of the independent characterization and reinforcement investigations are provided in Volumes 2 and 3, respectively. Combined, the field investigations offer guidance on identifying the factors that affect slope stability at a particular location and also on designing slope reinforcement using pile elements for cases where remedial measures are necessary.

Research Summary

Characterization of slope failures is complicated, because the factors affecting slope stability can be difficult to discern and measure, particularly soil shear strength parameters. Extensive research has been conducted on slope stability investigations and analysis. The current research, however, focused on applying an infrequently-used testing technique comprised of the Borehole Shear Test (BST). This in-situ test rapidly provides effective (i.e., drained) shear strength parameter values of soil. Using the BST device, fifteen Iowa slopes (fourteen failures and one proposed slope) were investigated and documented. Particular attention was paid to highly weathered shale and glacial till soil deposits, which have both been associated with slope failures in the southern Iowa drift region. Conventional laboratory tests, including direct shear tests, triaxial compression tests, and ring shear tests were also performed on undisturbed and reconstituted soil samples to supplement BST results. The shear strength measurements were incorporated into complete evaluations of slope stability using both limit equilibrium and probabilistic analyses.

Remediation of slope failures requires stabilization alternatives that address causes of slope instability. Slope reinforcement using pile elements can be an effective method of remediation in preventing slope movements in weak soils where enhanced drainage does not provide adequate stability. Soil load transfer to pile elements from the downslope soil movement as occurs in slope failures is a complex soil–structure interaction problem. Soil–structure interactions for small-diameter, grouted pile elements subject to lateral soil movement were investigated by conducting full-scale pile load tests, in which piles installed through a shear box into stable soil were loaded by uniform lateral translation of soil. Instrumentation of the shear boxes and pile reinforcement indicated the load distributions that developed along the piles. The load test analyses which followed the pile load tests support the claim that the distributed loads which are mobilized during pile loading depend on the relative displacement between the soil and pile elements. The reliable estimation of these load distributions is important, because the influence of piles on the global stability of the slope depends directly on the pile loading condition.

Research Conclusions

The following conclusions were drawn from slope stability case histories:

- The Borehole Shear Test often measures peak shear strength parameters, which are generally not operative for a slope failure, and sometimes measures the soften shear strength when the measurements are taken near the slip surface. Factors of safety for case histories of slope failures calculated using BSTs were generally greater than unity.
- The ring shear test using reconstituted samples gives residual shear strength parameter values corresponding to relatively large shear displacements. Factors of safety for case histories of slope failures calculated using ring shear test results were generally less than unity.
- Back calculated shear strengths for slope failures that provided factors of safety equal to unity were generally between shear strengths from ring shear tests and Borehole Shear Tests. Slope failures can be attributed to soil softening or progressive failure and may have been caused by high water tables.
- For some slope failures, the use of the BST are useful in better estimating the operative (or the mobilized) shear strength in conjunction with the residual shear strength and back calculated shear strength.
- For the slope failures, the glacial tills generally have lower clay fraction and lower plasticity index than the clay shales. All the tills are classified as low plasticity clay (CL) according to Unified Soil Classification System, while most of the shales are classified as high plasticity clay (CH).
- The peak BST results for the slope failures show that, the glacial tills and the clay shales have similar average values of effective friction angle, which are 22.5^{o} and 22.1^{o}, respectively; but the glacial tills have considerably lower average value of effective cohesion (11.6 kPa) than the clay shales (17.7 kPa). However, the glacial tills have higher residual shear strength (residual friction angle of 8.4^{o} to 26.9^{o}) than the clay shales (residual friction angle of 6.2^{o} to 15.1^{o}).
- Sensitivity analyses showed that soil shear strength is the most sensitive parameter affecting factors of safety. Water table location additionally has a significant influence on slope stability.
- Probabilistic slope stability analyses are useful when a relatively large amount of input parameters are available, such as shear strengths obtained from BSTs. The probability of slope failure is evaluated based on statistical distribution of soil shear strengths.

The following conclusions were drawn from investigating pile reinforcement:

- The installation of slender piles in weak soils offers considerable resistance to lateral soil movement, with improvement factors from the load tests ranging from 1.2 to 6.6. Improvement factors are defined as a ratio of peak loads for reinforced tests and unreinforced tests.
- Pile section moment capacities were mobilized, indicating that a “flexible” pile failure mode was achieved. The depth of maximum moment and pile failure ranged from 1.8 to 5.4 pile diameters below the shear plane.

- The relative soil-pile displacement at the soil surface indicates the behavioral stages of small-diameter piles as (1) mobilization of soil shear stresses and elastic bending of pile, (2) mobilization of pile concrete compressive strength, and (3) incipient pile failure due to pile moment capacity mobilization. The behavioral characteristics of slender piles are controlled by structural pile behavior through moment-curvature relationships as much as they are by soil behavior.
- Displacement-based lateral response analysis methods which use soil p-y curves accurately predict the deflection and bending moment of piles subject to lateral soil movement. From these pile behavior characteristics, pile shear may be calculated and applied to the limit equilibrium equation for evaluating global stability of reinforced slopes.

Recommendations for Implementation

The research findings are expected to benefit civil and geotechnical engineers of government transportation agencies, consultants, and contractors dealing with slope stability, slope remediation, and geotechnical testing in Iowa. In-situ BST measurements provide reliable, site-specific soil parameters for design applications which can lead to substantial cost savings over using empirical estimations for critical soil properties. As the BST is an alternative to expensive and time-consuming laboratory testing, the device is particularly useful in obtaining relatively large amounts of data necessary for probabilistic analyses. Procedures for incorporating Borehole Shear tests into practice are documented in Volume 2 of this report. Nevertheless, some training may be required for effective and appropriate use. The BST is primarily intended to test cohesive soils. The device can produce erroneous results in gravelly soils. Additionally, the quality of boreholes affects test results, and disturbance to borehole walls should be minimized before test performance. A final limitation of widespread Borehole Shear testing may be its limited availability, as only about 4 to 6 test devices are currently being used in Iowa.

The research presented in Volume 3 demonstrates with experimental testing how lateral forces develop along stabilizing piles to resist slope movements. This report then documents a step-by-step procedure that can be used by both state and county transportation agencies to design slope reinforcement using slender piles. A state department of transportation may develop training seminars for all local transportation agencies to provide further guidance in using the proposed design method. This effort may be coordinated with the authors and might be extended so far as to conduct a pilot study to demonstrate the intended process of designing and evaluating the reinforcement solution. While slope reinforcement with slender piles by county transportation agencies is encouraged, such action is recommended to be coordinated with the state department of transportation. This organization can document all such remediation projects to better guide counties using successful and unsuccessful experiences, as the DOT will have working knowledge of other unstable slope characteristics and corresponding reinforcement designs. The proposed slope reinforcement solution has not yet been demonstrated at an Iowa slope failure site. As a result, difficulty in scheduling and bidding a pile reinforcement project and evaluating the effectiveness of the measure may impede successful implementation. Obtaining experience and feedback through data collection or visual inspection, however, will promote incorporation of the research findings into standard slope remediation practice.

Successful implementation of innovative slope stability reinforcement and characterization solutions can be evaluated by documenting the number of slopes reinforced with pile elements and those investigated using BST measurements, respectively. Cost savings of incorporating Borehole Shear testing into site investigation practice will be made evident by comparing costs corresponding to designs for geostructures making use of accurate and reliable soil properties (obtained from BST measurements) to those designs using estimated soil properties and higher factors of safety. Calculating long-term cost savings of slope reinforcement using piles considering maintenance costs associated with alternatives and the cost for rebuilding a failed drainage remediation, for example, can indicate the progress and consequences of implementation.

INTRODUCTION

Research Problem Statement

Failures of slopes occur throughout the world and contribute to economic and casualty losses. These losses, intuitively proportional to the magnitude of failure, are direct and indirect costs to individuals and institutions. Direct costs include the replacement and maintenance of structures and transportation facilities. Indirect costs include loss of tax revenues on properties devalued as a result of slope failures and loss of industrial and agricultural productivity due to the damage of land (Spiker and Gori 2003). The impact of slope failures on these losses is often undervalued. The U.S. Geological Survey (Spiker and Gori 2003) estimates that the United States, every year, experiences in excess of $1 billion in damages and approximately 50 deaths; worldwide, slope failures cause 100's of billions of dollars in damage and 100's of thousands of deaths. More locally, the annual cost for remediation and maintenance of slopes often exceeds state and county transportation budgets. The U.S. Geological Survey is leading a newly-developed, 10-year plan to "substantially reduce the risk of loss of life, injuries, economic costs, and destruction of natural and cultural resources caused by landslides and other ground-failure hazards" (Spiker and Gori 2003). Current understanding of such socioeconomic losses justifies the allocation of funds needed for slope stability research.

Technical Problems

Slope Failure Characterization

Slope instability continues to pose problems for highway systems in Iowa. Failures occur on both new embankment foreslopes and cut backslopes. Characterization of the failures is complicated because identifying factors that affect stability at a particular location, such as soil shear strength values, ground water surface elevations, and negative influences from construction activities are often difficult to discern and measure. The U.S. Geological Survey (Spiker and Gori 2003) recognizes that hazard identification is a cornerstone of landslide hazard mitigation. Once a failure occurs or a potential failure is identified, highway agencies need information and knowledge of which methods of remediation will be most effective to stabilize the slope. Ideally, these stability problems can be discovered and addressed before a slope failure occurs. When remediation is necessary, however, options are needed that give consideration to the remediation goals, cost constraints, environmental constraints, schedule constraints, and constructability. Newly-developed technologies for the investigation and repair of nuisance slope failures and maintenance of state transportation infrastructure are ideally simple, rapid, and cost-effective.

Load Transfer of Piles Subject to Lateral Soil Movement

Soil load transfer to relatively stiff pile elements from the downslope soil movement as occurs in a slope failure is a complex soil-structure interaction problem. The downslope soil movement of slope failures induces lateral load distributions along stabilizing piles that vary with soil type, pile size, pile spacing, and relative movement between the pile and soil. The reliable estimation

of these load distributions and resolution of the technical problem are important, because the influence of piles on the global stability of a reinforced slope depends directly on the pile loading condition.

Research Objectives

The objectives of the slope failure characterization investigations are as follows:

- Develop and validate appropriate test procedures for quickly determining *in-situ* shear strength parameter values using the BST technique through the investigations of 15 slopes in clay shale and glacial till soils, and show the significance of the application of the BST in understanding the failure mechanisms;
- Classify and characterize the weathered shales associated with potential slope instability for a major embankment slope project using the BST, and demonstrate the usefulness of the BST in shale characterization with respect to different weathering grades;
- Illustrate the importance and effectiveness of using the relatively large amount of the *in-situ* shear strength parameter values for slope stability analysis through the probabilistic approach.

The objectives of the slope reinforcement investigation are as follows:

- Interpret loads induced on stabilizing piles by lateral soil movement;
- Measure material properties of soil and pile elements;
- Predict pile behavior associated with lateral soil movement; and
- Develop a slope reinforcement design methodology.

Report Organization

The report for the research project is organized into a series of three independent volumes. Volume I provides a summary of the research project, including overviews of the slope characterization and reinforcement field investigations and also conclusions and recommendations from the study. Volume II is comprised of the detailed information on slope failure investigations and analyses. A total of 15 case histories concerning unstable slopes in Iowa are documented. Volume III describes the details of experimental testing for evaluating a slope reinforcement technique comprised of grouted micropiles.

SLOPE INVESTIGATIONS AND ANALYSES

Overview of Research Investigation

Shear strength of soil is perhaps the most critical factor in slope stability. Many methods have been used to obtain the shear strength parameter values of soil through both field (e.g., standard penetration test and cone penetration test) and laboratory measurement (e.g., direct shear test and triaxial test). A relatively infrequently-used testing device, the Borehole Shear Test (BST), can give a rapid, direct, and accurate in-situ measurement of both effective cohesion and effective friction angle (Handy 1986). The BST was used as the primary testing tool for obtaining the shear strength parameter values of soil for the study.

The BST apparatus is shown in Figure 1. In essence, a series of direct tests are conducted by (1) diametrically expanding opposed contact shear plates into borehole walls under a constant and known normal stress, (2) allowing the soil to consolidate, and (3) pulling vertically to measure the shear stress. After repeating the these steps, data points from the BST are plotted to generate a Mohr-Coulomb shear envelope corresponding to the maximum shear resistances of successively higher increments of applied normal stresses. The effective cohesion and effective friction angle of the soil are obtained from the failure envelope.

For this research, a total of 15 slopes (14 failures and one new slope) were investigated and analyzed. General information about the slopes is summarized in Table 1. The geographic locations of the slopes are shown in Figure 2. The slopes are mainly comprised of either clay shale or glacial till soils, both of which are commonly encountered in Iowa. Field investigations included measurement of slope geometry, boring and soil sampling, in-situ Borehole Shear testing, and groundwater table measurement. Lab investigations included ring shear tests, soil classification tests (grain size distribution and Atterberg limits), mineralogical analyses, natural water contents, and density measurements on the representative soil samples from each slope. Direct shear tests and triaxial tests were also performed on undisturbed soil samples for Slope 15.

Based on the results of field and laboratory investigations, each slope was analyzed to evaluate the possible factors responsible for either slope failure or potential slope instability using limit equilibrium methods. Deterministic analyses were performed for all the slopes. Probabilistic analyses were performed for Slope 15. The computer program SLOPE/W (GEO-SLOPE 2004) was used to perform all the computations.

The field investigation results and slope stability analyses for the Sugar Creek embankment (Slope 15) are presented in the next sections. The complete details for all of the investigations and analyses (15 slopes) are presented in Volume II of the report. The Sugar Creek slope is a recently proposed embankment fill slope. Through the case history, the application and the role of the BST technique in slope investigation and evaluation are demonstrated. The large amount of BST measurements was particularly useful for probabilistic slope stability analyses.

(a) base plates and pressure console

(b) ordinary pressure shear plates after shea

(c) high pressure shear plates after shearing

Figure 1. Borehole shear test device

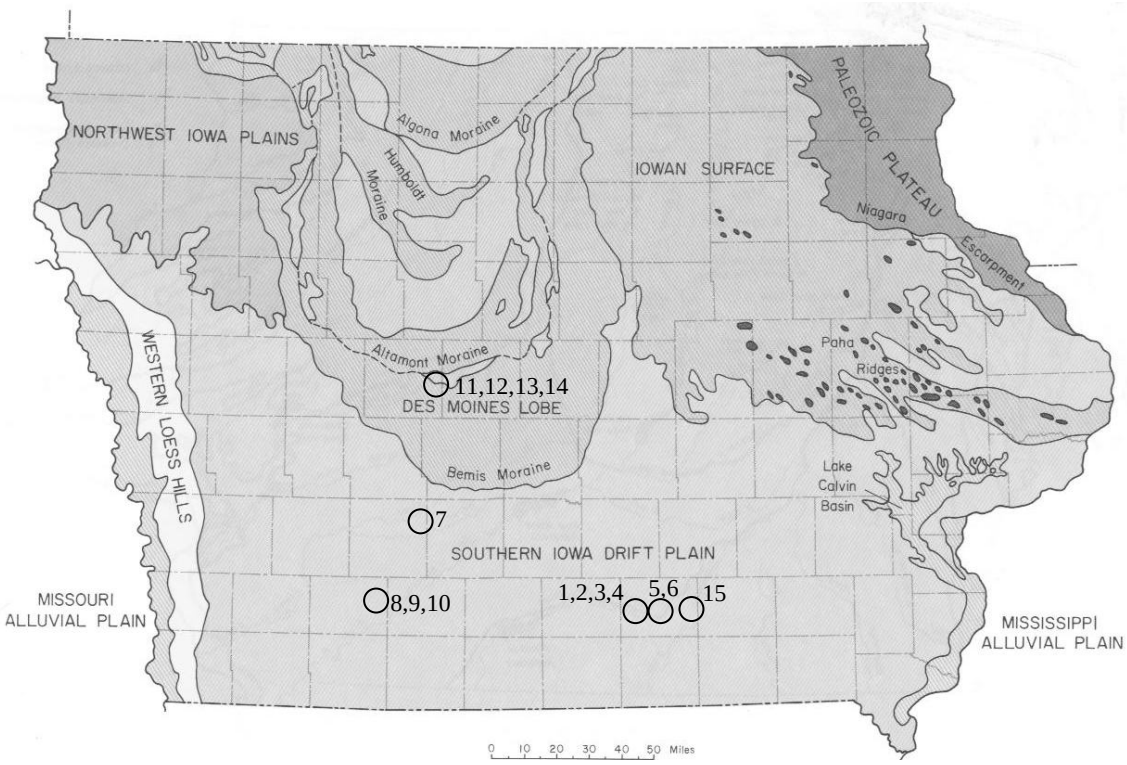

Figure 2. Slope investigation locations, with circles and numbers representing studied slopes

Table 1. Summary of the studied slopes

Slope	County	Hwy	Location	Type of Slope	Slope Geometry					Site Geology	Nos. of Bore-holes	Nos. of BST
					H:V (V=1)	Slope Angle (deg.)	Max. Height (m)	Max. Length (m)	Width (m)			
1	Monroe	34	MP169.3	Embankment	3.3	17	9	30	20	shale and glacial till	1	2
2		34	MP171.7	Back-slope	5.2	11	8	40	70	shale	4	9
3		34	MP175.3	Embankment	2.5	22	6	16	20	glacial till	1	4
4		34	MP175.5	Embankment	2.5	22	7	18	15	glacial till	1	2
5	Wapello	34	MP178.3	Embankment	3.0	18	7	20	25	glacial till	1	4
6		34	MP178.3	Embankment	4.0	14	6	22	30	shale	1	1
7	Madison	169	3 miles north of Winterset	Back-slope	4.4	13	7	33	60	shale	4	8
8	Union	169	2 miles south of Afton	Back-slope	2.5	22	10	27	60	glacial till	2	4
9		169	2 miles south of Afton	Back-slope	2.4	23	13	33	40	Mainly shale; glacial till at surface	1	2
10		169	4 miles south of Afton	Back-slope	2.8	20	7	21	25	shale	1	1
11	Boone	E57	0.5 mile west bank of Des Moines River, 4.5 miles west of Luther	Back-slope	3.5	16	23	85	80	glacial till	3	4
12		E57		Back-slope	3.0	18	20	63	70	glacial till	3	4
13		E57		Back-slope	3.0	18	16	58	10	glacial till	1	1
14		E57		Embankment	4.6	12	10	47	30	glacial till	1	1
15	Wapello	63	Sugar Creek, Ottumwa	Proposed embankment	3.0	18	19	59	60	silty clay /weathered shale	10	35

Field Investigation of Sugar Creek Embankment

Project Background

The Sugar Creek embankment is located in Wapello County, Iowa. Prior to the detailed site investigation, the approach embankment fills on both sides of Sugar Creek were to be designed using pile-supported abutments for support of the highway bridge crossing the creek. Based on the preliminary design guidelines of Iowa Department of Transportation (ϕ = 0 degrees, c = 10 kPa), slope stability analyses indicated that there was potential global instability for the slopes in front of the abutments with the slip surfaces passing through the highly weathered sloping shale interface. As a result, ground improvement and retaining wall alternatives were proposed with estimated costs ranging from 3 to 5 million dollars (Farouz et al. 2005). In view of these high costs, a supplemental subsurface exploration and test program was developed and performed in 2004 at a small cost to supplement the preliminary investigation conducted in 2001.

Site Geology and Characterization of the Shales

A total of 26 mechanically boreholes were drilled on the two sides of Sugar Creek to cover an area of about 200 m by 50 m for the project site. The subsurface soils of the project site can be roughly divided into two apparently distinguishable groups, i.e. the alluvium layer and the underlying shales. The shales underlying the alluvium layer have multiple colors of brown, grey and black, etc., and vary spatially and with depths. The shales have relatively low shear strength in the upper portion and behaves like soil; the shales become stronger with increasing depth, and behave like rock. The classification of the shales using three weathering grades resulted in three layers of shales for the site, i.e. highly weathered shale (H.W.Sh), moderately weathered shale (M.W.Sh), and slightly weathered shale (S.W.Sh). The surface of H.W.Sh generally parallels the existing ground surface. The boring results indicated that the spatial distributions of the shales were highly variable both vertically and laterally. The 24-hour ground water table was gently sloping towards the creek. A typical slope section showing the soil profiles and water table is presented in Figure 3.

Results of In-situ Borehole Shear Tests

A total of 33 BSTs and 2 Rock BSTs were performed at different layers in the ten borings, with emphasis on the highly weathered shale. All of the results show that the tests were well performed, as revealed by the large coefficients of correlation (R^2) between the shear stresses and the normal stresses, which are generally larger than 0.99. The variation of the shear strength values are illustrated by the c'-ϕ' plot for all the shales in Figure 4 and by the summary of statistical results in Table 2. Despite the variation of the shear strength values, the general trend that the shear strength values increase with the decrease in weathering degree is apparent. The highly weathered shale generally has low shear strength values; slightly weathered shale generally has high shear strength values, mainly exhibited by higher cohesion. Moderately weathered shale has shear strength values between highly and slightly weathered shale, indicating a transition layer. These observations suggest that the shear strength values of the shales are well correlated with the weathering classification, indicating the weathering classification scheme is valid. It is also noteworthy that the average shear strength values of highly weathered shale, which are $\phi' = 12.8^o$ and c' = 33.2 kPa, are much higher than that of c' = 10 kPa as assigned by the IDOT design guidelines prior to testing.

Results of Direct Shear Tests

A total of 20 consolidated-drained direct shear tests (DS) were performed in the laboratory, which included four tests on the alluvium soils, ten tests on H.W.Sh, and six tests on the M.W.Sh. The test results show that R^2 values are generally larger than 0.99 to indicate the effectiveness of the tests. The variability of the shear strengths of the soils were similarly illustrated by the statistical results as summarized in Table 3. The results show that the H.W.Sh had average shear strength parameter values of $\phi' = 21.4^o$ and c' = 20.4 kPa.

Case History Field Investigation Discussion

The site for the Sugar Creek embankment slope project was characterized, and engineering properties for soils were investigated. Both the stratification and shear strength values of the soil were highly variable. The classification of weathering of the shales that was specific to the site was proposed as an aid in characterizing the slope instability. It was found that the classification of weathering could not be purely relied on the index properties of the shales, but it was consistently correlated with shear strength values of the shales. The shear strength values obtained from different methods did not exactly match, but were comparable and showed reasonable agreement, considering the variable nature of the soil. The internal friction angles obtained from BST were generally lower than those obtained from direct shear tests, while the cohesion intercepts obtained from BST were generally larger than those from direct shear tests, for both the alluvium and the highly weathered shale. This observation could be mainly attributed to soil variability, test methods, and shear strength anisotropy. The use of the weathering classification and the measured shear strength values are expected to be economical and safe for the slope design and ground improvement measures.

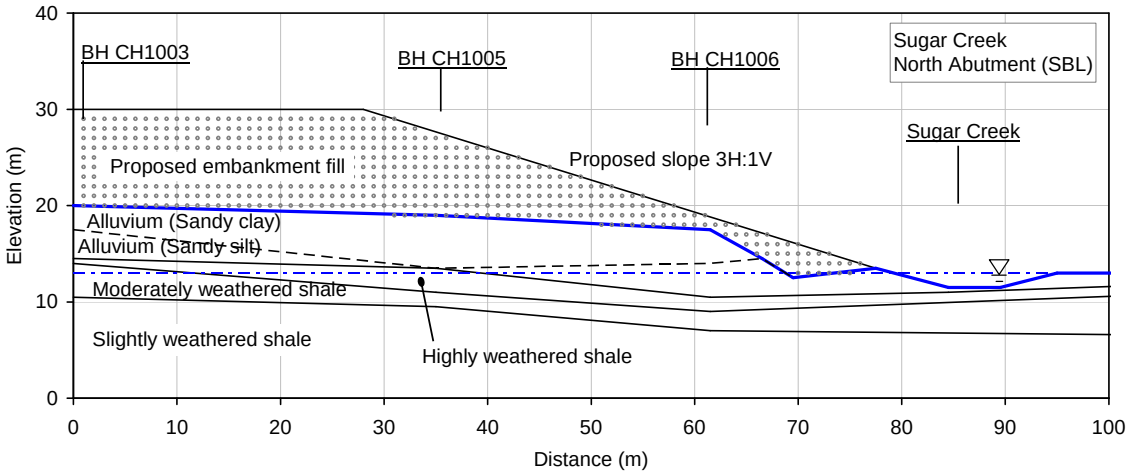

Figure 3. Soil profile for the embankment slope

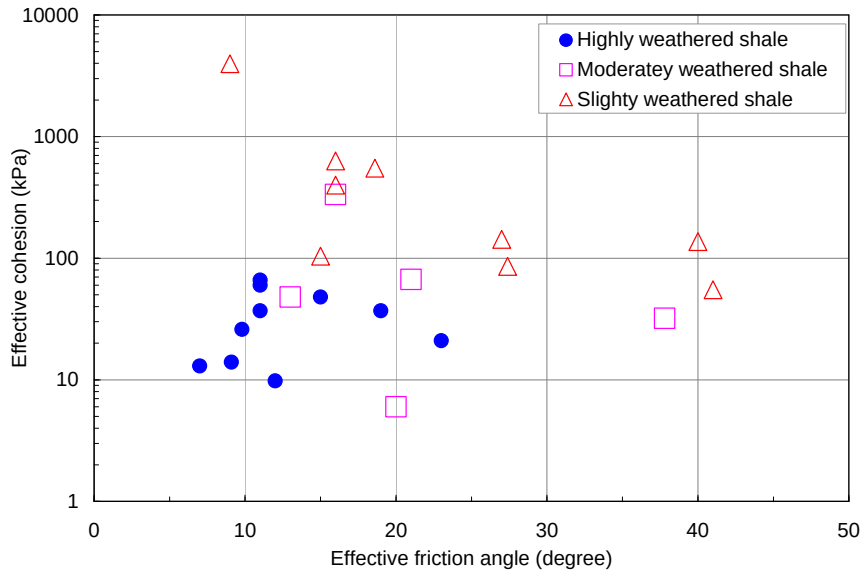

Figure 4. Borehole shear test results for all the shales

Table 2. Statistics of borehole shear test results

Soil	Total Number of Tests	ϕ'(deg.)				c' (kPa)			
		Max.	Min.	Ave.	S.D.	Max.	Min.	Ave.	S.D.
Alluvium	5	21	12	16.5	3.4	64	9	33.0	20.3
Highly weathered shale	10	23	7	12.8	4.9	66	10	33.2	19.9
Moderately weathered shale	5	38	13	21.6	9.6	334	6	97	134
Slightly weathered shale	9	41	9	23.3	11.3	3970	55	675	1254

Max. = maximum value Ave. = Average value

Min. = Minimum value S.D. = Standard deviation

Table 3. Statistics of direct shear test (DS) results

Soil	Total Number of Tests	Friction angle, ϕ'(deg.)				Cohesion, c' (kPa)			
		Max.	Min.	Ave.	S.D.	Max.	Min.	Ave.	S.D.
Alluvium	4	31	23	26.5	3.8	27	14	18.8	5.8
Highly weathered shale	10	28	12	21.4	4.8	38	0	20.4	10.4
Moderately weathered shale	6	29	14	19.4	5.7	43	5	23.6	15.6

Max. = maximum value Ave. = Average value

Min. = Minimum value S.D. = Standard deviation

Stability Analyses of Sugar Creek Embankment

Slope stability analyses were performed on the Sugar Creek embankment slope project. Shear strength parameter values from two independent sources of in-situ Borehole Shear Test (BST) and laboratory direct shear test (DST) were used in the analyses assuming normal distributions. Both circular and non-circular slip surfaces following the Morgenstern-Price (1965) method and the Bishop (1955) simplified method were used for comparisons.

Input Parameters for the Analyses

The two sets of the strength parameters, i.e. those from the BST (Table 2) and those from the DST (Table 3), were used for the slope stability analyses separately. Since no DST strength parameters were available for the layer of S.W.Sh, they were assumed to be the same as the BST strength parameters for the layer. This assumption was reasonable as the strength of the S.W.Sh was much higher than the overlying soils. Additionally, the S.W.Sh essentially had no effect on the slope stability analysis, which is supported by the fact that the critical slip surface does not pass through the layer as shown in the following analyses. For the compacted fill of the embankment soil, the mean values of strength parameters of ϕ' of 12° and c' of 29 kPa, as recommended by Iowa Department of Transportation (IaDOT), were adopted for all analyses. For the water table in the slope, the highest water table level was assumed to be the maximum water level in the creek according to the estimated 500 years flood event. The lowest water table level was assumed to be the ground water table as measured during the field investigation, and the average water level was assumed to be the mean water level.

Deterministic Slope Stability Analyses

Deterministic slope stability analyses were first performed to obtain the lowest FS (or the deterministic FS). The analysis was performed based on the mean values for all the soil properties and the mean ground water table level. Eight analyses in total were performed considering two sets of strength parameter values, two types of slip surfaces (see Figure 5) and two analysis methods; and the results are presented in Table 4 (under the column D.FS). A few observations can be made from the results. Firstly, FS values range from 1.521 to 1.587 when using BST strength parameters; and the FS values range from 1.599 to 1.624 when using DST strength parameters. These results demonstrate the influence of the lower mean values for the BST strength parameters compared to the mean values for the DST strength parameters, which resulted in lower FS values. Secondly, FS values for non-circular slip surface are consistently lower than FS values for circular slip surface, for the cases of using both BST and DST strength parameters. This suggests that the non-circular slip surface is more critical than the circular slip surface for the slope involving layered soils. Thirdly, the difference of FS values are small when comparing the MP method and the Bishop method for the circular slip surface (i.e., 1.576 and 1.587 when using BST parameters; 1.620 and 1.624 when using DST strength parameters), but the difference of FS values are relatively large between the MP method and the Bishop method for non-circular slip surface (i.e., 1.540 and 1.521 when using BST parameters; 1.599 and 1.610 when using DST strength parameters). This could be due to the fact that the MP method satisfies all conditions of equilibrium; while the Bishop method satisfies vertical equilibrium and overall

moment equilibrium only, it does not satisfy horizontal equilibrium. The Bishop method is normally recommended for circular slip surface (Abramson et al. 2002). Therefore, for the non-circular slip surface, MP method should be more accurate. Nevertheless, the results from the Bishop method still provide a comparison.

Probabilistic Slope Stability Analyses

A total of eight probabilistic slope stability analyses were performed corresponding to the deterministic slope stability analyses. All the soil properties and ground water levels were assumed to be of normal distributions, and the standard deviations are shown in Tables 2 and 3. The probability density functions (PDFs) of FS from the analyses are presented in Figure 6. The results are also summarized in Table 4 (under the column Probabilistic Analysis I).

A few observations can be made from the results of the analyses. Firstly, use of the BST strength parameters generally resulted in lower mean FS values than the use of the DST strength parameters, as indicated by the FS values at the peaks of PDF curves and mean FS values in Table 4 (shown as M.FS, which are 1.524 to 1.601 versus 1.615 to 1.660). These FS values are consistent with the deterministic FS values, as the mean FS values are mainly dependent on the mean values of the input parameters. The discrepancy of corresponding FS values was attributed to the analysis procedures involving Monte Carlo simulations. Secondly, the use of BST strength parameters generally gave smaller reliability indexes than the use of DST strength parameters (Table 4, i.e. 1.422 to 1.733 versus 2.163 to 2.479), which are also indicated by the flatter PDF curves (Figure 6). The flatter PDF curves are due to the larger standard deviations of FS, which resulted in smaller reliability index values. These results reflect the fact that the overall variability of BST strength parameters are larger than those of DST strength parameters. Thirdly, corresponding to the smaller reliability index values, the use of the BST strength parameters generally resulted in higher probability of failure (PF) (Table 4, i.e. 3.68 to 7.78% versus 0.40 to 1.45%).

The probabilistic analysis results also show the effect of the slip surface and the analysis method. For the same slip surface, either circular or non-circular, PF obtained by the Bishop method (Analyses 2, 4, 6 and 8, Table 4) is always larger than those obtained by the MP method (Analyses 1, 3, 5 and 7). However, the PF values for the circular slip surface are relatively close when using the MP method and the Bishop method (e.g.., Analyses 1 and 2; Analyses 5 and 6); the PF values for the non-circular slip surface are relatively different when using the MP method and Bishop method (e.g., Analyses 3 and 4; Analyses 7 and 8). The difference of PF values on the non-circular slip surface between the use of MP method and the Bishop method, especially that for Analyses 3 and 4, could be again due to the limitation of the Bishop method. Consequently, the results for the non-circular slip surface obtained from the MP method are considered to be more accurate.

Case History Stability Analysis Conclusions

The following conclusions can be drawn from the analyses:

- The locations of the critical slip surfaces using the BST shear strength parameter values are different from those using the DST values due the difference in the two sets of the shear strength parameter values.

- The calculated factors of safety against slope instability are slightly smaller and the probability of failure is higher when using the BST values compared to the DST values. The difference in results is due to the fact that BST measurements have lower mean values but more variability than the DST measurements. The higher variation in BST measurements may be a result of testing on the same soil, while DST averages three or more soil samples.

- The highly weathered shale contributes much more to the overall probability of failure when using the BST measurements compared to the DST measurements.

- With respect to the assumed slip surfaces, the non-circular critical slip surfaces gave lower factors of safety, but the circular "critical" slip surfaces gave higher probability of failure, indicating the inconsistency on the locations of the "critical" slip surfaces resulted from the uncertainties of the input parameters.

- Morgenstern-Price method and Bishop simplified method gave very close results on circular slip surface, but gave considerably different results on non-circular slip surface, especially with respect to the probability of failure. This may be due to the limitations of Bishop simplified method on non-circular slip surface.

- The use of the two independent sources of shear strength parameter values provided comparison and check for the evaluation of the slope stability and probability of failure.

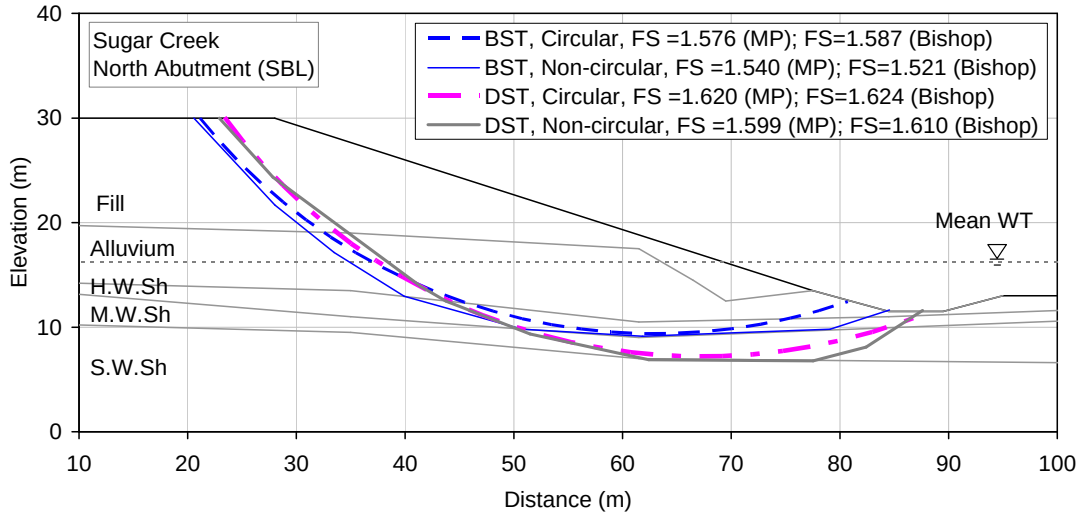

Figure 5. The circular and non-circular critical slip surfaces corresponding to the different shear strength parameter values obtained from BST and DST

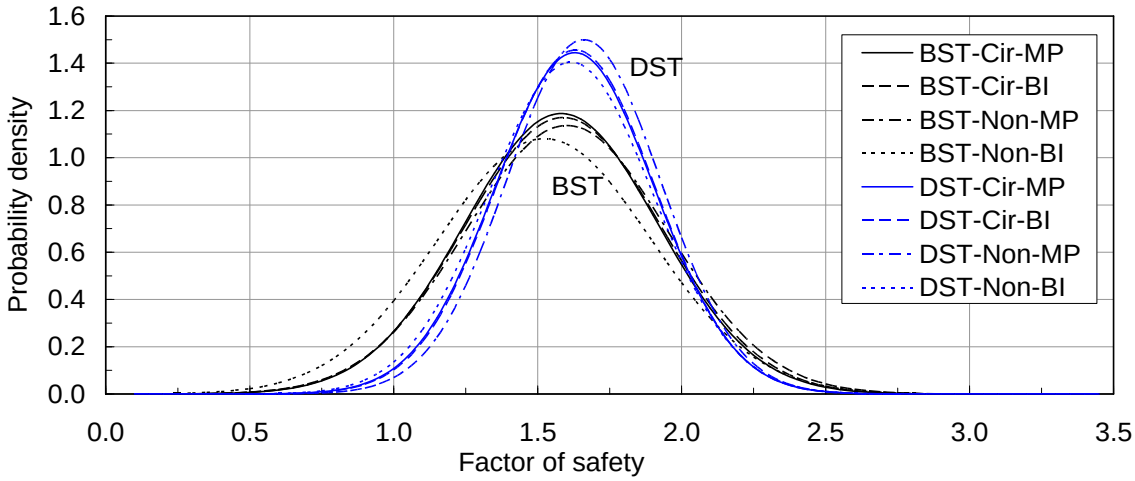

Figure 6. Probability density functions of factor of safety

Table 4. Summary of the results of slope stability analysis

No.	Analysis	Probabilistic Analysis I[a]				Probabilistic Analysis II[b]		
		D.FS	M.FS	RI	PF (%)	M.FS	RI	PF (%)
1	BST-Cir-MP	1.576	1.582	1.733	3.99	1.581	1.985	2.21
2	BST-Cir-BI	1.587	1.588	1.725	4.18	1.587	1.979	2.41
3	BST-Non-MP	1.540	1.601	1.714	3.68	1.576	1.704	3.62
4	BST-Non-BI	1.521	1.524	1.422	7.78	1.517	1.469	7.04
5	DST-Cir-MP	1.620	1.629	2.280	1.04	1.621	11.711	0.00
6	DST-Cir-BI	1.624	1.632	2.303	1.12	1.629	11.306	0.00
7	DST-Non-MP	1.599	1.660	2.479	0.40	1.606	12.404	0.00
8	DST-Non-BI	1.610	1.615	2.163	1.45	1.612	11.402	0.00

Notations - BST: Borehole shear test; DST: direct shear test; Cir: circular slip surface; Non: non-circular slip surface; MP: Morgenstern-Price method; BI: Bishop simplified method; D.FS: deterministic factor of safety; M.FS: mean factor of safety; RI: reliability index; PF: probability of failure.

a. Considering variations of soil properties for all layers and variations of ground water table level.

b. Considering variations of strength parameters for the highly weathered shale only. Parameters for other layers and ground water table level were set to the mean values.

SLOPE REINFORCEMENT USING SMALL-DIAMETER GROUTED MICROPILES

The current research program aims to develop a rapid, cost effective, and simple remediation system that can be implemented into slope stabilization practices for relatively shallow slope failure (< 5 m) conditions. The non-proprietary remediation technology consists of small-diameter grouted micropiles, and the experimental testing establishes small-diameter grouted micropiles as a feasible remediation alternative.

Field Testing Program

The field testing program consisted of measuring the shear strength of soil reinforced with pile elements. The pile load tests were performed in a manner similar to large-scale direct shear tests. The direct shear boxes contained compacted soil with known properties and piles that extended through the box into existing ground. The shear boxes were pushed laterally to impose uniform lateral translation of soil, modeling the movement of a unit cell of a sliding soil mass. The interface of the shear box and the at-grade elevation resembled the failure surface of a slope failure, and the soil below grade resembled the stable soil of a slope in which piles are installed to provide passive resistance to movement. Instrumentation of the direct shear boxes (displacement gauges and load cell) was installed to measure the load-displacement response of the reinforced soil. Instrumentation of the pile reinforcement (strain gauges) indirectly indicated the loads induced on the piles due to lateral soil movement and the pile response to the loads. Figure 7 shows the large-scale direct shear test set-up.

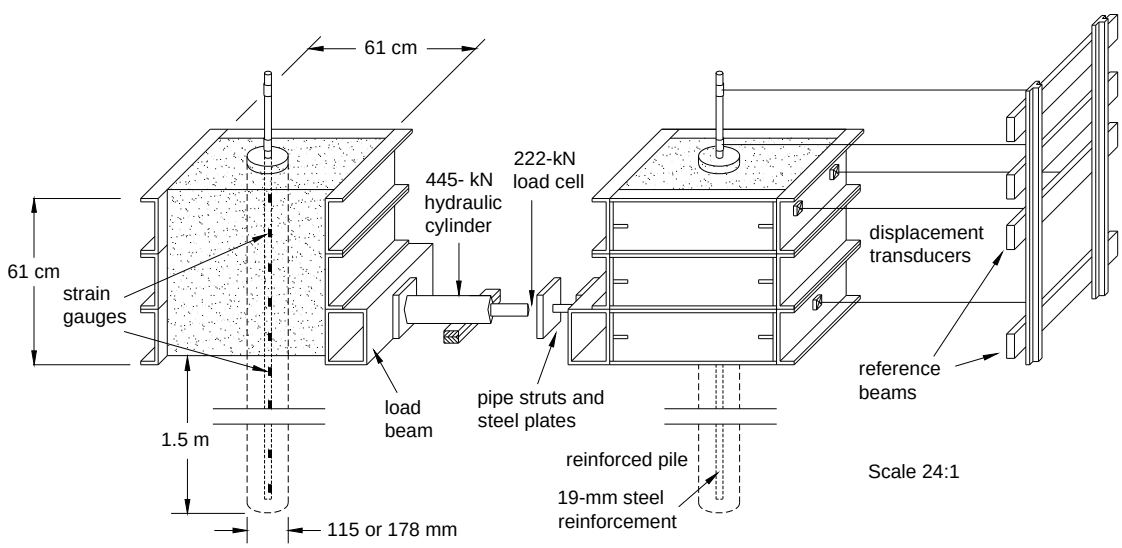

Figure 7. Large-scale direct shear test set-up

The pile load test plan evaluated soil type, pile size, and the effect of pile grouping as each parameter relates to the performance of the slope reinforcement system. Each reinforcement parameter influences the response of piles subject to lateral soil movement. The influence of the

parameters on pile behavior is evidenced by the dependence of p-y curves on the parameters. The pile load test plan, provided in Table 5, included seven load tests of 14 different pile configurations. Direct shear boxes were loaded against each other, where each test involved the simultaneous loading of two boxes. The full-scale tests were conducted to evaluate the performance of nominal 115-mm and 178-mm piles, each reinforced with a centered No. 19 steel rebar.

Table 5. Pile load test plan

Test Number	Box Number	Soil Type	Pile Size*
1	1	Loess	No Pile
	2	Weathered Shale	No Pile
2	3	Glacial Till	No Pile
	4	Loess	114-mm
3	5	Glacial Till	112-mm
	6	Weathered Shale	117-mm
4	7	Weathered Shale	114-mm**
	8	Loess	183-mm
5	9	Glacial Till	178-mm
	10	Weathered Shale	(2) 113-mm
6	11	Loess	(2) 114-mm
	12	Weathered Shale	173-mm
7	13	Glacial Till	(2) 113-mm
	14	Glacial Till	(2) 115-mm

Notations:
All piles with No. 19 rebar
* Measured after pile exhumation
** No pile reinforcement

Load Test Results

Shear Box Load-Displacement Relationships

The load test results for piles subject to lateral soil movement facilitate the load test analysis and support the proposed design methodology. The measured load-displacement relationships of the shear boxes, in particular, indicate the contribution of the pile to the shear strength of the system. The difference between the reinforced soil load and the unreinforced soil load, for a given soil type and lateral displacement, is the load carried by the pile. These total loads applied to the piles can be used for estimating the load distributions along the piles with increasing lateral translation of soil.

The 115-mm-diameter piles offered considerable resistance to lateral soil movement. The installation of the small-diameter, isolated piles resulted in peak loads ranging from 215 to 325 percent of the loads for unreinforced soil. The use of 178-mm-diameter piles offered additional resistance with peak loads ranging from 325 to 390 percent of the loads for unreinforced soil.

The installation and loading of grouped piles offered some quantitative evidence of soil arching and increased capacity due to group effects. Peak loads of grouped piles were matched against peak loads of isolated piles, and the use of grouped piles offered 19 to 105 percent increase in reinforcement capacity. Percent increases of approximately 100 percent indicate a potential influence due to group effects.

Table 6 provides the peak loads of each test and a comparison of the loads with other tests of the same soil type. The presented improvement factors are ratios of peak loads for reinforced and unreinforced tests and tests of one and two piles.

Table 6. Peak loads and improvement factors

				Improvement Factors	
Box	**Diameter (mm)**	**Soil Type**	**Peak Load (kN)**	**Reinforced / Unreinforced**	**2 Piles / 1 Pile**
1	—	L	1.65	—	—
2	—	S	5.47	—	—
3	—	T	4.04	—	—
4*	114	L	5.34	3.24	—
5*	112	T	10.45	2.59	—
6*	117	S	11.70	2.14	—
7*	115	S	6.01	1.10	—
8*	183	L	6.41	3.88	—
9*	178	T	14.10	3.49	—
10**	113	S	13.96	2.55	1.19
11**	114	L	10.94	6.63	2.05
12*	173	S	17.79	3.25	—
13**	113	T	16.01	3.96	1.53
14**	115	T	16.28	4.03	1.56

Notations:
— not applicable
* single pile
** multiple piles
L = loess
T = glacial till
S = weathered shale

Relative Displacement of Shear Box and Pile

The relative displacement of shear boxes and pile heads are provided to support the observed pile behavior during the performance of the load tests. During loading, a gap formed in front (i.e. load-side) of the pile at the soil surface. Figures relating gap width (corrected pile head δ – shear box δ) and load, in addition to displaying the test data, indicate the behavioral stages of piles subject to lateral soil movement. Figure 8 illustrates the behavioral stages, as follows:

- Stage 1 – mobilization of soil shear stresses and elastic bending of pile,
- Stage 2 – mobilization of pile flexural stiffness, and
- Stage 3 – incipient failure due to mobilization of pile moment capacity

Stage 1 is characterized by relatively linear behavior of the soil and the intact pile element. The stress development at the soil-pile interface is insufficient to cause yielding of soil or cracking of the pile, such that a gap of negligible width forms. Stage 2 commences with the development of a bending moment in the pile element that causes the tension-carrying concrete to crack. The pile stiffness immediately drops, and the pile element becomes more flexible. Further loading of the pile causes more rapid pile rotation and pile head deflection. Coincidentally, the gap formation occurs more rapidly. Stage 3 commences with the mobilization of the pile moment capacity. Gap formation which occurs during Stage 3 occurs under constant load. The failed pile element is incapable of carrying additional load. Gaps of significant width (approximately 10 mm) form with the mobilization of pile moment capacity. Table 7 provides the loads corresponding to each behavioral stage of loading.

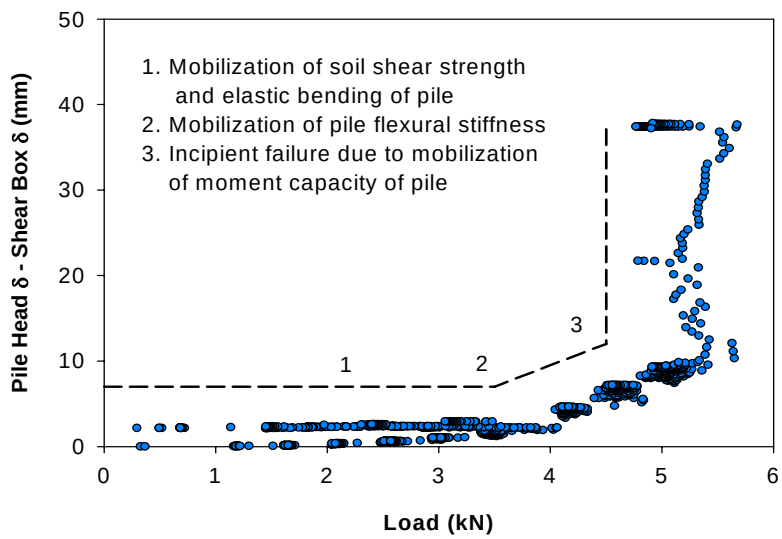

Figure 8. Behavioral stages of piles subject to lateral soil movement (Pile 4)

Table 7. Loads and slopes of behavioral stages of loading

	Load (kN)		
Pile	**Stage 2**	**Stage 3**	**Peak****
4	3.8	5.3	5.34
5	6.3	10.0	10.45
6	7.8	10.9	11.70
8	5.3	6.3	6.41
9	10.0	13.9	14.10
10	9.7	12.8	13.96
11	8.0	10.6	10.94
12	13.8	16.9	17.79
13	10.9	15.9	16.01
14	12.5	16.3	16.28

Notations:
** peak loads from Table 16

Load Test Analysis

The principal objectives of the load test analysis and characterization of load transfer of piles subject to lateral soil movement were to (1) describe the finite difference lateral response analysis method proposed by Reese and Wang (2000), (2) evaluate the analysis method by comparing predicted pile behavior with measured results, and (3) verify the predicted structural performance of pile elements under the loading conditions of slope reinforcement. Achievement of the analysis objectives supports an understanding of load transfer mechanisms of the system and the development of the proposed design methodology.

The governing differential equation for the system of piles subject to free-field lateral soil movement closely resembles that for conventional laterally loaded piles with a fixed free field (Byrne *et al*. 1984). The finite difference lateral response analysis method has recently been modified to suit the p-y method of laterally loaded piles by Reese and Wang (2000). In this analysis, the lateral pressure due to pile-soil interaction is obtained from the relative displacement between the pile and soil and the specified p-y relationship. The beam flexure equation, for the case of a pile subject to free-field lateral soil movement, is:

$$EI\frac{d^4y}{dx^4} + Q\frac{d^2y}{dx^2} - p(y - y_s) + w = 0$$

with EI equal to the pile flexural stiffness, Q equal to the axial load, p equal to the soil reaction per unit length, y equal to the lateral deflection of the pile, y_s equal to the free-field soil movement, and w equal to an externally-applied load distribution.

The *LPILE* analysis setup and corresponding free-field slope movement assumption is illustrated in Figure 9. Structural behavior of piles followed the moment-curvature relationships of reinforced concrete pile sections, as previously discussed. The shear and bending moment at the pile head equaled zero to satisfy pile head fixity conditions. The final input for performing the analysis was the free-field horizontal soil movement. Soil movements corresponded to the uniform lateral translation of the shear boxes imposed during the experimental testing. This soil movement was measured and, therefore, available for input into the analysis.

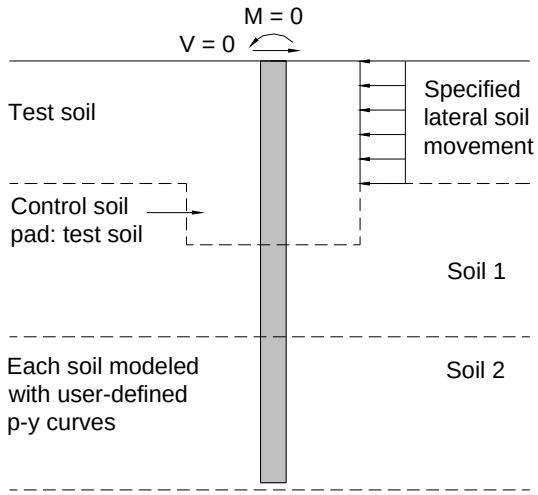

Figure 9. LPILE analysis setup

The objective of the load test analysis was achieved by comparing measured pile behavior with predicted pile behavior estimated from the finite difference method. Correlation of pile head deflection and maximum moment values indicated that the predicted soil reaction matched the loading condition achieved during testing. The correlations of measured and predicted values of pile head deflection and maximum moment were linearized by plotting measured data against predicted data. Ideal correlation, in which measured data equals predicted data, was indicated by a 1:1 line, provided in the figures as a reference. Figures 10 and 11 indicate that statistically-significant correlation of measured and predicted pile behavior was achieved.

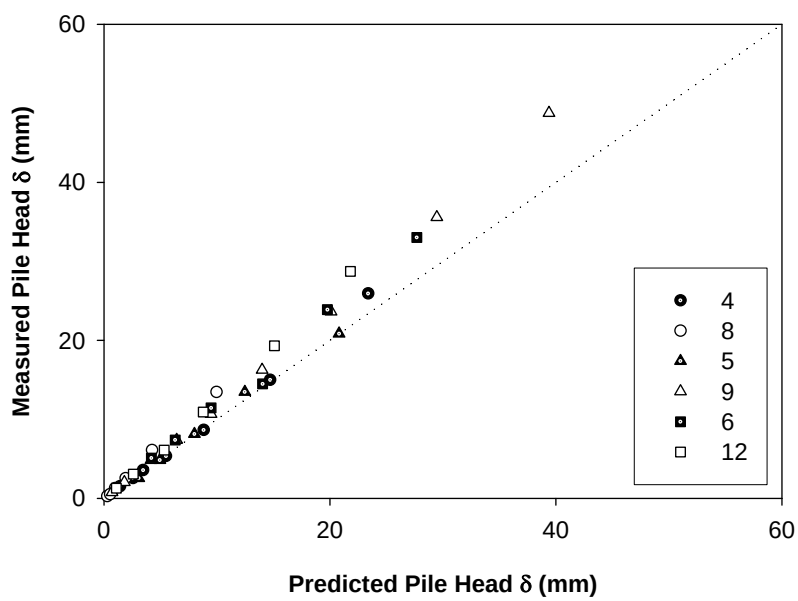

Figure 10. Pile head deflection correlation for isolated piles

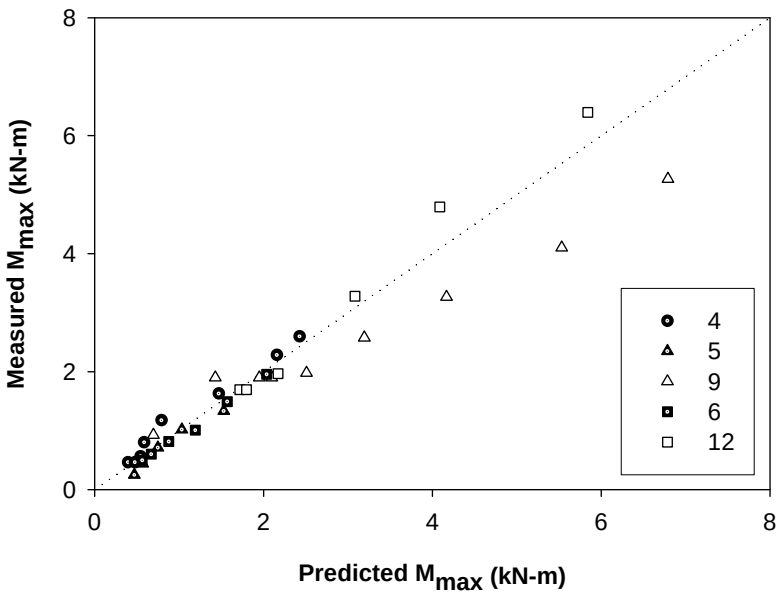

Figure 11. Maximum moment correlation for isolated piles

SDGM Design Methodology

The proposed design method offers a rational approach to slope stabilization with small-diameter grouted micropiles. The design methodology incorporates the following elements:

- Limit equilibrium analyses of unstable, unreinforced slopes
- Reinforcing effect of small-diameter pile elements, including structural capacity of the pile sections and the effect of the pile elements on the global stability of the reinforced slope
- Approach for designing pile sections, based on calculated moment capacities
- Recommendations for arrangement of piles on slopes

To provide adequate stability for unstable slopes, inclusive of considering the potential failure of the reinforced slope, the proposed design procedure incorporates limit states. Specifically, the design procedure incorporates strength limit states that address potential failure mechanisms of pile-stabilized slopes. These possible modes of failure for slopes stabilized with pile elements include: (1) mobilization of the ultimate soil pressure and failure of the soil above the sliding surface, (2) passive failure of soil below the sliding surface due to insufficient anchorage, and (3) structural failure of individual pile elements due to bending forces developed in the piles that exceed the capacity of the pile sections. The service limit states associated with the design of other earth and building structures are less important to the stabilization of nuisance slope failures. Small deformations of the slope are generally accepted, provided the slope maintains its primary function.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The main conclusions developed from the research study are summarized as follows:

Slope Failure Characterization

- BSTs are competent to characterize slopes, especially to obtain the *in-situ* soil shear strength parameter values that are essential for slope stability analysis. BSTs have the advantages in that they gave direct, *in-situ* measurement of soil shear strength in a relatively quick manner.
- The BST measured the peak shear strength and partially softened shear strength, while the ring shear test measured the residual shear strength of the stiff clay shales in the first-time slope failures.
- A range of mobilized shear strengths at the slope failure was obtained from back calculations due to the unknown ground water conditions at failure. The most probable mobilized shear strength at failure was estimated by considering the partially softened and residual shear strengths in the failure zone.
- The strength changes, or the "strength path", due to the slope movement, can be fully established and used to examine the failure mechanisms of the slopes.
- The evaluated slope failures are attributed to progressive failures, and were likely triggered by high ground water tables.
- The findings in the Albia slope case represents an improvement compared to the empirical method of using "good engineering judgment or experience" to estimate the mobilized shear strength parameter values for first-time slope failures.
- The classification of weathering of the shales for the Sugar Creek embankment slope correlates well with the peak shear strength values of the shales, i.e. higher weathering degree consistently corresponds to lower shear strength values; but does not correlate well with residual shear strength values or other soil index properties.
- The shear strength values obtained from different test methods did not exactly match, but they were comparable and showed reasonable agreement, considering the large variation of the soil.
- The internal friction angles obtained from the BST were generally lower than those obtained from direct shear tests (DST), while the cohesion intercepts obtained from BST were generally larger than those from DST, for both the alluvium and the highly weathered shale. This observation could be mainly attributed to the soil variability, test methods and shear strength anisotropy.
- The use of the weathering classification and the measured shear strength values for the Sugar Creek project are expected to provide an economical and safe design for the slope and ground improvement measures.
- The findings for the investigation of Sugar Creek Project represents a detailed case study for using geotechnical information including *in-situ* BST measurements to characterize weathered shale materials with emphasis on weathering classifications for slope stability analyses.

- The results of the probabilistic slope stability analyses performed on the Sugar Creek embankment slope show that the location of the critical slip surface using the BST shear strength parameter values is different from that using the DST values.The calculated factors of safety against slope instability are slightly smaller and the probability of failure is higher, when using the BST values compared to the DST values. The difference in results is due to the BST measurements providing a lower mean value but larger variability than the DST measurements.
- With respect to the assumed slip surfaces, the non-circular critical slip surfaces gave lower factors of safety, but the circular "critical" slip surfaces gave higher probability of failure, indicating inconsistency on the location of the "critical" slip surface resulted from the variability in the input parameters.
- The Morgenstern-Price method and the Bishop simplified method gave very close results on circular slip surface, but gave considerably different results on non-circular slip surface, especially with respect to the probability of failure of the slope. This may be due to the limitations of the Bishop simplified method on non-circular slip surface.
- The use of the two independent sources of shear strength parameter values of BST and DST provided a comparison and check for the evaluation of the slope stability and probability of failure.
- The slope analysis results for the Sugar Creek Project represents the first detailed analyses and application of in-situ BST results in probabilistic slope stability analysis.

Slope Reinforcement

- Slender pile elements are effectively installed with simple construction equipment (i.e. small drill rig and concrete mixer) and minimal labor.
- Displacement and strain gauges indicate the load-displacement behavior of reinforced soil and also the loads induced on piles due to lateral soil movement, respectively.
- The 115-mm-diameter piles offered considerable resistance to lateral soil movement. The 178-mm-diameter piles offered additional resistance, beyond that achieved with smaller pile elements.
- Structural performance of pile elements under the loading conditions of slope reinforcement is effectively predicted with LPILE software.
- Design of pile stabilization with small-diameter grouted micropiles is performed with relative ease.
- The proposed design methodology is robust, in that the method is readily adaptable to achieve reinforcement requirements for a wide range of slope failure conditions. Piles are potentially designed to be strong or weak, depending on the project-specific requirements and the preferences of the design engineer.
- Designs of pile stabilization with small-diameter grouted micropiles are cost-effective with regards to material costs. The pile elements are installed with traditional engineering materials (i.e. concrete, steel), and the installation does not require specialized equipment.

Recommendations for Implementation

The research findings are expected to benefit civil and geotechnical engineers of government transportation agencies, consultants, and contractors dealing with slope stability, slope remediation, and geotechnical testing in Iowa. In-situ BST measurements provide reliable, site-specific soil parameters for design applications which can lead to substantial cost savings over using empirical estimations for critical soil properties. As the BST is an alternative to expensive and time-consuming laboratory testing, the device is particularly useful in obtaining relatively large amounts of data necessary for probabilistic analyses. Procedures for incorporating Borehole Shear tests into practice are documented in Volume 2 of this report. Nevertheless, some training may be required for effective and appropriate use. The BST is primarily intended to test cohesive soils. The device can produce erroneous results in gravelly soils. Additionally, the quality of boreholes affects test results, and disturbance to borehole walls should be minimized before test performance. A final limitation of widespread Borehole Shear testing may be its limited availability, as only about 4 to 6 test devices are currently being used in Iowa.

The research presented in Volume 3 demonstrates with experimental testing how lateral forces develop along stabilizing piles to resist slope movements. This report then documents a step-by-step procedure that can be used by both state and county transportation agencies to design slope reinforcement using slender piles. A state department of transportation may develop training seminars for all local transportation agencies to provide further guidance in using the proposed design method. This effort may be coordinated with the authors and might be extended so far as to conduct a pilot study to demonstrate the intended process of designing and evaluating the reinforcement solution. While slope reinforcement with slender piles by county transportation agencies is encouraged, such action is recommended to be coordinated with the state department of transportation. This organization can document all such remediation projects to better guide counties using successful and unsuccessful experiences, as the DOT will have working knowledge of other unstable slope characteristics and corresponding reinforcement designs. The proposed slope reinforcement solution has not yet been demonstrated at an Iowa slope failure site. As a result, difficulty in scheduling and bidding a pile reinforcement project and evaluating the effectiveness of the measure may impede successful implementation. Obtaining experience and feedback through data collection or visual inspection, however, will promote incorporation of the research findings into standard slope remediation practice.

Successful implementation of innovative slope stability reinforcement and characterization solutions can be evaluated by documenting the number of slopes reinforced with pile elements and those investigated using BST measurements, respectively. Cost savings of incorporating Borehole Shear testing into site investigation practice will be made evident by comparing costs corresponding to designs for geostructures making use of accurate and reliable soil properties (obtained from BST measurements) to those designs using estimated soil properties and higher factors of safety. Calculating long-term cost savings of slope reinforcement using piles considering maintenance costs associated with alternatives and the cost for rebuilding a failed drainage remediation, for example, can indicate the progress and consequences of implementation.

Recommendations for Future Work

Slope Failure Characterization

The following recommendations are made for future work on slope failure characterization:

- Incorporate pore water pressure measurement into Borehole Shear testing so that measurement of effective stresses can be monitored and verified, particularly for low-permeability, clayey soils.
- Perform the BST more frequently near the slip surface of a slope failure or the likely failure surface of a proposed slope. The location of these failure surfaces can be estimated by stability analyses using available information such as slope geometry and empirical shear strength parameter values.
- Establish long-term monitoring of ground water condition and slope deformation for some critical slopes, particularly for newly constructed slopes susceptible to slope instability. This measure can verify or calibrate the shear strength parameter values measured by the BST or indicate progressive failure.
- Accumulate information and establish detailed landslide inventory for the state. This investment will be helpful to overview the slope instability problems from a regional prospective.
- Perform quantitative mineralogical analysis for weathered shale to investigate the possible correlation of the mineralogical compositions with the weathering grades.
- Perform additional laboratory tests to investigate the anisotropic strength of the weathered shales. The tests can be stress-path triaxial compression tests or direct shear tests with shearing planes at various directions.
- Investigate the possible effect of the strength anisotropy of the weathered shale on the slope stability from both deterministic and probabilistic perspective.

Slope Reinforcement

The recommendations for future research in the area of pile stabilization include the monitoring of pilot studies of slope reinforcement with small-diameter grouted micropiles, supplementary experimental studies, and advanced numerical studies, as follows:

- Conduct slope stabilization and monitoring pilot studies to: (1) develop site-specific stabilization designs based on in-situ soil tests (e.g. borehole shear test, Ko stepped blade test) and pile load tests, and (2) monitor slope movement and load transfer of the stabilization system with inclinometers, piezometers, daily rainfall records, strain measurements, and survey markers.
- Conduct experimental studies, including: (1) direct measurement of soil load-displacement (p-y) relationships, and correlation of p-y curves with standard soil properties to develop ultimate soil pressure (p_u) envelopes with respect to overburden and/or confining stress for given soil and pile properties; and (2) perform pile load tests on battered and truncated piles to investigate the influence of orientation on the stabilization potential of slender pile elements. This experimental study is the next most

important task for improving remediation with small-diameter grouted micropiles.

- Perform 3-D finite element analyses of experimental testing of this research study. The analyses serve as calibration for constitutive models of engineering materials and boundary conditions of slope reinforcement.
- Perform 3-D finite element analyses of slope reinforcement to investigate the complicating issues of slope stabilization, as follows:
    - Numerical investigations (3-D FEA) indicate the influence of interactions between adjacent piles, namely soil arching.
    - The imposition of displacement compatibility between piles and adjacent soil results in stress concentrations of which current analytical models fail to consider.

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