Load and Resistance Factor Design in Geotechnical Engineering

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Sponsors: CGPR

Start/Completion Dates: August 2007 / May 2008

Project Background

As of October 1, 2007 AASHTO is now requiring that load and resistance factor design (LRFD) be used for all new bridge projects. LRFD is a limit state design that uses load factors and resistance factors to account for a factor of safety. This is different from the traditional method of analysis in geotechnical engineering, allowable stress design (ASD), for which designs are based on factor of safety values.

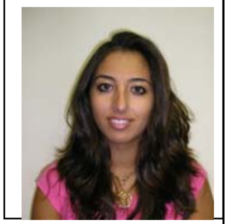
Project Objectives

The purpose of this project is to create a reference document that summarizes LRFD design methodology for engineers in practice. Even though there are several LRFD codes in publication, this report will focus on the AASHTO code because it is used most often in U.S. practice. In addition to reviewing the design process, the report will also go over the load and resistance factors specified by AASHTO. Another goal of this report is to help clarify some of the potentially confusing applications of LRFD to geotechnical engineering. LRFD and ASD designs of a 25 ft tall tieback, cantilever, and MSE wall will be compared.

Research in Progress

A literature search was performed with two objectives. One was to gain a comprehensive understanding of LRFD, and the other was to determine how the factors were selected. After the literature search was completed, the research focused on the AASHTO code in particular instead of LRFD as a whole. A survey was sent out to CGPR members who voted for the initiative at last year's meeting asking for input and any potentially confusing areas of LRFD that had been encountered. Some of these issues included seismic design, global stability, lateral pile analysis, the application of load tests, and the differences between LRFD and ASD. The next phase focused on finding definitive information about how AASHTO dealt with each of the situations. Currently, analyses are being performed for a tieback, cantilever, and MSE wall of the same geometry in both LRFD and ASD. The goal is to compare the designs from each method to see what types of differences arise, and whether LRFD is more or less conservative than ASD for each application.

Liquefaction Mitigation Using Jet-Grout Columns—1999 Kocaeli Earthquake Case History and Numerical Modeling



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Sponsor: National Science Foundation

Project Background

The Kocaeli Earthquake (M = 7.4) struck Turkey on August 17, 1999 and caused significant damage along Izmit Bay. One commercial site of particular interest was recently reclaimed from Izmit Bay using gravely fill and is underlain by soft clays, alluvial sediments and alternating strata of liquefiable sands. The Carrefour Shopping Center is a partially constructed shopping area containing a main building, warehouses and several large parking lots. 60% of the construction was finished at the time of the M7.4 earthquake. To better protect against settlements, the area was reinforced with small-diameter jet grout columns. Numerical analyses were conducted to better understand the performance and effectiveness of this method of ground improvement.

Site Analysis

Typical pre-improvement geotechnical parameters were performed for the site analysis. Cone Penetration Tests (CPT) and Standard Penetration Tests (SPT) yielded low resistances and blowcounts. Shear wave velocities were measured to be around 110-140 m/s. Liquefaction potential was a concern to the designers and the jet-grout columns were placed to safeguard against large settlements under static and dynamic loads. The primary layout of the jet-grout columns were placed at the full length of 9 m on 4 m centers. Additionally secondary truncated jet-grout columns were placed within only the liquefiable sand layer at lengths of 2.5 m on 2 and 4 m centers. A post-earthquake team was utilized to perform a detailed inspection of the affected area and collect performance data on both the reinforced and unreinforced sections of the construction. The data shows that the treated areas performed dramatically different from the untreated areas. Extensometers suggested that most of the settlement was associated with the ML/CL stratum. While no settlement or damage had taken place in the jet-grout reinforced sections, the untreated areas had suffered 5-12 cm of settlement resulting in ponding water and slight structural damage.

Dynamic Numerical Modeling

The reinforced construction site was modeled in three dimensions using DYNAFLOW. A finite element mesh containing 22,000 elements was fit to the grout columns, and soil parameters were based on laboratory and field tests performed by Martin and Olgun. The soil was modeled as a fully non-linear mass during shaking using total stress analysis. For comparison, the jet-grout columns were taken out in several other test runs in order to simulate an unimproved soil mass. The models were shaken in two horizontal directions using the horizontal ground motions recorded 2 kilometers away in Izmit (IZT recording). The estimated peak ground acceleration of the site was 0.24g.

Key Findings

Results indicate the stiff columns underwent negligible shear strains while peak shear strains in the reinforced soil model reached 1%. Contrary to belief, the reinforced soil mass did not perform as a composite body. This incongruity concerning shear strains between column and soil mass are further apparent in the performance of the column within the soil mass. Rather than shearing along with the surrounding soil, the columns tended to behave in flexure rotating at the ends during dynamic modeling. Additionally the predicted peak seismic shear stresses for the grout column were consistently higher than the surrounding soil, as would be expected due to the column's high stiffness. The columns did not strain sufficiently to attract the bulk of shear loading imposed by the surrounding soil, and thus did not reduce large excess pore water pressures. Instead it is believed that the negligible settlements in the reinforced soil mass were due to the high vertical stiffness of the jet-grout columns which provided support against settlements in the soft surroundings. Of particular concern, current methodology in determining the level of seismic improvement obtained by integrating discrete reinforcement may be greatly overestimated due to the soil mass's failure to effectively transfer substantial shear loading onto the jet-grout column.

Summary and Conclusions

The Carrefour Shopping Center in Izmit Bay, Turkey underwent significant earthquake damage. Areas of the construction site unreinforced by jet-grout columns underwent substantial settlements whereas those reinforced by jet-grout columns underwent no settlement. The behavior and effectiveness of the columns were analyzed using a three-dimensional finite element program, DYNAFLOW. The soil was modeled as a fully non-linear mass and pore water pressure generation was neglected. An estimated peak ground acceleration (PGA) of 0.24 was used during the modeling. Results indicate that the low strain levels in the column were inadequate in reducing high shear strains in the soil mass. Additionally, the high peak seismic shear stresses in the column were too high to accommodate the shear stresses in the soil. Contrary to initial belief the columns' effectiveness in reducing settlements during dynamic loading is attributed to the jet-grout columns' high vertical stiffness. In light of this, current methodology in determining the level of seismic improvement in terms of shear behavior may be greatly overestimated.

Determination of Performance-Based Earthquake Engineering Parameters Using Paleoseismic Techniques

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Sponsors: National Science Foundation
Via Foundation

Start/Completion Dates: May 2007 / May 2010

Project Objective

The objective of the research is to develop and validate a framework for assessing seismic hazard parameters using paleoseismic techniques for regions where moderate-to-large earthquakes are high-consequence, low-probability events so that performance-based earthquake engineering can be properly implemented.

Project Background

Tremendous advances have been made in structural and geotechnical earthquake engineering, and in the supporting sciences, over the past several decades. However, in spite of these advances, the seismic risk to the infrastructure in the US has increased, as quantified in terms of economic losses resulting from earthquakes. To reverse this trend, the earthquake engineering community has been moving towards performance-based earthquake engineering (PBEE). The implementation of PBEE requires both the fragility of structural systems and the probabilistically quantified seismic hazard to be known in order to establish the annual probability of specific losses due to seismic events. In relation to this latter requirement, the recurrence times of various magnitude earthquakes are needed for the region of interest. In many regions of the central-eastern United States (CEUS), the historical earthquake record is too short to provide information regarding the recurrence time of earthquakes above approximately M4.5. Yet, there is historical knowledge and/or geological evidence of the occurrence of moderate-to-large magnitude earthquakes (i.e., $\geq$ M5.5) in this region. Consequently, paleoseismic investigations are the most plausible way to determine the recurrence time of moderate-to-large in these regions. By extending the earthquake record into prehistoric times, paleoseismic investigations remove one of the major obstacles to implementing PBEE in the CEUS. However, as discussed subsequently, at the present state of development, paleoseismic techniques are not without limitations for generating results that can be directly used in PBEE.

During an earthquake, the occurrence of liquefaction often manifests itself on the soil surface in the form of sand boils. These sand boils are often preserved, in whole or in part, in the soil profile. In the Wabash Valley region of Indiana and Illinois, as well as other regions, rivers have cut into these deposits, often exposing the paleoliquefaction features. The age of the features can be estimated by radiocarbon dating, optically stimulated luminescence, archeological evidence, etc. Precise dating (+/- 100 to 200 yrs) of sand boils typically requires conditions where the liquefied material vented to the ground surface bearing organics, or requires the dikes to cross-cut a relevant buried organic bearing stratum.

Three fundamental questions underlie all paleoseismic investigations performed in support of seismic hazard analyses:

1. Has there been strong Holocene/late Pleistocene shaking in the area and how often?
2. Where was the tectonic source?
3. What were the magnitude(s) of the event(s) and the characteristics of shaking?

The use of primary paleoseismic evidence (e.g., fault displacements) for answering these questions in the CEUS is limited because the locations of the faults are often unknown and/or inaccessible, precluding fault trenching studies. Additionally, primary evidence does not provide any information regarding the areal distribution of the strength of shaking. This shortcoming is particularly important for the CEUS because the characteristics and attenuation of ground motions are highly uncertain. In contrast, secondary evidence, such as paleoliquefaction features, provides direct evidence of the areal distribution of the strength of shaking, even when the exact location of the seismogenic fault responsible for the secondary evidence is unknown.

The vast majority of paleoliquefaction studies has been carried out by geologists and has largely focused on answering Questions 1 and 2 listed above. This is because the approaches used to answer these questions require significant geologic interpretations. The contributions made by geologists to paleoliquefaction studies cannot be overstated. On the other hand, the mechanics of liquefaction is a topic that falls more in the realm of geotechnical earthquake engineering than earthquake geology, and consequently, the most significant contributions by engineers to the field of paleoliquefaction has been in answering Question 3 above.

Research Plan

(1) Develop and Validate Paleoliquefaction Procedures using a Modern Earthquake Analog.
  a. Assemble liquefaction/non-liquefaction data from recent earthquakes and assess quality.
  b. Plot maps of all liquefaction/non-liquefaction observances.
  c. Estimate the provisional location of the earthquake energy center.
  d. Perform back-calculations at individual sites to estimate the likely a_{max} – M combinations.
  e. Integrate results from individual sites into a regional assessment to verify the estimated location of the earthquake energy center and to estimate the magnitude of the earthquake.
  f. Compare back-calculated values with known values for the earthquakes.
  g. Modify the procedure as necessary and repeat until the developed procedure is valid.

(2) Quantify the Aleatory and Epistemic Uncertainties in the Developed Procedures.
  a. Repeat the steps a-f listed for Task 1 above using subsets of the liquefaction/non-liquefaction case history data for recent earthquakes. The subsets will be comprised of varying amounts and quality of data.
  b. Compare the back-calculated a_{max} – M values with the values from Task 1 and with the known values for the earthquake.
  c. Quantify the aleatory and epistemic uncertainties as functions of the amount and quality of the liquefaction/non-liquefaction data.

(3) Demonstrate the proposed procedure by determining the magnitude-recurrence relationship for the Wabash Valley Seismic Zone.
  a. Perform site selection for field investigation.
  b. Locate and date paleoliquefaction features.
  c. Perform geotechnical site characterization of sites showing paleoliquefaction evidence, as well as sites in the general region that do not.
  d. Using dating information, group data according to time of causative earthquake.
  e. Use the steps a-f listed in Task 1 to estimate the magnitude of each causative earthquake.
  f. Using the paleoseismic data in conjunction with historical seismic data, develop the magnitude-recurrence relationship for the region.

Effects of River Flow Conditions on Slope Stability and Bank Erosion

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Sponsors: Dominion Power
US Army Corps of Engineers

Start/Completion Dates: Jan 2007 / Dec 2008

Project Background

This research involves the study of the hydraulic and geotechnical aspects of bank erosion and slope stability in the lower Roanoke River near Scotland Neck, North Carolina, where the river water elevation changes mostly depending on the discharge patterns from an upstream dam. The processes and the major factors that affect river bank stability include: 1) fluvial erosion due to shear stresses induced by hydraulic forces, and 2) slope failure due to changes in bank geometry, river water elevation, pore pressures, seepage forces and soil shear strength. Due to changes in ground table, unsaturated soil behavior will also play important role. Hence, slope stability analysis which integrates erodibility effects and unsaturated soil mechanics is expected to provide better prediction of a riverbank failure and erosion in the field. A comprehensive study of the processes and factors affecting river bank stability downstream a dam can provide a more ecologically-friendly discharge pattern which can limit the damaging effects of bank failure and erosion.

Project Objectives

This research will study the different processes contributing to bank erosion and instability under periodic discharge from Roanoke Rapids Dam.

The major goals of the research are:

i) improve the understanding of hydraulic and geotechnical characteristics of designated test sites at the lower Roanoke River in North Carolina.
ii) determine factors affecting bank erosion and slope failure under unsaturated soil conditions.
iii) assess the effects of various within-day and within-week hydropower operation scenarios on bank stability and erosion.
iv) suggest discharge patterns that may reduce slope failure and bank erosion.

The activities and outcomes from this research include: i) site investigation and soil sampling, ii) field and laboratory experiments, iii) modeling of slope stability for unsaturated soil condition coupled with bank erosion and seepage, and iv) discharge scenarios that may reduce slope failure and bank erosion.

Research plan

• Field Investigation and laboratory works

The field investigation will include the geomorphological information, hydraulic information, and geotechnical information of the selected sites. Four sites will be selected for field investigation. The bank geometry and bathymetry will be acquired by using LIDAR (Light Detection and Ranging) and ADCP (Acoustic Doppler Current Profiler) respectively. In-situ tests such as borehole shear test, matric suction measurement, and jet erosion test will be done. In laboratory, the soil samples taken from the field will be tested for physical soil properties as well as shear strength and matric suction.

• Coupled seepage, slope stability and bank erosion analyses

Bank erosion is time dependent. It changes the geometry of river bank with time, and can cause mass failure type of bank instability. Thus, the bank stability will be investigated considering the effect of bank erosion as well as the other time dependent variables such as river water elevation and ground water table, which change with the dam discharge rates. Bank erosion rate will be estimated with variables determined by jet erosion test. The coupled analyses will be performed using modeling programs such as SMS, SEEP/W, SLOPE/W, SLIDE, and UTEXAS4ED.

• Discharge pattern

The ultimate goal of this research is to provide discharge patterns that may reduce downstream bank erosion and slope failure. Critical cross sections including straight channel, outside of bend will be analyzed for different conditions of river water flow. All information collected in the previous tasks will be integrated and generate models that show the effect of discharge patterns. The models will include the four different discharge modes currently being used by Dominion Power, which are normal operation, flood control operation, fish spawning operation, and drought flow operation modes. Ultimately, based on the modeling results, discharge patterns that can minimize the bank erosion and slope failure will be determined.

Preliminary Results

Geometric information of the selected sites were acquired using LIDAR, and bathymetry data were obtained by ADCP measurement supported by USGS. Three field trips have been accomplished in Mar. Aug. and Oct. in 2007. Soil profile is established with 28 soil samples for one cross section. Physical soil property tests have been done. Four soil layers were indentified, and classified as SM, CL, MH, and CL, respectively from the surface. The borehole shear tests were performed at the field resulting about 25 degrees of friction angle and 12 kPa of cohesion for silt and clay. Matric suction is measured with tensiometers on Mar. and Oct. trips. Laboratory tests for SWCC (soil water characteristic curves) and osmotic suction measurement are on-going. More field trip as well as laboratory tests are planned in summer for further investigation.

Levee Stability on Deep-Mixed Foundations

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Sponsors: National Science Foundation, U.S. Army Corps of Engineers

Start/Completion Date: May 2006/Jan 2009

Project Background

Increasing interest in using deep-mixing methods (DMM) to improve the foundation of levees constructed on soft ground is driven by the need to reduce levee footprints and environmental impacts and to allow for more rapid construction. Suitable methods for analysis and design of these systems are needed to insure that the DMM technology is properly applied.

DMM shear walls can be completed using specialized equipment for multiple-axis mixing or by overlapping single-axis DMM columns. Vertical joints in the walls, due to the reduced design width of the wall at the overlap between adjacent installations, can be made weaker by misalignment during construction. Ordinary limit equilibrium analyses do not account for potential failure modes other than shearing; whereas, numerical stress-strain analyses can account for other failure modes, such as racking of the deep mixed shear walls due to slipping along vertical joints between adjacent installations in the shear walls.

Project Objectives

The overall objective is to develop recommendations for the design of levees founded on DMM shear walls. The goal is to determine if numerical methods are necessary to accurately asses the stability of these systems and to provide recommendations for modeling weak joints within the shear walls.

Research Accomplished

Stability analyses have been completed for a 17-foot high levee constructed over an improved foundation consisting of a 35-foot wide and 40-foot deep zone of continuous dry-mixed single-axis DMM columns. This configuration was based on the P24 levee project recently completed by the U.S. Army Corps of Engineers. The cross-sectional geometry and material properties were provided by the Corps.

Limit equilibrium stability analyses using UTEXAS3 and Spencer's method were completed for a wide range of potential failure surfaces, including a shallow failure surface downstream of the DMM columns and a deep failure surface beneath the columns. Numerical analyses were completed using the finite difference computer code FLAC to evaluate critical shallow and deep failure modes. Vertical joints were included in the DMM improved zone in order to model potential weak joints between columns. The analyses were completed for a full range of joint efficiencies. The joint strength corresponding to 0% efficiency is for a condition of no overlap between columns (i.e., the strength of the native soil). The joint strength corresponding to 100% is for a condition of full design overlap of the columns. The joint strength for intermediate efficiencies is obtained by interpolation between the values for 0% and 100% efficiencies. The analyses were performed using 5 and 8 equally spaced vertical joints to investigate the influence of the number of such weak joints on the values of factor of safety.

Key Findings

For the conditions used to represent the P24 levee project:

- For the critical shallow failure surface, which passes downstream of the DMM columns, factors of safety from numerical analyses for 0% and 100% vertical joint efficiencies are 1.29 and 1.33, respectively. The factor of safety for this failure mode is only slightly dependant on the efficiency of vertical joints between columns and is also in good agreement with the results from limit equilibrium analyses (FS = 1.32).
- For a deep failure surface, the factors of safety from numerical analyses for 0% and 100% vertical joint efficiencies are 1.37 and 1.51, respectively. As shown in Figure 1, the factor of safety from numerical analyses for a deep failure surface is in exact agreement with the results of the limit equilibrium analyses using Spencer's Method when the efficiency of vertical joints between columns is at least 30%. For joint efficiencies smaller than 30%, the factor of safety decreases with decreasing joint efficiency due to increasing influence of racking failure mode on the results. There is very little difference between the results for 5 and 8 vertical joints. The deep mixing literature indicates that a vertical joint efficiency of about 50% should be used for design. At this efficiency, the factor of safety from numerical analyses for a deep failure surface is unaffected by the racking failure mode and the results are in good agreement with those from limit equilibrium analyses.

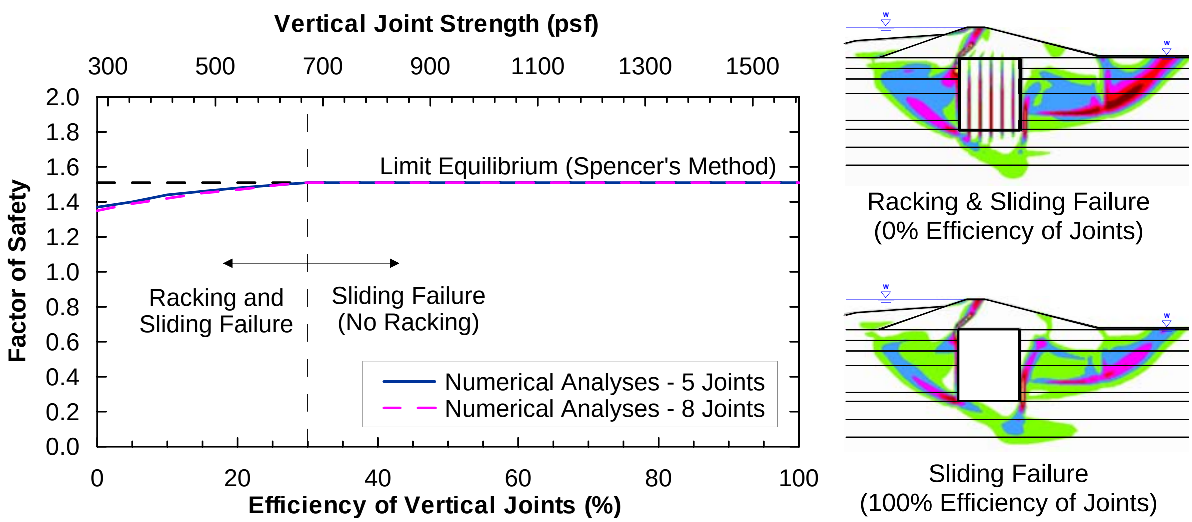

Figure 1. Factor of Safety Versus Efficiency of Vertical Joints, Deep Failure Surface

Future Research

- Settlement analyses will be completed to evaluate the potential for cracking of the levee.
- The potential effects of tension cracks on stability will be evaluated.
- Reliability analyses will be performed.
- Analyses will be completed for a range of levee and DMM shear wall configurations to develop general design recommendations.

Interaction of Integral Abutment Piling and MSE walls

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Start/Completion Dates: August 2007 / August 2010

Project Background

Integral abutment bridges offer several comparative advantages over bridges built with joints and bearing supports. Integral abutment bridges considerably reduce maintenance costs because they do not have exposed metal parts. Alampalli and Yannotti et al. (1998) found that the predominant cause of bridge deterioration is the flow of deck drainage waters contaminated with deicing chemicals through expansion joints. The most important advantages of Integral Abutment Bridges can be summarized as (Arsoy et al. 1999):

- Lower construction cost due to joint elimination
- Lower maintenance costs due to elimination of joint and bearing supports
- Superior seismic performance
- Fewer piles are needed per foundation, and no battered piles are needed
- Simpler and faster construction
- Improved riding quality

When abrupt changes in grade are required, integral abutment bridges are constructed with the abutment piling extending through the backfill of mechanically stabilized earth (MSE) walls, as shown in Figure 1. New road alignments are requiring that longer bridge spans be constructed, and longer spans produce greater magnitudes of movement of the abutments due to daily and seasonal thermal changes, with the potential for substantial loads to be applied to the MSE wall facing and connections, especially during bridge contraction in the winter months. Other research needs related to integral bridge abutments are based on a survey of practice by Maruri and Petro 2005, which found that:

- There is no consensus among states regarding the orientation of H-piles
- The distance between the abutment piling and the MSE wall face varies greatly
- Some states use casings infilled with sand around the abutment piles, and others do not
- Some states use expanded polystyrene (EPS) behind abutment walls, and others do not
- Some states use a “hinge” in the abutment, and others do not
- There is a lack of consensus regarding:
    - The earth pressures used to design integral abutments and piles
    - Detailing of integral abutments around MSE walls
    - Backfilling around integral abutments
    - Limits for bridge skew angle and its influence on performance and design

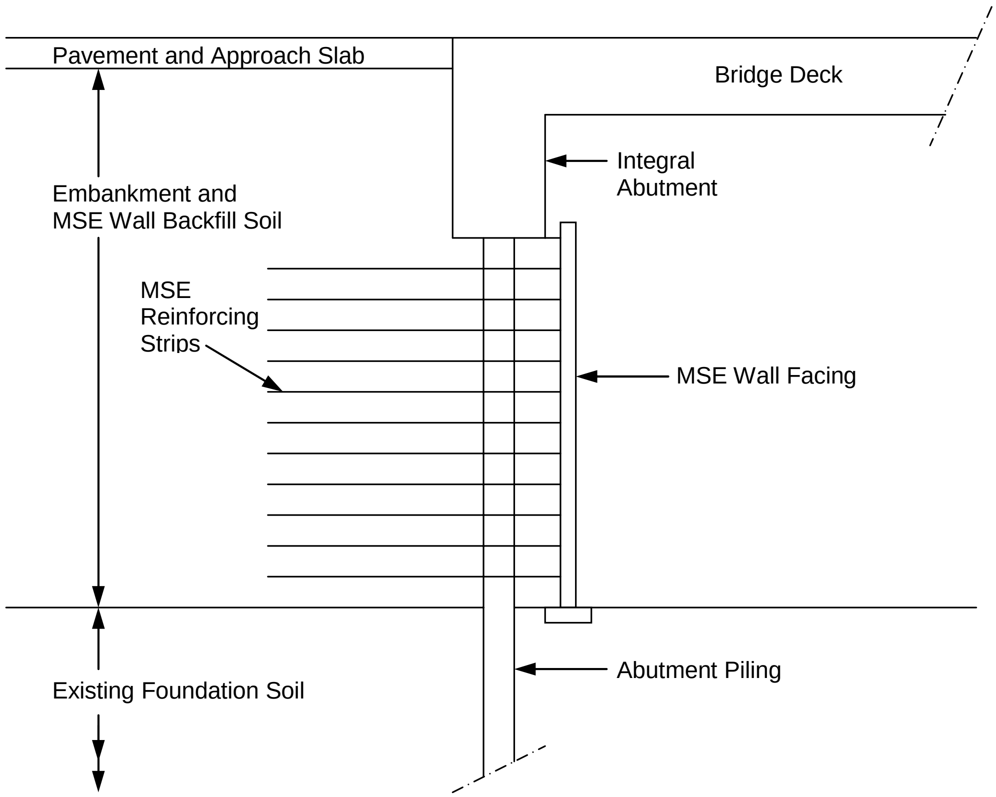

Figure 1. Profile view of MSE system around piling supporting integral bridge abutment.

Work Tasks

The research includes the following tasks:

- A literature review has been completed.
- A survey of practice that focuses on MSE wall and integral abutment bridge interactions has been completed. The survey data are being processed.
- VDOT's integral abutment bridge at Telegraph Road, which has abutments in MSE wall backfill, will be instrumented. This case will be analyzed numerically as data become available.
- We will analyze the instrumented field case described by Hassiotis et al. (2005) using two- and three-dimensional numerical analyses.
- An extensive series of parametric analyses using the calibrated numerical model will be performed to investigate the influence of important parameters on system performance.
- In close collaboration with VTRC and VDOT engineers, we will develop recommendations for design of these systems. That the recommendations will be developed in the form of tables, charts, simple equations, and/or a spreadsheet, without requiring use of numerical analysis on the part of design engineers for applications that are within the range of the parameter variations investigated.

Application of Geofoam for Earth Pressure Reduction

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Sponsors: NSF IGERT

Start/Completion Dates: February 2007 / December 2007

Project Background

Backfill soil behind a retaining wall is typically compacted and exerts lateral pressures on the wall increasing with depth below the ground surface. These lateral earth pressures can be reduced by the installation of vertical layers of synthetic material, such as geofoam, at the wall and soil interface prior to soil compaction.

One type of compressible material for this type of application is expanded polystyrene (EPS) geofoam blocks, which have predictable stress-strain behavior when loaded, low-density, and resistance to decomposition and moisture. The use of this light-weight, Styrofoam-like material may be more cost effective than designing the structure to withstand a greater lateral load.

Relatively large lateral earth pressures can cause a retaining wall to fail structurally or by excessive displacement through rotation about its base and/or translation away from the soil. With the presence of geofoam, when the soil is compacted, the material will deform due to the compaction-induced lateral earth pressures. As a result, the backfill soil will be able to expand laterally, thereby reducing lateral pressures on the wall. Similarly, if the backfill is loaded by a building foundation or traffic, the surcharge-induced loading will cause lateral expansion of the soil as well, and lateral pressures will again be reduced.

Past research on lateral earth pressure reduction due to geofoam has been primarily focused on case studies. This current study aims to provide a general tool when using geofoam in retaining wall design to determine compaction-induced earth pressures, surcharge-induced earth pressures, and backfill settlement.

Project Objectives

The purpose of this research is to develop relationships among the coefficient of lateral earth pressure, backfill settlement, distance from the retaining wall, compressibility of the geofoam, and surcharge load applied to the backfill. These relationships will be in terms of dimensionless parameters, meaning that the results will not be case-specific for one type of wall configuration or for specific material properties. The results will be presented in graphical form to provide engineers with an easy-to-use tool to determine the impact that geofoam with certain properties will have on lateral earth pressure reduction and backfill surface settlement.

Research Accomplished

- Literature review of past work has been conducted which has included work on compaction-induced earth pressures on retaining walls and the effect of geofoam thickness on lateral earth pressures.
- Guidance on choosing appropriate geofoam modulus values has been presented.

- Finite element analyses of the retaining wall, backfill, and geofoam system with surcharge loading have been completed.
- Normalized parameters to relate all of the system parameters have been derived.
- The normalized results have been presented in easy-to-use figures.

Key Findings

The study is in the final editing stages with the intent being to submit the work to the *J. of Geotechnical Engineering*. This work will provide design engineers with a generalized tool that will account for geofoam properties, soil properties, compaction pressure, surcharge pressure, and system geometry when calculating lateral earth pressure distribution and backfill settlement magnitude.

Liquefaction Susceptibility of Uncemented Calcareous Sands from Puerto Rico

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Sponsors: United States Geological Survey

Start/Completion Dates: January 2007 / May 2008

Project Background

This study investigates the dynamic properties of uncemented calcareous soils from the coastal plains of Puerto Rico. Calcareous sands differ from terrigenous (quartzitic) sands in origin and mineralogy. These soils are composed of the skeletal remains of marine organisms. Calcium carbonate is in general stiffer, but exhibits a more brittle stress-strain behavior compared to predominantly quartzitic sands. Generally calcareous sands are angular and have large void ratio. Void structure consists of intra-granular pore space, and bulky inter-granular pore-space due to the highly angular soil particles. Particle rearrangement and crushing upon shearing has a profound effect on the dynamic behavior of these soils. Because of these fundamental differences between calcareous and quartzitic sands, current earthquake design practices may not be directly applicable to design in calcareous soils.

Project Objectives

Laboratory experiments are geared towards identifying how such differences in the grain characteristics are reflected in the engineering behavior. This project is a joint-collaboration between Virginia Tech and the University of Puerto Rico at Mayaguez (UPRM). The first phase of the study involved mineralogical analysis, particle characterization, resonant column testing, shear wave velocity testing, 1-D consolidation testing, and basic shear strength testing. The objective of this phase of the project is to study the cyclic properties and liquefaction susceptibility of two calcareous soils using conventional monotonic triaxial and cyclic triaxial testing. In addition to Cobo Rojo sand, studied in phase one, a similar sand, Playa Santa sand, is being tested. Cyclic and monotonic triaxial testing is currently being performed at both institutions, Virginia Tech and UPRM. These tests are evaluated and the cyclic behavior of these calcareous sands is compared to quartzitic sands at similar relative densities.

Research Program

- **Geotechnical Characterization Testing**

  A series of basic tests were initially conducted to define the fundamental engineering properties of the calcareous sand. These include; Specific Gravity, Maximum and Minimum dry unit weight, and Gradation Analyses. An isotropic consolidation tests has been completed to a confining pressure of 500 kPa (73 psi). Further 1-D consolidation testing will be completed.

- **Cyclic Triaxial Testing**

  The cyclic triaxial testing program is close to being completed. Samples were prepared at three different relative densities, 20, 40 and 60%, and confined at 100 kPa (14.5psi). Three to four tests are used to define each curve on a Cyclic Stress Ratio (CSR) vs. Number of Cycles to failure (pore pressure ratio ≈ 1.0 or 5% double amplitude strain). Additionally a fourth curve will be defined for a relative density of 60% under a confining pressure of 200 kPa (29 psi).

- **Undrained Monotonic Triaxial Testing**

  Monotonic testing provides valuable insight into the soils tendency for volume change and liquefaction potential. Several points are of interest. The critical or steady state point is the point at which the sample strains at constant stress state and constant volume; constant load and pore pressure. The phase transformation point is defined the point at which the soil changes from having a contractive tendency, pore pressure generation, to dilative tendency, pore pressure reduction. Phase transformation lines and critical state lines can be established. CU triaxial tests have been completed at all relative densities and associated confining pressures. Additional tests have been completed to further define the steady state and phase transformation lines for a given void ratio. Other studies have shown that the cyclic behavior is dependant on the phase transformation and steady state lines.

Key Findings

The testing program has not been concluded and the analysis of the data is not complete. We have determined that generally the Playa Santa calcareous sand has greater cyclic resistance to liquefaction than quartzitic sands formed at similar relative densities as Figure 1 shows. This corresponds to results of similar studies. This is most likely due to the highly angular particle shape of our sand. For most soils it can be said that as confining pressure is increased resistance to liquefaction is reduced. We are looking forward to seeing how the results change when the confining pressure is increased. It could be theorized that an increase in confining pressure would more significantly impact the resistance to liquefaction in a soil that is highly angular and having a complex structure such as a calcareous sand.

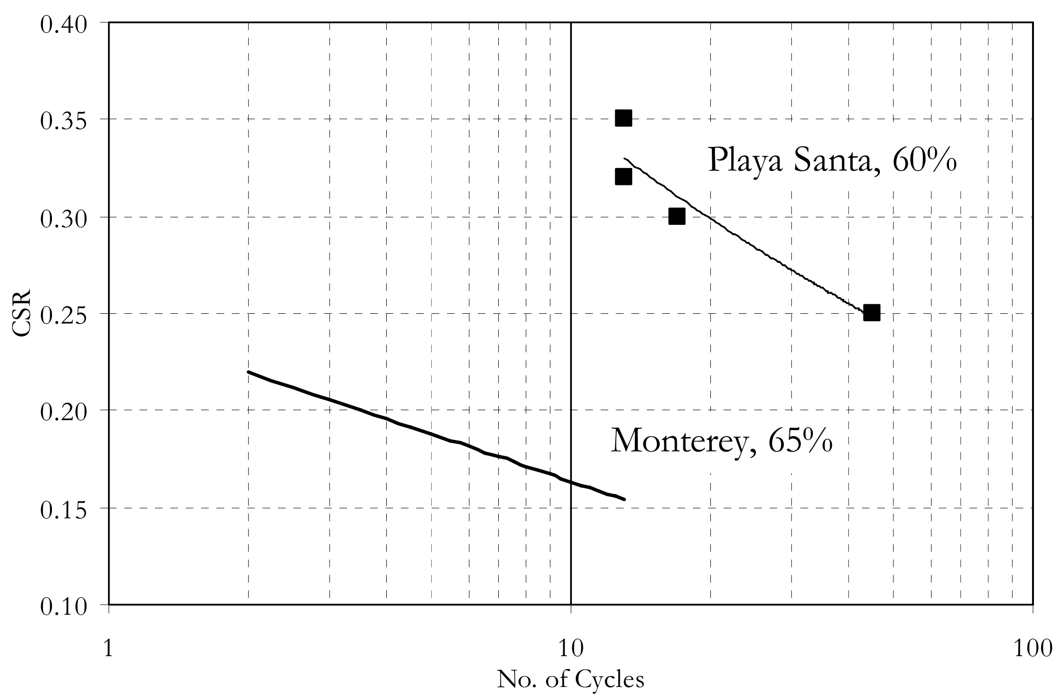

Figure 1. Cyclic strength of Playa Santa calcareous sand with Monterey Sand

Fully-Coupled Solution of Fluid-Flow Behavior in Porous Media Based on the Biot's Theory

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Sponsors: American Chemical Society

Start/Completion Dates: August 2004 / May 2008

Project Background

In geotechnical engineering, many physical phenomena can be explained by geomechanics and fluid-flow coupling (e.g. soil consolidation, hydrocarbon production, and contaminant transport). Therefore, there is a strong interest in the modeling of fluid flow behavior in deformable porous media that takes into account geomechanical effects. Terzaghi's one-dimensional theory is the most popular and widely used in the field. However, more rigorous coupling analyses should follow Biot's theory which is multi-dimensional consolidation theory.

There are various ways to achieve coupling between geomechanics field and fluid-flow field. In general, coupling can be categorized into three forms such as one-way coupled, iterative-coupled, and fully-coupled approach. The fully-coupled approach is based on the Biot's theory which has become a powerful framework for modeling three-dimensional fluid flow in deformable porous media in soil and rock mechanics. The fully-coupled approach is the most rigorous approach and produces the most correct result. However, large computational efforts are required because of the need to solve the geomechanics and the fluid-flow unknowns simultaneously and monolithically. Also the geomechanical or fluid flow mechanisms are often simplified in uncoupled geomechanics or fluid-flow simulators in comparison with the fully-coupled systems. In order to avoid these limitations, most researches have focused on the iterative coupling. In the iterative coupling, porosity and the rock compressibility are used as key parameters of coupling between the fluid flow and geomechanical analysis. However, most of the iterative coupling approaches assume that the porosity (or volumetric strain) change is caused by the mean effective stress alone. This is not necessarily true because deviatoric stresses also cause volumetric strain, and porosity can change even at constant effective mean stress conditions, and compressibility can become negative for dilating materials.

Project Objectives

The research focuses on developing modular solution techniques that can exploit existing geomechanical/fluid-flow simulations. The solution techniques are based on the fully-coupled Biot's theory and will be implemented into Finite Element based geomechanical simulator and Finite Element (or Finite Difference) fluid-flow simulators. The main goal is to develop efficient and rigorous algorithms to implement full geomechanical effects into existing fluid flow simulator.

Research Accomplished

In conventional fluid-flow simulators, geomechanical effects are oversimplified with compressibility term which is scalar or at most diagonal matrix. This compressibility term can be updated with a full tensorial compressibility matrix based on the fully-coupled Biot's theory. Also, this compressibility matrix can be diagonalized and easily implemented in a conventional fluid-flow simulator. The diagonalization process reduces the tensorial compressibility matrix to its principal components. Pore pressures are then calculated using the updated full compressibility matrix in the fluid diffusion equation, and this information is passed to the geomechanics code for the stress calculations. Due to the staggered or modular characteristics, the proposed algorithm can be used in pre-developed fluid-flow simulation and geomechanics codes by providing a rigorous coupling between the two codes consistent with Biot's theory. Additionally, the proposed procedure does not require massive programming and computational efforts. Detailed results that have accomplished so far from this research are following;

- 2D geomechanical code was built based on linear elastic, elasto-plastic (e.g. Modified-Cam clay model) theory
- 3D Geomechanical code was built based on linear elastic theory.
- Finite Element Code for the fully-coupled and monolithic solution based on the Biot's theory was built (e.g. elastic, and elasto-plastic stress-strain relation).
- Single-phase transient fluid-flow code (e.g. FEM and, FDM) were built based on Darcy's law
- The rigidity effects for Mandel-Cryer effects of the surrounding material on the porous medium were researched
- Coupling algorithms appropriate modular approach based on updating compressibility matrix were proposed (e.g. FE geomechanical simulation – FE, and FD fluid-flow simulation)
- The code was validated using available closed-form, and numerical solution (e.g. Mandel's problem, linear 2D consolidation from Schiffman et. al, and non-linear 2D consolidation from other researchers)
- A simplified problem of subsidence in the Ekosfisk was analyzed using modular approach

Future Work

- Develop multi-phase fluid-flow code using FE and FD method
- Implement developed coupling algorithm into multi-phase fluid-flow simulator
- Analyze case histories

Seismic Implications of the International Building Code – Central and Eastern United States

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Sponsors: ECSUS

Start/Completion Date: Fall 2006/Spring 2008

Project Background

Seismic buildings codes have been developed over the past forty years to provide a level of safety against earthquake damage for buildings and lifelines constructed throughout the United States. Since the majority of earthquakes have occurred in the Western United States (WUS), these codes have tended to be based on knowledge and data collected in that part of the country. Recently, numerous states as well as the Department of Defense have adopted the International Building Code (IBC2000, 2003). In the central and eastern United States (CEUS), this new building code has introduced more stringent seismic considerations of constructed facilities and lifelines. The code is a combination of recent US regional model codes and relies mainly on provisions and standards that were initially developed in the WUS. As a result, it appears that in some cases the code may not be directly applicable to some CEUS regions due to geologic conditions and other seismological factors that are different than those for which the code was developed.

The central and eastern United States has felt large earthquakes during its' past, but they occurred during periods when the population and infrastructure were small and our knowledge of seismicity was premature. Therefore, the consequences were minimal in comparison to if a large earthquake hit the CEUS today. It is vital that the building codes provide reasonable seismic design concepts for regions in the CEUS to prevent or reduce earthquake related damage.

Two CEUS sites are presented to illustrate conditions where the building code is deficient: Charleston, and Columbia, South Carolina are selected for this purpose. These sites are of increased importance from a seismic standpoint because of the historical "1886 Charleston, SC" earthquake (Moment Magnitude, M_w 7.0 – 7.3) which caused approximately 100 deaths and caused millions of dollars in economic losses. An important point of consideration is the population growth of the CEUS from the 19th to 21st centuries and the fact that the infrastructure has not been designed to withstand a large earthquake. It is important that future structures in the CEUS are built to withstand the possibility of a devastating earthquake and that existing structures are classified and modified to prevent potential loss of life. More importantly, the code methodology and concepts need to be tested and scrutinized to insure that the designs are suitable and appropriate for use in all regions of the United States, especially in the CEUS where the potential for large consequences would be disastrous.

Project Objectives

This research attempts to address the issues faced by the CEUS with regards to seismic building codes and provide background regarding how the codes have evolved to their current status. The main objective of this research is to illustrate areas where the code may be deficient such that future versions of the code can alleviate these concerns. Site-specific site response studies of Charleston and Columbia sites are performed to illustrate the deficiencies of the code.

Key Findings

1. The deep sediment stack in Charleston, S.C. is not accounted for by the IBC leading to un-conservative estimates of ground shaking for flexible structures such as bridges.
2. In Charleston, the depth to marl and the depth to hard rock are critical parameters for predicting ground surface response.
3. Hard rock close to the ground surface in Columbia, S.C. is not accounted for by the IBC leading to low estimates of ground shaking for shorter buildings.
4. In Columbia, the thickness of the weathered transition zone can greatly influence the predicted ground response.
5. The selected input motion greatly influences predicted ground surface response. The input motion should be selected or generated to model hard rock motions which are propagated through the entire soil stack to fully account for unique geologic conditions.

“Best Practices” for Site and Soil Characterization

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Sponsor: CGPR
Start Date: August 2007

Objectives

The objective of this project is to develop a guide that will be useful as a summary of the benefits of comprehensive site characterization, as a guide for entry-level geotechnical engineers, and as a guide to information sources.

Format

The format of the guide was chosen to create an efficient means of locating sources of information. An “expanded outline” form was used to make the document easily scannable and to serve as a reminder and check-list for site and soil characterization. Instead of adding another guide to the many resources currently available, emphasis was placed on using brief statements and specific page-by-page references to published sources of information.

Scope

Projects & Associated Geotechnical Concerns
- Building Foundations
- Permanent Excavations
- Pavements
- Highway Embankments
- Dams
- Levees
- Permanent Retaining Structures
- Tunnels
- Culverts
- Landfills

Site Characterization
- Desk Studies
    - Previous Investigations
    - Geologic Information
    - Aerial Photography & Remote Sensing
- Field Studies

    - Planning Field Studies
    - Site Access Considerations
    - Borings & Test Pits
    - Drilling & Sampling
    - Geophysical Methods
    - Ground Water Investigations
- In situ tests

Soil Characterization

- Laboratory Tests
    - Index Tests
    - Properties Tests
- Correlations
- Hazards Associated with Various Soil Types
    - Swelling Soils
    - Granular Soils
    - Cohesive Soils
    - Rock
    - Residual Soils
    - Compacted Soils

Construction Considerations

- Excavation Support
- Dewatering
- Compaction
- Quality Control
- Ground Improvement
- Noise & Vibration

Instrumentation & Performance Monitoring

- Settlement
- Seepage & Pore Pressure
- Lateral Movement
- Temperature

Engineering Manual for Organic Soils and Peat

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Project Background

Organic soils and peat pose a variety of engineering challenges. The steps to working with organic soils and peat on a job site include: classifying the soil, assessing possible problems, assigning engineering properties and developing a mitigation plan. As land in desirable areas becomes less and less available, it is often necessary to construct in areas that have traditionally been avoided due to poor soil conditions. The Engineering Manual for Organic Soils and Peat will bring together and summarize published data for use by design professionals faced with sites containing organic soils and peat.

Project Objectives

The objectives of this research were to (1) collect and compile data on classification and engineering properties of organic soils and peat (2) compile and discuss mitigation methods for organic soils and peat, based on case histories.

Characterization

Classification of organic soils and peat is accomplished initially in the field using visual-manual techniques. Laboratory testing (ASTM D2974) is conducted to determine the quantity of organic material in a soil. NAVFAC DM 7.1 classifies organic soils according to the following:

Organic Content		Soil Classification
75% or more	→	Peat
30% to 75%	→	Peaty Organic Soil
5% to 30%	→	Organic Soil
1% to 5%	→	Soil with Organic Content
Less than 1%	→	Inorganic

Engineering Problems

Once identified on site, organic soils and peat pose multiple engineering challenges. First, the deposits of organic soils and peat are generally not uniform, and can change significantly over short distances. Organic soils and peat often have large void ratios and great water uptake and holding potential. The soils tend to exhibit large primary and secondary settlements. Primary settlement will occur relatively quickly in comparison to inorganic clay; however secondary settlement is often a significant portion of the total settlement in organic soils and peat.

In addition to large settlements, organic soils and peat often have low strengths. The undrained strength ratio for organic soils and peat is not significantly different from inorganic clays; however the effective vertical stress on the soil is usually significantly less because the soils have lower unit weight values. Another major engineering problem with organic soils and peat is potential corrosivity. Organic soils and peat tend to be highly acidic, with substantial cation exchange potential.

Mitigation Techniques

When organic soils and peat are encountered mitigation techniques need to be considered carefully. In locations where it is possible, avoiding the soil and building in a more suitable area is the first option. Other common techniques are to excavate and replace the undesirable soil, or to bypass the soil layer with deep foundations such as drilled shafts or piles. Preloading the soil to induce settlement along with applying admixtures to improve material properties, such as lime to reduce corrosivity, are also used to mitigate engineering problems with organic soils and peat.

Development of a Simplified Laboratory Filter Test

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Start/Completion Date: December 2005/May 2008

Project Background

The filter zone is one of the most important components of embankment dams. They are constructed not only to protect the core materials during steady state seepage, but they also must perform satisfactory in the event of cracking due to either static or seismic events. Although considerable efforts have been made by several organizations to develop procedures to determine the suitability of filters in embankment dams, limited research has been conducted regarding the ability of filters against collapse during static or seismic loading. In the past, several laboratory testing methods were developed to evaluate filter performance. However, most of them are either difficult to conduct or expensive. Therefore, it is necessary to develop a simplified laboratory test method in order to evaluate the suitability of filters to function effectively in an embankment dam.

Project Objectives

The objectives of this research are:

(1) Study the ability of filters to collapse under the event of cracking under either static or seismic conditions, and
(2) Develop a simplified and less expensive filter test method.

Approach

The following presents the different tasks to be performed for the project. It consisted of collecting and analyzing data to use in developing the simplified laboratory filter test:

- Perform a desk study and report to summarize gradations and mineralogy of existing USBR dams. The purpose is to establish the range of conditions to be simulated in the experimental testing program.
- Perform a literature review, survey, and report investigating the depth of cracking that has occurred in dams worldwide. The purpose of this task is to determine the depths of cracks and appropriate range of overburden pressures that should be simulated in the experimental testing program.

- Perform a literature search and review of (1) chemical and biological causes of cementation in granular soils, and (2) experiences with development of cementation in granular soil filters. The review would focus on the conditions likely to lead to development of cementation in filters, methods of detecting cementation in filters, and methods of remediation. The purpose of this task is to develop the background necessary for the experimental testing program, and application of the results to embankment dams
- Perform an experimental testing program, using the laboratory testing devices developed at Virginia Tech for testing cracked filters, to investigate the effects of the amount of fines and the plasticity of fines on the performance of cracked filters. The purpose of this task is to establish quantitative results that can be used as the basis for determining which materials are acceptable or unacceptable for use in filters.
- Perform laboratory experimental studies of the self-healing ability of broadly graded filters, using the devices developed at Virginia Tech. The purpose of this task is to determine under what conditions these broadly graded materials would be capable of self-healing and establishing stable behavior without effective filters downstream.
- Develop a simplified index test method to assess potential filter performance. The purpose of this task is to make it possible to determine whether candidate materials are acceptable or unacceptable using simple tests that can be performed in laboratories that do not have the specialized devices developed at Virginia Tech.

Research Progress

The following describes the specific task items performed to date for the project:

- <u>Gradation and Mineralogy of Existing USBR Dams</u> (Tiwari, 2005): The study had the main objective of collecting data on existing USBR dams regarding gradation, mineralogy, and placement conditions of both filter and core materials. It aided in establishing a range of conditions to be simulated in the experimental testing program.
- <u>Depth of Cracking in Dams Worldwide</u> (Bolton, 2006): The study had the main objective of reviewing, surveying, and investigating available reports on the depth and causes of cracking that have occurred in dams worldwide. It aided in determining the depth and orientation of cracks as well as the approximate range of overburden pressure that should be simulated during the experimental program.
- <u>Cementation of Granular Soil Filters</u> (Bolton, 2006): The study had the main objective of reviewing the chemical and biological causes of cementation of granular soil while obtaining case histories on the cementation effects in granular filters. The study mainly focused on the favorable conditions for the development of cementation in filters. It aided in giving the necessary background for the testing program in terms of materials and methods to be induce cementation.
- <u>Tensile Strength of Soil and Tension Cracks</u> (Ochoa, 2007): The study had the main objective of reviewing the mechanics of cracking in embankments due to settlements. It aided in the interpretation of the cracking phenomena while attempting to predict depths of cracks. It will also used to evaluate the effects of fine content in granular soils to develop and sustain a crack.
- Tests developed and performed to address the given conditions were:
    - Hour Glass Test: developed to fulfill the requirements of the simplified index test. Testing ceased after no good quality conclusions could be withdrawn from the test.

- Soil Slump Test: developed to fulfill the requirements of the simplified index test. Testing of 21B gravel began in August 2006 and was completed in January 2007. A preliminary report summarizing the findings was submitted. Dam filter materials were tested during the first part of the year 2007. Testing ceased due to inconsistency in the results.
- Isotropically Consolidated Undrained Active Pressure Triaxial Test (ICU AP): developed to address the cracking phenomena from a more soil mechanics standpoint. Test is more difficult and expensive than others but still accessible. Testing on 21B gravel was performed during the summer of 2007. Testing on dam filter materials commenced on August 2007 to the present.

Future Research Activities

The following describes the items to be performed for the remainder of this project:

- Finish the testing program on the dam filter materials,
- Interpret results from all testing,
- Summarize all components of the research, and
- Submit a final report wrapping the entire scope of the research.

Investigation of Surface Deformation in Column-Supported Embankments

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Sponsors: National Science Foundation, U.S. Department of Education
Start/Completion Dates: January 2006 / May 2010

Project Background

Geosynthetic-reinforced, column-supported embankments have been used in soft ground conditions when there is a need to accelerate construction and/or protect adjacent facilities from the settlement that would otherwise be induced by the new embankment load. For instances when the embankment height is short relative to the clear spacing between adjacent column, there is the risk of surface expression of the differential settlement that occurs between the columns and the soft soil at the foundation level. Currently, there is no consensus regarding procedures to design embankments to be safe against such surface deformation.

Project Objectives

The purpose of this research is to explore the mechanisms of surface deformation in column-supported embankments. The approach to the research consists of a combination of physical and numerical modeling of the deformation that occurs within an embankment when differential settlement occurs between the columns and the soft soil at the foundation level. The ultimate goal of this research is to develop a set of design guidelines that mitigate the risk of this type of surface deformation.

Research Accomplished

A bench-scale test apparatus has been developed to study the relationship between surface deformation and differential settlement of the foundation for a variety of testing conditions. The apparatus consists of a circular open tank with an inside diameter of just over 22 inches. To simulate differential settlement at the foundation level, the tank has an opening in the bottom that allows a single 3 inch diameter piston to be penetrated into the soil sample representing the embankment material. The piston is instrumented to capture the magnitude of penetration as well as the load acting on the piston. The displacement of the piston is controlled by a motorized jack that advances the piston into the base of the soil sample at a rate of about 1 inch in 20 minutes. At various increments of penetration, the piston motion is stopped and the surface of the sample is scanned using a profiling device that consists of a non-contact laser distance transducer and a string-pot sensor. The laser device measures the distance from the instrument to the sample surface and the string-pot measures the horizontal position of the laser. The profiling system is capable of capturing the shape of the sample surface with a high degree of accuracy and resolution at four orientations around the circular sample tank.

Light Castle sand was selected for use as the sample material based on its well-understood soil properties. This manufactured sand classifies as poorly-graded sand (SP) according to the Unified Soil Classification System (USCS), which is outlined in ASTM D-2487. The samples were prepared dry at selected relative densities using the technique of air pluviation. For this application, air pluviation was accomplished by empting sand from a hopper through a disk with a known porosity. From the hopper, the sand freefalls a distance sufficient to achieve terminal velocity before striking a pair of diffuser screens. Below the diffuser screens, the sand again reaches terminal velocity before coming to rest in the tank. The relative density of the sand was controlled by varying the porosity of the hopper disk.

In addition to testing samples of different height and relative density, the apparatus includes a vacuum system that provides the ability to test samples at sub-atmospheric conditions. The system is capable of applying up to 425 psf of equivalent overburden pressure on the surface of the sample. In order to maintain sub-atmospheric conditions within the tank, a latex membrane is placed at the sample surface and sealed against the inside walls of the tank. The vacuum is applied and monitored through separate ports located at the bottom of the tank.

The presence of geosynthetic reinforcement in the sample is also being investigated. Three types of biaxial polypropylene netting with different tensile stiffnesses were selected for use as the geosynthetic reinforcement. The netting was selected based stiffness and aperture size criteria determined to be appropriate by approximate application of scaling laws for a 1:10 to 1:20 scale model. The influence of reinforcement stiffness on surface deformation is investigated by changing either the stiffness or number of the reinforcement layers. The bottom layer of reinforcement is placed ½ inch above the base of the sample with ½ inch separating any overlying layers.

Key Findings

Shape of surface deformation: The surface deformation produced by penetration of the piston resembles a circular dimple. The results of the testing indicates that as the sample height and/or relative density of the sample is increased, there is a corresponding linear increase in the radius of the dimple formed at the sample surface. The magnitude of piston penetration does not appear to influence the radius of the dimple, but does increase the height of the dimple. The ratio of the dimple height to the piston penetration is shown to be constant for a given sample height. As the sample height increases, the ratio of dimple height to piston penetration magnitude decreases.

Piston load-displacement relationship: As the piston is penetrated into the base of the sample, there is a sharp increase in the load registered on the piston. At a certain magnitude of penetration, the load peaks and then declines to a stabilized post-peak load value. The penetration magnitude required to reach the peak load on the piston increases as the mean effective stress level in the sample increases, either due to increasing sample height or applying a vacuum pressure. The penetration magnitude at peak load ranges from about 0.02 to 0.2 inches for the tests conducted so far. For stabilization of the post-peak load, it appears that the corresponding penetration magnitude increases as the sample height is increased. For the tests conducted under atmospheric conditions, the magnitude of the post-peak load approaches the estimated weight of the wedge of soil displaced by the piston.

Influence of geosynthetic reinforcement: The presence of geosynthetic reinforcement has not been shown to influence the shape or retard the development of surface deformation. For testing under atmospheric conditions, the presence of reinforcement increases the magnitudes of the peak and post-peak piston loads. There is no clear corresponding relationship for testing under sub-atmospheric conditions. The stiffness of the reinforcement has not been shown to influence the shape of the surface deformation or the piston load for the cases studied so far.

Future Work

The next phase of the physical modeling program will be the investigation of the effects of an array of pistons on surface deformation. The results of the physical testing program will provide valuable information for the development, calibration, and verification of the numerical model.

Aging of Sand

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Start/Completion Dates: August 2007 / December 2011

Project Background

Recent laboratory and field studies show that soil properties of freshly deposited and disturbed granular materials change over time at constant effective pressure and with little or no change in void ratio, a process known as aging. This process has been evidenced as a time-dependent increase in penetration resistance, liquefaction resistance and stiffness; and a reduction in the compressibility of the soil.

Aging effects have not been incorporated into practice due to the lack of reliable methods to predict their quantitative effects on soil properties. In order to account for aging in engineering design two important concerns have to be solved: (1) what is the rate at which a given soil property changes with time?, and (2) what is the magnitude of that change?

This project was developed as an outgrowth of the preparation of a state-of-the-art and practice paper on aging processes titled "Aging of Sand – A Continuing Enigma" written by Dr. James K. Mitchell.

Project Objectives

The purpose of this research is to develop methods to estimate the rate and magnitude of change in soil properties due to aging in granular materials. Possible mechanisms responsible for aging have been assessed based on the compilation and analysis of available data. The principal factors that influence aging are to be defined in order to determine the general behavior of the granular material during this process. Once the mechanism is understood, a model based on interparticle interactions will be developed to predict the aging effects on soil properties. The results will be compared with those reported in literature.

Research Accomplished

- **Rate and Magnitude of Aging Reported in Literature**

Available information concerning the rate and magnitude of change in soil properties during aging in granular soils was compiled and analyzed. The increase in any specific property was normalized by its initial value at the end of primary consolidation following its deposition or densification. Comparison of the results shows that there can be a marked increase in soil properties such as initial shear modulus, cone penetration resistance, standard penetration resistance, cyclic shear strength and pile shaft capacity (driven piles). In many cases a certain soil property may as much as double during the first year after deposition or densification without measurable decrease in void ratio. Available data shows that there is great variability among the results obtained or predicted by different investigators.

- **Aging Mechanism**

Four possible aging mechanisms have been reported: (1) chemical processes such as dissolution and precipitation of silica or other materials, (2) micro-biological processes, (3) physical processes involving particle rearrangement, and (4) a combination of the above.

Chemical processes such as dissolution and precipitation of silica producing cementation were discarded as a main cause of aging in sands, given that the levels of dissolution and precipitation of quartz are too small to account for any significant increase in soil resistance. Micro-biological processes may generate beneficial changes in soil properties, but, in order to develop, special conditions such as large amounts of bacteria and a constant flow of nutrients are required. It is very unlikely that this type of process could be responsible for the aging effects evidenced in the field.

While chemical processes and micro-biological activity may be involved up to a certain level in the results observed (depending on environmental and compositional factors), it was found that time-dependent physical processes involving particle rearrangements and stress redistribution under the new in-situ stress conditions after disturbance are the main cause of the time-dependent behavior observed during aging.

Key Findings

Many field observations have demonstrated the existence of an aging process that follows deposition or densification of granular soils. This process results in an increase in mechanical properties such as stiffness, penetration resistance and liquefaction resistance. It was concluded that physical processes involving particle rearrangement and stress redistribution are the main cause of this behavior.

Physical processes during aging involve particles sliding or rotation to obtain a more stable structure; this process is performed with very little resulting change in void ratio. The mechanism is very similar to creep, where particle rearrangement is carried out under constant effective stress. The process is controlled by particle interaction and interparticle force redistribution. The resulting structure cans exhibit metastability, similar to sensitibity in clays.

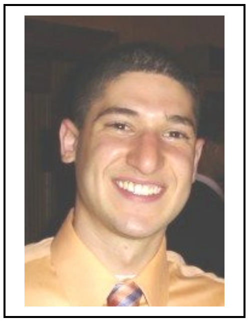
Initial stiffness of granular soils may increase by about 10 to 30 percent per log cycle of time as a result of aging after deposition or densification. Penetration resistance may also increase with time; reports show that cone penetration resistance increases by a factor of about 1 to 3 during the first year after deposition or densification. Aging does not have any significant impact on ultimate strength of granular soils, as the aged structure of sands is destroyed under large deformations.

Following Studies

In order to develop better predictive tools for the aging effects in granular materials a model that describes these processes quantitatively will be developed. The initial approach will be to test the use of discrete elements as a method to model time-dependent changes in particle arrangement and its correspondent effects on soil characteristics.

Discrete element models permit an estimate of changes in soil structure with time. Methods to transform particle scale quantities such as these to a macroscopic scale have to be established in order to calculate their effect on soil properties such as stiffness. This will allow to more reliably predict the rate and magnitude of change of mechanical properties of the soil experienced during aging.

Geotechnical Solutions for Soil Improvement, Rapid Embankment Construction, and Stabilization of the Pavement Working Platform



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Sponsors: National Cooperative Highway Research Program
Strategic Highway Research Program

Project Duration: August 2007-August 2011

Project Background

Although in existence for several decades, many ground improvement technologies face both technical and non-technical obstacles preventing full utilization in geotechnical engineering practice. To aide in the advancement of these technologies, the Strategic Highway Research Program Project Number R02 (SHRP2 R02) is investigating the state of practice of soil improvement, and it will assess ways in which these technologies may be exploited to their full potential. Several researchers and consultants from around the country are involved in this project effort.

Project Objectives

The objectives of the Strategic Highway Research Program are to promote the rapid renewal of transportation facilities, minimize the disruption of traffic, and produce long-lived facilities. Specific to project number R02, focus has been placed on ground improvement technologies that meet these objectives and have potential to contribute to new embankment and roadway construction, the widening of existing embankments, and the stabilization of pavement working platforms. The goal of the project is to assess these technologies and overcome any identified obstacles that prevent their widespread use in practice.

Results and Work Products

Several resources have been developed to aid in the assessment of the 46 ground improvement technologies identified as meeting project objectives. These resources include a literature review database currently containing over 400 documents, a survey that collected expert opinion on each of the technologies, and an extensive list of contacts in the field. A workshop was held in December 2007 in Atlanta, GA to review these resources and discuss the technical and non-technical obstacles facing ground improvement technologies. A sampling of the technical obstacles includes the lack of design method, poorly defined performance criteria, and inadequate QA/QC procedures. Non-technical obstacles were found to include a general lack of knowledge about a technology, a state DOT structure non-conducive to adopting new technologies, and proprietary processes.

Future Research

Remaining work on the project involves the development and testing of techniques to mitigate the obstacles impeding widespread use of ground improvement technologies. This will include review, refinement, and/or development or new design procedures, QA/QC methods, construction specifications, educational materials, and cost estimating tools. The result of the work will provide public agencies with easy, accessible, and comprehensible tools to facilitate ground improvement solutions to geotechnical problems in transportation construction.

Reliability in Geotechnical Engineering

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Sponsor:	CGPR
Start/Completion Date:	August 2007/February 2008

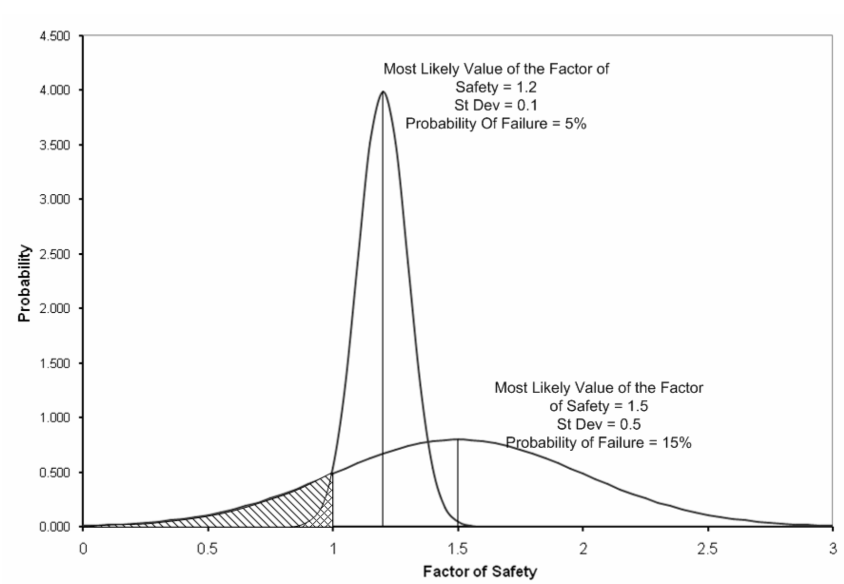
Project Background

A previous CGPR manual, Reliability in Geotechnical Engineering, has been revised and updated. The new manual includes several examples and four methods for calculating the probability of failure, three of which were not included in the previous manual. In addition, a new chapter titled, The Language of Statistics and Probability, is included in the manual. The methods used to calculate the probability of failure are explained with several example problems.

Approach and Results

The previous CGPR manual, Reliability in Geotechnical Engineering, focused on using the Taylor Series method to calculate probability of failure. The new manual includes the Taylor Series method and also the Point Estimate method, the Simplified Hasofer Lind method, and the Monte Carlo Simulation method to calculate the probability of failure.

The Language of Statistics and Probability chapter includes a set of definitions that explains common terms used in reliability calculations. For example, the figure below shows two different distributions of the factor of safety. The two distributions have different values of standard deviation. The lower narrow distribution, with a smaller standard deviation, corresponds to a lower probability of failure, even thought the factor of safety is smaller. This shows the importance of uncertainty in the variables involved in the computation of factor of safety.



All of the methods used in the manual are explained with the use of the same, simple retaining wall example problem. Using the same example problem for all the methods allows for easier comparison of the methods. In addition to the retaining wall example, a slope stability and seepage example problem are provided to aid in understanding the methods.

Seepage Monitoring Practices and Techniques

Students: Matthew Sleep

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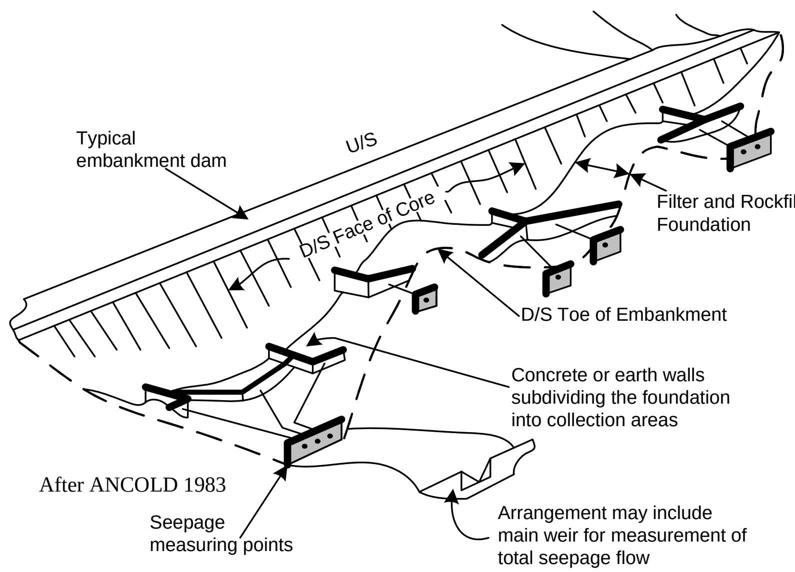
Sponsor: United States Army Corps of Engineers and CGPR

Start/Completion Date: August 2007/February 2008

Project Background

A report has been completed as a CGPR publication titled Seepage Monitoring Practices and Techniques. The report was written for the United States Army Corps of Engineers to assist in the development of a seepage monitoring report for FEMA.



Project Objectives

In response to a request from FEMA to the U. S. Army Corps of Engineers Research and Development Center in Vicksburg, a draft report has been prepared summarizing desirable practices for seepage monitoring. The report summarizes different methods to monitor the location, quantity, and condition of seepage in dams. Reviewed were the guidelines of several different federal agencies as well as state agencies on how to monitor seepage in dams.

Seepage Monitoring

Seepage monitoring is an essential aspect of protecting a dam from failure due to erosion and piping. Knowing if and when a dam is deteriorating due to erosion and piping is an important aspect of determining the need for repairs or modifications

The most important aspect of seepage monitoring is visual inspection. Included in the report are several examples of visual inspection checklists which can be very helpful for dam owners. Visual inspections can locate areas of seepage in dams as well as help in determining if the seepage threatens the safety of the dam.

Also discussed are instrumentation, geophysical methods, and methods of evaluating data from these types of measurements. Instrumentation can monitor seepage quantity and pressure, both useful quantities for evaluating seepage, and changes in seepage over time.

In addition to seepage monitoring, the report summarizes methods to calculate risk and consequences from dam failure. Because failure due to erosion and piping is often rapid once it begins, having an effective monitoring plan is essential to a dam safety program.

Levee Seepage Berm Design Spreadsheet

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Sponsor: United States Army Corps of Engineers and CGPR

Start/Completion Date: August 2007/February 2008

Project Background

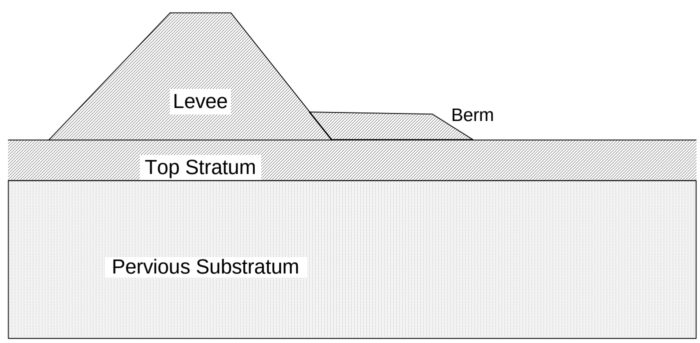
An Excel spreadsheet has been developed that can be used to determine the factor of safety against erosion and piping at the toe of a levee. The spreadsheet can also be used to determine the appropriate dimensions and type of seepage berm to increase the factor of safety. This spreadsheet was developed for the United States Army Corps of Engineers in conjunction with a proposed revision to the Engineering Manual 1110-2-1913 The Design and Construction of Levees.

Project Objectives

Seepage berms protect levees from erosion and piping due to underseepage. The Corps of Engineers Engineering Manual 1110-2-1913 Design and Construction of Levees provides equations for the design of seepage berms. The equations are difficult to use and to interpret. The seepage berm design spreadsheet can be used by engineers to aid in the determination of the factor of safety against erosion and piping at the toe of a levee and also the design of seepage berms.

Approach and Results

As part of the original project to update EM 1110-2-1913 Design and Construction of Leves, the equations presented in the engineering manual were incorporated into a seepage berm design spreadsheet. This spreadsheet provides a means of calculating the factor of safety at the toe of a levee against erosion and piping. Seven different cases are presented in EM 1110-2-1913. Each of these seven cases is programmed into the spreadsheet.



Depending on the calculated factor of safety, a seepage berm or other remedial measure may be needed. Four different seepage berm types (impervious, semipervious, sand, and pervious with collector) are included in the spreadsheet. The spreadsheet allows the user to calculate the dimensions of a seepage berm (both length and thickness) to increase the factor of safety to a desired level at the toe of the levee and also at the toe of the seepage berm. In addition, seepage berm dimensions can be entered into the spreadsheet and the factor of safety at the levee toe and the toe of the seepage berm can be calculated.

Identification of Expansive Clays using Field Spectroscopy

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Start/Completion Dates: August 2004/August 2008

Project Background

The International Building Code (IBC) requires that fine-grained soils underlying foundations be tested for expansion potential and stipulates that ASTM D4829 *Expansion Index of Soils* be run if swelling soils are likely to be found. According to the US Corps of Engineers, these soils occur frequently in roughly half of the United States.

ASTM D4829 is perhaps not well-suited for use as a diagnostic test because it is time consuming to set up and run, frequently taking several days in the authors' experience. In addition, the test returns only a relative expansion index that indicates whether or not further testing in necessary. Soil property values that can be used in design require additional testing be performed. Therefore a more rapid procedure for diagnosing the presence of expansive soils would be very beneficial.

Project Objectives

This research evaluated field reflectance spectroscopy as an alternative to ASTM D4829 with the goal of rapidly correlating field spectral signatures to expansive index and weighted plasticity index. Reflectance spectroscopy takes advantage of a material's light reflecting property. This property is a function of the specific chemical components within a material; they combine to create a unique reflectance profile, or spectra signature, of the material. Numerous spectroscopic techniques are used in the laboratory, and increasingly in the field, by chemists, materials scientists and geoscientists to identify a wide range of materials. Since a material's spectral signature is largely a function of it's chemical composition, any material property that is also dependent on chemical composition should be correlated directly to spectral signatures.

Methods

A sample set of 21 natural and artificial soils was used in this study. The natural soils all occur in southwestern Virginia, and the artificial soils were mixed from industrial clays and natural soils to provide a wide range of expansion indices. The expansion index, weighted plasticity index, and spectral signatures were found for the soils in the sample set, and mathematical correlations between the spectral signature, and the expansion index and weighted plasticity index were sought. The spectrophotometer used in this study is fully field portable.

Main Findings

It was found that excellent correlation exists between the near-infrared spectral signatures, and expansion indices and weighted plasticity indices of the soil samples tested. A variety of mathematical data pretreatments were used; the quality of the correlation was found to depend on these pretreatments.

The best results were found by applying a second derivative pretreatment to the spectral data, then using regression to correlate spectra to expansive index and weighted plasticity index. This combination of pretreatment and regression yielded a prediction model for which the correlation coefficient (R^2) was greater than 0.9.