"Best Practices" for Site and Soil Characterization

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Sponsor: CGPR

Start/End Date: August 2007 / January 2009

Objective

The objective of this project was to develop a guide that will be useful as a resource for entry level geotechnical engineers, and will serve more experienced engineers as a checklist and convenient source of references for geotechnical studies. It may also prove useful in communications with clients and potential clients with regard to the appropriate scope of geotechnical studies.

Format

The format of the guide was chosen to provide an efficient means of locating sources of information. The guide provides an expanded checklist of topics that are important in soil and site characterization, and references to useful information on these topics. The cited sources include specific page numbers, making it possible for the reader to locate the relevant information quickly and efficiently.

The guide is not intended to be a stand-alone source of information. Rather, it is a guide to useful sources of information that can be found in engineering manuals, textbooks, and professional papers. Collecting those references, and having them readily available, is itself a "best practice."

Scope

The guide is divided into topics covering the pervasive issues for geotechnical site and soil characterization. These divisions and an explanation of their scope are:

- **BENEFITS OF THOROUGH SITE CHARACTERIZATION** discusses communicating the benefits of thorough site characterization with clients and the risk of inadequate site characterization.

- **SITE CHARACTERIZATION PROCEDURES** discusses desk studies and field studies used to characterize sites.

- **SOIL CHARACTERIZATION** discusses correlations and laboratory tests used to determine the characteristics of soils, as well as the essential content of soil descriptions.

- **HAZARDS ASSOCIATED WITH VARIOUS SOIL TYPES** discusses particular geotechnical hazards associated with various soil types.

- **CONSTRUCTION CONSIDERATIONS** discusses the importance of constructability and the impacts of various construction activities.

- **CONTRACTS FOR GEOTECHNICAL SERVICES** discusses reducing risk through properly written contracts.

- **INSTRUMENTATION AND PERFORMANCE MONITORING** discusses the importance of monitoring performance and monitoring equipment.

Seismic Design of Retaining Walls

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Sponsors: Center for Geotechnical Practice and Research

Start/Completion Dates: August 2008/December 2009

Project Background

Incorporating seismic considerations into retaining wall design is often necessary to reduce the risk of catastrophic damage and loss of life. Guidelines outlining the design of retaining walls for static loading are frequently used by practicing engineers. Additionally, numerous studies have been conducted recently examining the loads and/or displacements of various types of retaining walls subjected to earthquake motions. However, no practice-oriented manual exists that concisely and consistently summarizes the results of these studies.

Project Objectives

The purpose of this research is to develop a practice-oriented design manual for the seismic design of retaining walls. The manual will consolidate the extensive research and design procedures into one concise reference. The design manual is expected to be a companion to existing guidelines for the static design of retaining wall systems.

The manual will present a summary of the theories for predicting the loads and/or displacements of several retaining wall systems. The types of retaining walls that will be addressed will include gravity, cantilever, tie-back, reinforced earth, and rigid building walls. The procedures to determine the seismic design requirements will be presented in detail for each type of retaining wall system. Furthermore, sample problems will be provided to illustrate the design procedures.

Finally, the manual will include instructions for the determining design ground motion parameters. The manual will outline how to obtain and interpret seismic hazard data for a site of interest from the USGS web-based program. The information from the USGS can then be used to determine the design ground motion inputs used to design retaining walls.

Research Accomplished

- **Literature Review**

A review of research papers/reports on the seismic response of retaining walls has been started. The various procedures and theories that are applicable to individual wall systems have been reviewed. The degree of yielding that various retaining wall types can undergo greatly influences the equations that govern wall stability. Consequently, design procedures are dependent upon wall type. The determination of which design procedure is most appropriate for a given wall type has received considerable emphasis. For example, the use of the commonly used Mononobe-Okabe procedure has often been erroneously utilized for retaining walls which do not meet the procedure’s inherent assumptions. Also, significant focus is being placed on the displacement based design method for gravity retaining wall systems.

Key Findings

The project is still in the early phases and no there are no key findings to report at this time.

Remote Sensing for Landslide Monitoring and Early Warning Systems

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Project Background

The use of remote sensing for monitoring ground deformations is gaining wider use worldwide. Landslides and levee failures are examples for situations where a monitoring system enhances the decision making process. Conventional monitoring, or surveying, methods are costly and can be inefficient for large scale monitoring of geo-hazards before and after a disaster. Satellite-based synthetic aperture radar (SAR) technology, as an example for remote sensing, provides a new tool to monitor ground surface displacements as small as 1mm, for large areas and even when conventional methods could not be used effectively.

SAR technology was first was developed during World War II to track aircrafts and ships during bad weather and at night. SAR systems can be ground-based, plane-based, or satellite-based. Since its inception, SAR has greatly improved and is now being applied to problems far beyond those initially conceived. Advances in radio-frequency technology and signal processing have been primarily responsible for these improvements. Using advanced methods such as the Persistent Scatters (PS) approach, satellite-based SAR can now detect ground displacements as small as 1 mm that have occurred since the satellite last scanned the area.

Project Objectives

The purpose of this research is to utilize remote sensing technology, especially SAR, to monitor landslides in near real-time environment and finally to develop an automated GIS based risk assessment and automated warning system.

Research Plan

Several active landslides are being studied on a pilot scale basis to implement early warning systems. Two of these landslides are located in Romania, one of these in Sinaia and the other in Sacele. Sinaia landslide is located within a mountain resort area with expensive real estate and ongoing development. The movements in this area are measured at 2-3 ft/year. The Sacele slide involves the movement of a 150 m high slope behind the water intake tower of an earth dam. The dam is 35 meters in height and provides water for about 1 million people living downstream. The slide behind the water intake tower coupled with the high seismicity of the region poses a significant threat. The third slide is located near Cairo, Egypt and involves a vertical rockface about 100 meters in height. The landslide prone area extends several kilometers in length and poses a threat to the people living up and down hill. The last landslide that occurred on September 6, 2008 killed several hundred people. The early warning systems for these landslides will involve a weather station to monitor precipitation, manual and automated inclinometers and surface displacement measurements with remote sensing.

Removal and Replacement beneath Shallow Foundations

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Start/Completion Date: August 2008/May 2009

Project Background

Removal and replacement is often used to deal with soft soils encountered during the construction of shallow foundations. Current practices are based on local experience and judgment, and involve removing the soft soil and replacing it with a stiffer material. Despite this wide-spread use, there appears to be a lack of standardized procedures for decision-making and construction.

Project Objectives

The intent of this report is to provide guidance for decision-making in the event pockets of soft soils are encountered during construction. Recommendations for removal extent and selection of replacement materials will be provided.

Research Accomplished

- **Literature Review**

  Literature reviews conducted by Andrew Bursey and Kurt Schimpke indicated that few standards for the implementation of removal and replacement exist, emphasizing the need for this research. Discussion of removal and replacement in the literature is limited to general recommendations, rather than standardized procedures.

- **Decision-Making Flowcharts**

  Flowcharts were developed to assist in the decision-making process. These flowcharts provide a step-by-step method for implementation of removal and replacement, and can be used either in the field or the office. Separate flowcharts were developed for two scenarios: soft soils identified during site investigation and soft soils identified during construction.

- **Investigation of Replacement Materials**

  Virginia Department of Transportation (VDOT) aggregates 21B and #57 and flowable fill were investigated as possible replacement materials. General information for each material was compiled, and recommendations for material selection will be provided.

- **Spreadsheet Solution for Removal Depth**

  The critical depth concept was used to develop recommendations for removal depth. The critical depth is the point at which the induced stress is 10% of the initial overburden pressure. It is assumed that all compression occurs at or above this depth. Determination of the critical depth and the use of relative compressibilities of the soft soil, design soil, and replacement material allow the user to determine an appropriate removal depth. This can be done using a spreadsheet solution, which will be included with the report. If relative compressibilities cannot be estimated, the removal depth should extend to the minimum of the critical depth or the depth to a firm stratum, whichever is less.

Future Work

Upcoming work will focus on further development of the spreadsheet to make it versatile and user-friendly. A concise report summarizing the method will also be prepared.

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/or disturbed granular materials can 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 by time-dependent increases in penetration resistance, liquefaction resistance, and stiffness; and a reduction in the compressibility of the soil.

Aging effects have not yet been routinely incorporated into practice quantitatively due to the lack of reliable methods for predicting their 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? Current understanding of aging phenomena is summarized in the paper, “Aging of Sand – A Continuing Enigma” by J. K. Mitchell, 2008.

Project Objectives

The objective of this research is to develop methods to estimate the rate and magnitude of changes in soil properties due to aging in granular materials. Possible mechanisms have been assessed based on the compilation and analysis of available data. The principal factors that influence aging are defined in order to determine the general behavior of the granular material during this process. A Discrete Element Model (DEM) based on interparticle interactions is being developed to predict the aging effects on soil properties. The results will be compared with those reported in literature and obtained from laboratory testing.

Research Accomplished

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

The increase in value of any specific property was normalized relative to its value at a specific time, usually 1000 minutes, following its deposition or densification. Comparison of the results shows that there can be an increase over a log cycle of time ranging from a few percent to more than 100 percent in initial shear modulus, cone penetration resistance, standard penetration resistance, cyclic shear strength and pile shaft capacity (driven piles).

- **Aging Mechanism**

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

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.

- **Discrete Element Model**

A Discrete Element Model based on particle interactions was developed in order to predict the rate and magnitude of change in soil properties, such as stiffness and dilatancy, during aging. The DEM uses the software OVAL, written by Dr. Matthew Kuhn, of the University of Portland.

Air pluviation of particles was simulated using the software MAYA, in order to obtain initial particle arrangements that resemble those of freshly deposited sands. These arrangements were then subjected to an isotropic confining stress, allowed to age, and sheared (const. vertical rate of strain and const. lateral stress). In the model aging is manually induced by increasing drastically the viscosity of the dashpot in the particle contact model during the application of the isotropic confinement, to later return it to its real value before shearing.

- **X-Ray Computed Tomography**

X-Ray Computed Tomography (CT) scanning was used to detect possible particle rearrangement in granular samples subjected to constant vertical effective stress and restrained lateral strain. The samples were prepared by air-pluviation of sand into a 4 cm tall by 1 cm diameter cylinder. The sample was then placed into the CT scanner, and a constant vertical stress of 62 kPa was applied for up to 7 days. Images were obtained at different times during the aging period.

Key Findings

Although the 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, aging does not have any significant impact on ultimate strength, as the aged structure of the sand is destroyed after large deformations.

Results from the DEM show a small increase in the stiffness and dilatancy of the sample with aging, with no significant change in the ultimate strength. These changes in macroscale properties in the DEM were caused by the stress redistribution at interparticle level, evidenced by an increase in number of interparticle contacts and the appearance of stronger load chains during aging. Particle rearrangements, if they have occurred are small, as they have not yet been detected, either in the discrete element model or by using X-Ray CT scanning.

Following Studies

Further study is needed to achieve simulations that properly predict the magnitude and rate of change in soil properties with time during aging. For this purpose, rate theory is currently being introduced into the DEM model to provide a more realistic time dependent model than can be obtained by simple variations in the viscosity of a dashpot. This model will be calibrated using aging data from laboratory tests and field observations on real sands.

The response of samples composed of smaller diameter particles, and different particle compositions, under X-Ray CT scanning, is currently being studied in order to obtain better resolution in the 3D reconstructions and avoid possible interference of boundary effects.

Bio-inspired Soil Silicification

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Project Involvement Period: August 2008/December 2009

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Project Sponsor: National Science Foundation, Geomechanics and Geotechnical Systems Program

Project Start/Ending Dates: February 2008/January 2011

Project Background

The geoconstruction and mining industries have employed sodium silicate grouts in ground treatment for more than 50 years. Silicate grouts are pure solutions which are injected into soil with the purpose of cementing soil particles together and improving the engineering properties of the soil mass. Binding occurs through a chemical reaction where liquid sodium silicate polymerizes into a relatively strong hydrous gel, bonding the soil grains together and filling void space. Gelling is brought about through the use of organic and inorganic reactants, some of which have proven to be harmful to humans and the environment.

The goal of this project is to develop a new type of soil treatment method that is environmentally sustainable and nonhazardous. The *silicification process* uses recent research results on how marine organisms create their silica-based shells and skeletons from the dilute concentrations of silica available in ocean waters. The method consists of first introducing a macromolecule solution followed by injecting a sodium silicate solution. This technology has a number of potential advantages over current silicate grouting methods: 1) Uses readily-available, inexpensive and environmentally benign chemical materials; 2) Creates a cemented and strengthened soil whose improved properties may be tailored to specific geomechanical performance problems; 3) Does not require changes to soil and groundwater chemistry because the process proceeds within the pH range of most natural subsurface environments; and, 4) Never needs to use or maintain actual organisms.

Research Approach

The overall objectives of this research project include:

1. Conduct basic laboratory research using the silicification process to determine practical ranges of chemical components and their concentrations. Characterize the in-situ microstructure and distribution of cement in the sample using x-ray tomography and optical microscopy methods.
2. Assess basic geomechanical behavior of silicified sands using a laboratory testing program consisting of unconfined compression, triaxial compression and creep tests.
3. Evaluate the potential for a biomimetic self-healing effect, the strength of the cement and the strength of the cement to grain bond.

Accomplishments to Date

Silicification Material Development

The project's first year focused on selecting chemical components, designing optimal component concentrations and determining the mechanical properties of the silicified soil. This research consisted of preparing a series of Ottawa 20/30 sand specimens in accordance with ASTM 4320 over varying macromolecule and silica grout compositions.

Sand is pluviated into 2 inch inside diameter split molds creating a dense sample. The ends of the molds are capped and the assembly is held together by stainless steel nuts and threaded rods. Plastic elbow fittings are then connected to ports on the top and bottom caps to allow flow of the grout components.

Specimens are treated from the bottom to the top under approximately 18 inches of gravity head from bulk reservoirs. The soil is first saturated with pure water, and then a macromolecule solution is allowed to permeate the specimens. Outflow from the specimens is accumulated in a beaker and returned to the reservoir for at least three repeated treatments to insure uniform distribution of the macromolecule. Finally, a sodium silicate solution is prepared and allowed to permeate the specimen. At this point the soil is saturated with solution and drainage from the top and bottom is not allowed. Specimens are "cured" for a minimum seven days, then extracted and tested in unconfined compression to determine the effectiveness of the mix relative to control samples.

Key Findings

Unconfined tests on grouted samples of Ottawa sand indicate that the silicification method produces high strengths with respect to both traditional and other non-traditional grout mixtures at the same or higher silicate concentrations. Unconfined compressive strengths of 30 psi and 25 psi are obtained in silicification experiments using 25 percent and 20 percent sodium silicate by volume, respectively. For comparison, the unconfined compressive strength of specimens of the same sand grouted with a traditional mixture composed of 20 percent sodium silicate, 5 percent formamide and ethyl acetate is about 10 psi. Strengths appear to be developed in 7 days or less.

Future Work

Research in the second project year involves an extensive investigation into the geomechanical properties of silicified soils. This will include silicification, curing and testing of samples under a confining pressure in a triaxial cell. The effects of relative density, grout composition and confining pressure on the grouted soil strength will be determined. Comparisons will be made between grouted and ungrouted soils to determine the effect of the silicification process on stress-strain-strength behavior.

In addition tests will be performed to determine the impact of silicification on hydraulic conductivity. Hydraulic conductivity is important to many ground improvement operations and these results will provide an indication of the applicability of soil silicification for water cutoff improvement operations in addition to applications for stability and strength.

Updating USACE EM 1110-2-1913 Seepage Analysis Methods (including Blanket Theory)

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Start/Completion Dates: December 2008 / August 2009

Project Background

EM 1110-2-1913, *Engineering and Design Manual for the Design and Construction of Levees*, is currently being revised to incorporate lessons learned from the events of Hurricane Katrina and to bring the manual up to date. The revisions will address the design seepage criteria for levees, with a focus on incorporating new seepage analysis procedures. The methods detailed in Appendices B and C for the mathematical analysis of underseepage and substratum pressure, and the design of seepage berms, is based on the *Blanket Theory* by Bennett (1946). These equations were developed during a Waterways Experiment Station (WES) study of underseepage and seepage control of the lower Mississippi River levees. There have been few changes to this method since the initial adoptions, but recent failures of levees during Hurricane Katrina have prompted the revision due to its wide use across the USACE districts for seepage evaluation and design of levees.

There are no published proofs of the derivations of equations present in the engineering manual. Therefore, it is desirable to document the derivations and to make corrections where necessary. In addition, there are several simplifying (and sometimes limiting) assumptions made in the derivation of the equations. These include considering the foundation as 2-layer model, consisting of an impervious substratum above a pervious substratum of uniform thickness and permeability. These assumptions may not be appropriate for many cases, thereby reducing the applicability of the blanket theory equations for certain geometries encountered. There is a need for other methods to be used for performing the seepage analysis, with guidelines for their application in the revised engineering manual.

A readily applicable method is the finite element method with commercially available software. This method reduces the limitations of the blanket theory and provides added flexibility to effectively model different foundation conditions. The California Department of Water Resources (DWR) already requires the use of the finite element method as primary means for seepage analysis, and allows blanket theory only as a secondary check. Therefore, the finite element analysis will included in the revision of the EM and guidelines will be provided for its use in seepage analysis.

Project Objectives

The purpose of this research is to document the derivations of the blanket theory and to check whether the equations are mathematically satisfied, and correct the equations if required. In addition, the results of blanket theory analysis will be compared to finite element analysis. A final goal is to provide guidelines for the use of finite element method for seepage analyses for the type of seepage cases which have historically been analyzed using blanket theory.

Adopted Approach

- Verify hand derivations of the blanket theory equations and formally publish these derivations for reference as published derivations of these equations are not available.
- Correct errors in the equations presented in Appendices B and C of the current EM.
- Perform comparison analysis on several design examples using the blanket theory and finite element method. This comparison analysis will be based on actual as well as hypothetical cross sections exploring various geometrical conditions.
- Develop guidance for advantages and disadvantages regarding the use of either blanket theory or finite element method based on the above comparison.
- Develop guidance for the use of the finite element method for seepage analysis for levee systems.

Research Accomplished

The literature review has been completed to allow a better understanding of the blanket theory equations. This includes the review of TM-3-424 (volume-1) and *Mathematical Analysis of Landside Seepage Berms* by R.A Barron. Relevant chapters of the textbooks *Groundwater and Seepage* by M. E. Harry; Seepage*, Drainage and Flow Nets* by Harry Cedergren; and *Flow of Homogeneous Fluids* by M. Muskat have been reviewed. In addition, hand derivations proved by Mr. D. Spaulding, formerly of the St. Paul District, have proved to be a valuable resource. Progress is being made on the verification of the derivations of the equations present in Appendix B of the Engineering Manual.

New and Emerging Technologies for Monitoring Seepage through Dams and Levees

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Start/Completion Date: January 2008/December 2008

Project Objectives

Approximately 1 in 200 dams fail as a result of piping and erosion, and 1 in 60 dams experience erosion and piping incidents that would result in failure if not mitigated (Fell et al. 2003). Most such failures and incidents can be prevented by monitoring seepage effectively.

The report includes a description of the near failure of A.V. Watkins Dam in Ogden, Utah in 2006. If not for the fortuitous presence and vigilance of a downstream landowner, the dam would very likely have failed. The incident illustrates the importance of effective monitoring of dams and levees.

Emerging Technologies for Detection of Seepage

The report supplements a previous CGPR report on conventional methods of seepage monitoring ("Seepage Monitoring Practices and Techniques," CGPR Report #47, December 2007). It focuses on new and emerging technologies that have potential for monitoring seepage in dams or levees automatically and remotely. Eight new technologies are described, one of which (DTSS) is being used to monitor seepage in more than 40 dams in Europe.

The report establishes ten criteria of the ideal seepage monitoring system, and uses these criteria as a basis for evaluating the eight technologies that were investigated.

The emerging technologies evaluated include:

DTSS (Distributed Temperature and Strain Sensor)
RTS (Robotic Total Stations)
GPS (Global Positioning System)
SAR (Synthetic Aperture Radar)
LIDAR (Light Detection and Ranging)
Electrical Resistivity
Change Detection
Thermal Imagry

The characteristics of these systems are described, and references are provided for each.

Analyzing LIDAR Data for Rock Mass Characterization Using a Fast and Simple Mesh-Less Technique

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Start/Completion Dates: May 2008 / May 2009

Project Background

Rock mass characterization is considered very important prior to excavation, and is used also for cost analysis, numerical modeling and many other design processes. Ground based LIDAR imaging is an emerging technology for rock mass characterization. The output from LIDAR is a point cloud consisting of millions of x, y, z coordinates of the 3-dimensional surface that was scanned. Due to high precision (is about ± 3-10 mm) speed, and accuracy, ground based LIDAR technology offers the potential for rapid and accurate surveys. There are a few software's, which help us evaluate the orientation distribution of the rock mass, but the process of triangulating the entire point set makes it a very complex and inefficient process.

Project Objectives

To suggest a new method for analyzing point cloud data obtained using a ground based LIDAR system, to determine the orientation distribution of a rock surface. The main application of this technique will be rock mass characterization and shear strength determination of rock fractures. The specific focus of the method is the measurement of rock fracture orientation and orientation distribution. To design a powerful data exploration tool with maximum flexibility and efficiency.

Research Accomplished

- **Study of current methods**

  The current surface meshing algorithms, which help us look at the orientation distribution of a given rock mass, triangulate on the entire point set. By triangulating, we are constraining subsequent analysis by the initial choice of triangulation mesh. As the point cloud data increases in size the speed of the process decreases. An attempt is being made to analyze the point cloud without triangulating (mesh-less).

- **Development of the Algorithm**

  Instead of creating of a triangulated surface mesh, the present approach generates a 2d custom grid of circles, with each such circle defining a right circular cylinder normal to the reference plane of interest. Data points in the point cloud that lie in a given cylinder are grouped together, and the best fitting plane for each such group of data points is determined. Cylinder radius and spacing and the grid origin and orientation are user-defined and can be adjusted as necessary. In fact, circle spacing need not be uniform but could be varied based on point density in the point cloud.

  This powerful data exploration tool is designed for maximum flexibility and efficiency. The technique allows the user to examine orientations, orientation distributions and variability on any selected scale, either in terms of absolute orientation or with reference to a selected reference plane.

- **Representation of Orientation Distribution**

  The dip and dip direction distribution of the rock mass is obtained by the application of the given algorithm. These results are represented in 2d in a couple of different ways. The dip direction is represented in color scale (R, G, B values scaled for dip direction varying between 0° - 360°). The dip values are represented as contour lines (varying from 0° - 90°). The dip direction & dip magnitudes are also represented as a vector field. The Origin (X, Y) of each such vector is the center of each circle defined on the 2d grid, the orientation being the dip direction and the length representing dip magnitude. This representation allows us to look at the entire data set and assess the overall characteristics of the rock mass and determine which parts are flat, dipping or steeply dipping.

- **Example for representation of results**

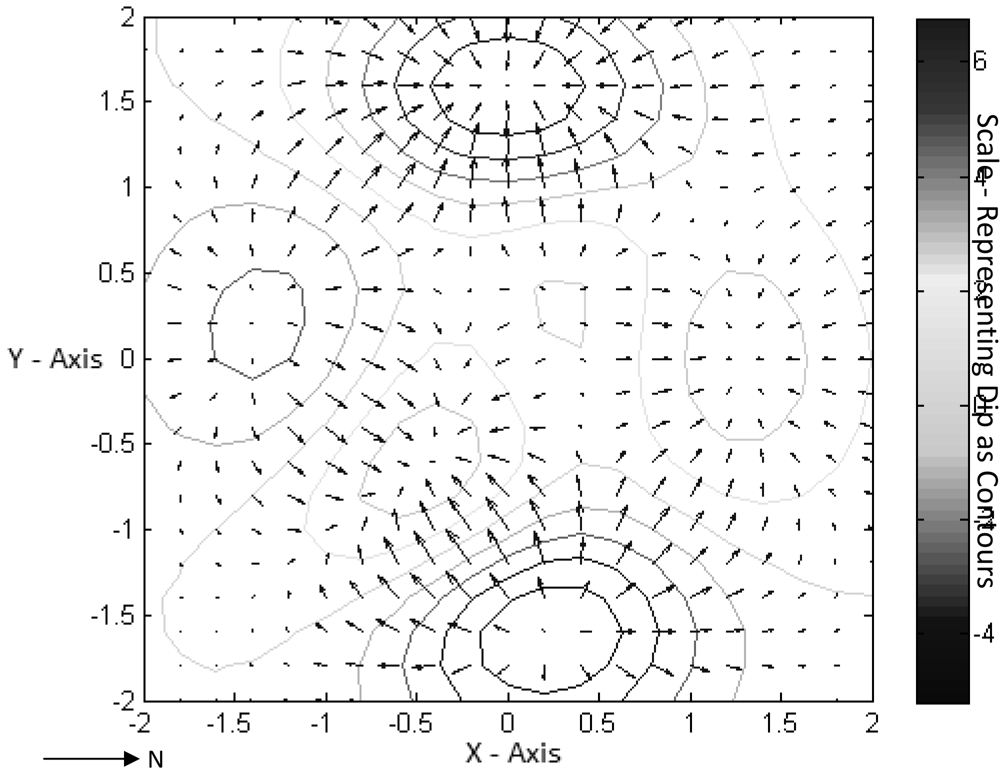

Fig. 1 Sample representation of results

In figure on we can see that the vectors represent both dip and dip direction and the contours represent the dip magnitude.

Cone Penetration Test Correlations in New Orleans Area Practice

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Sponsors: ERDC and New Orleans District, USACE

Start Date: January 2009

Project Background

The post-Katrina geotechnical explorations conducted in the New Orleans area represent the largest collection of high quality in-situ and laboratory tests ever collected in a specific geographic region. Soil property and strength data are currently being obtained using time-proven correlations that were developed for various soil types throughout the world. The large amount of high quality subsurface data collected in the New Orleans area gives us a unique opportunity to refine these correlations for use in geotechnical engineering practice in this geographic region. The analyses will attempt to increase the accuracy of soil properties and strength values for the alluvial and lacustrine deposits derived from in-situ tests.

Project Objectives

The objectives of this study are to refine the use of the cone penetration test (CPT) to determine soil stratigraphy and undrained shear strength. An attempt will be made to adjust the time-proven correlations to increase their accuracy in determining soil properties in New Orleans area practice.

Specifically, the first objective will be to refine and calibrate the current soil behavior type (SBT) classification chart developed by Robertson and Campanella (1983). Soil conditions in the New Orleans area consist of thick layers of organic clay, peat, and marsh soils; and the original Robertson and Campanella classification charts were developed predominately for mineral soils.

The second objective will be to develop a more precise determination of soil unit weights based on CPT results. Unit weights are often inferred from CPT data to be used to calculate total or effective vertical stresses at depth. These stresses are then used to calculate undrained shear strengths using N_k or N_{kt} methods.

The final objective of this study is to assess the N_c, N_k, and N_{kt} values for organic clays, peat, and marsh materials. Although typical ranges for these cone factors are readily available for mineral clays, scant data are available in the literature for organic rich soils. The goal of this objective will be to recommend values to be used to determine design strengths in the New Orleans area.

Research Plan

A spreadsheet is being developed to process cone data, both from the raw data files and from files output by commercial cone data reduction software. Particular sites have been targeted where both CPT and VST data exist for tests conducted by the Savannah District and the Vicksburg District. The Savannah and Vicksburg CPT crews exhibit the highest level of field testing prowess of any crews operating in the New Orleans area, therefore their data is considered to be of the highest available quality. After initial correlations are developed from their results, the data collected from other CPT crews will be assessed as well.

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., ≥ M5.5) in this region. Consequently, paleoseismic investigations are the most plausible way to determine the recurrence time of moderate-to-large magnitude earthquake 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.

Stability of Levees on Deep-Mixed Foundations

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

Start/Completion Date: May 2006/May 2010

Project Background

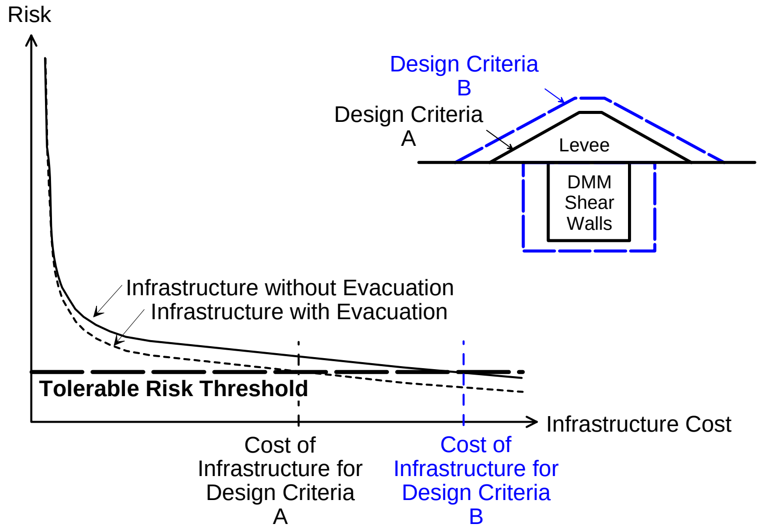
In the wake of the Hurricane Katrina levee failures in New Orleans, the engineering community has been working to apply new technologies and design methods to improve the performance of levee structures and the safety of hurricane protection systems. Deep-mixing-method (DMM) strengthening of levee foundations is a promising technology for strengthening existing levees constructed on soft ground and for reducing the footprint of new levees. The potential failure modes of embankments and levees with DMM shear panels can be complex and suitable methods for analysis and design of these systems are needed to insure that the DMM technology is properly applied.

In addition to the geotechnical aspects of developing design methodologies that accurately asses the failure potential of the levee structures, the safety of a hurricane protection system also depends on the selection of appropriate design criteria for the levees. For systems with low infrastructure costs and minimal consequences, tolerable levels of risk can be achieved with structural measures and typical design criteria. In New Orleans, where levee failure can result in flooding depths in excess of 10-ft in densely populated areas, success of a flood protection system depends on the combination of the probability of failure of the levee and the probability that the at-risk population will successfully evacuate if the levee does fail. If the population cannot evacuate in time, the levee design criteria may need to be changed or additional protective measures may be necessary. Conversely, if it is not feasible to increase the level of protection from levees, then steps must be taken to improve the effectiveness of evacuation and to educate the public about the risk of levee failure.

Increasingly, natural hazard risk mitigation literature is calling for research that integrates the technical, societal, economic and political aspects of the problem. One of the primary factors of evacuation response is the way that individuals and households make decisions about when and how to evacuate. This is especially critical for socially vulnerable populations, such as the elderly or disabled. During Katrina, it is estimated that 70% of fatalities were aged 65 or older.

Risk Mitigation for Hurricane Protection Systems

Risk assessment tools used in engineering design base the acceptability of the structure or system on a comparison between the risk associated with that system for a given hazard and the acceptable level of risk for that event. If the estimated risk is higher than the tolerable risk threshold, mitigation measures are needed to reduce the risk to the desired level. In order to consider the effect of evacuation as a mitigation measure in our risk assessments, we need to be able to quantify the potential for risk reduction from evacuation. If this potential can be quantified, decisions about how much mitigation must be accomplished through infrastructure versus evacuation can be made at the system or project level.



Potential Impact on Levee Design Criteria when Risk Mitigation from Evacuation is Included in Risk Assessment

Project Objectives

The primary objective of this research 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. In addition to the primary objective of providing recommendations for evaluating the stability of these systems, a secondary objective is to develop a research plan for quantifying the evacuation potential of at-risk populations.

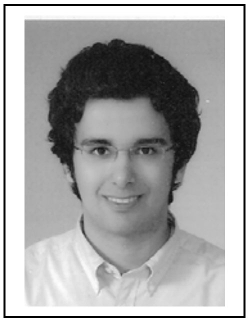
Research Plan for Risk Mitigation Through Levee Design

- Perform stability analyses using numerical methods for a range of levee and DMM shear wall geometries and properties.
- Compare numerical results with results from limit equilibrium methods and other simplified methods to assess the potential for developing a design methodology that does not require numerical analyses.
- Perform settlement analyses to evaluate the potential for cracking of the levee from differential settlement around the DMM shear walls.
- Evaluate potential effects of tension cracks on stability.

Research Plan for Risk Mitigation Through Evacuation

- Develop a research plan with an interdisciplinary team.
- Concentrate on vulnerable population of aging families.
- Assess factors that affected evacuation decisions during Katrina.
- Assess evacuation decision process and quantify the time delay between warning and evacuation.

Evaluate potential for improving evacuation decision making and reducin



The Effect of Soil-Mix Panels on Ground Motions

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Sponsor: DRM

Start/Completion Dates: August 2008 / August 2010

Project Background and Objectives

Ground modification methods such as vibrodensification, soil-mix walls and stone columns are commonly used to improve subsoil conditions. However, current building codes provide no explicit guidelines related to modified ground conditions. Such a reduction in ground motion for improved ground conditions can have significant payoff as the seismic loads on the upper structure are reduced, resulting in lower design levels and construction costs.

In most of the cases the purpose of ground improvement is either for foundation support and/or liquefaction mitigation. This study focuses on the reduction of ground motions for improved ground conditions. New ongoing research has shown that certain soil improvement techniques like panel type reinforced ground have the potential to reduce the intensity of ground shaking beneath the structures. Developing performance based seismic design guidelines for modified ground conditions is one of the main objectives of this study.

Research Accomplished

A series of dynamic nonlinear finite element analyses were performed to investigate the effect of soil-mix panels on ground motions. The analyses were conducted by using the dynamic finite element code Dynaflow. To provide a benchmark for comparison, a series of runs were also performed where the soil-mix panels were removed from the model and the soil profile was assumed to be unimproved. The motions at the ground surface for improved and unimproved cases were compared to assess the effectiveness of soil-mix panel reinforcements for reducing ground motions.

A grid pattern of 1.8-m thick soil-mix panel system with 9-m center-to-center spacing was selected for the analyses. A schematic plan view of this soil-mix panel arrangement is shown in Figure 1. The replacement ratio for this improvement geometry is 36%. Soil-mix panels are installed at the top 10-m of the soil profile. A 30-m deep profile with constant Standard Penetration Test (SPT) blow counts of N = 10 blows/ft was used in the analyses. The average shear wave velocity of the 30 meter thick soil profile is about $V_{s,30}$ = 190 m/s, corresponding to a soft soil site which classifies as Site Class E as per the NEHRP site classification system. An unconfined compressive strength of 1500 kPa was used for the soil-mix in the analyses. The geometrical constraints of the analyzed improvement scenario necessitated a 3-dimensional finite element model with about 25,000 nodes. The model was formed using a unit cell of the soil-mix panel system to encapsulate a square geometry (9 m by 9 m) through the centerline of the panels in both directions. The model was shaken at the base in two horizontal directions simultaneously.

The response of the unimproved profile was also investigated in which the soil-mix panels were removed from the model. The ground motion on top of both improved and unimproved profiles were computed in response to the same base shaking.

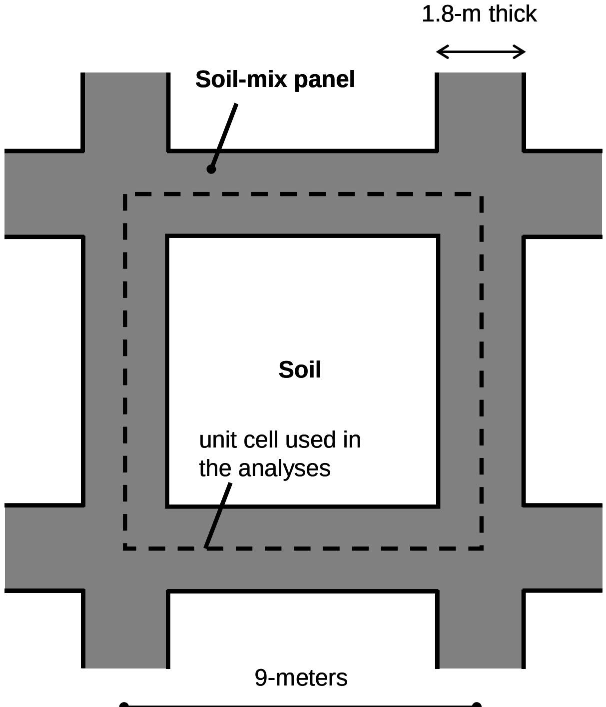

Figure 1. Plan view of soil-mix panel improvement, 1.8 meter thick soil-mix panels at 9 meter center-to-center spacing (Replacement Ratio = 36%)

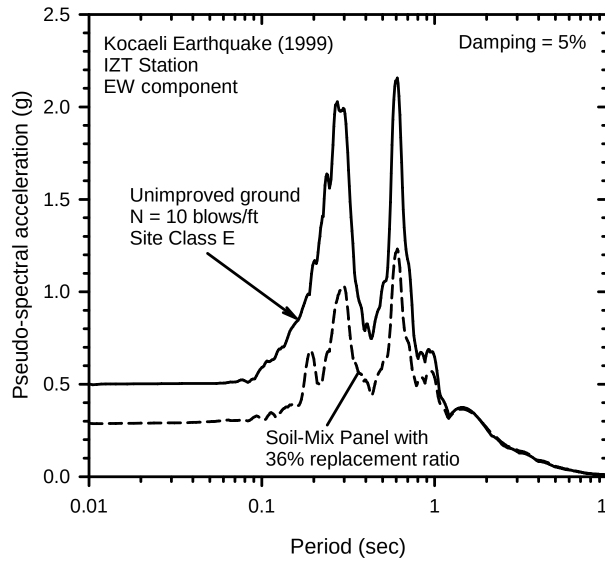

Figure 2. Response spectra at the ground surface of improved and unimproved profiles

Key Findings

A sample response spectrum on top of the improved profile is shown in Figure 2, along with the spectrum atop the unimproved profile. As can be seen the spectral motions are much less for a range of periods. The soil-mix panel reinforcement resulted in about 40% reduction in motions for up to periods less than 0.6 seconds. The panel reinforcement is less effective for longer periods. In any case this is a considerable reduction in ground motions in the short-to-mid period range for the improved profile. In analogy to the response of profiles with different site classes, the response of the improved profile corresponds to more-or-less a Site Class D as opposed to the unimproved profile with Site Class E. Therefore stiffer site classes may be more appropriate to use for sites reinforced with soil-mix panels. Current building code procedures do not address this issue and this should be further investigated.

Additional analyses were performed with 1.8-m thick soil-mix panels spaced at 14 meters center-to-center. This corresponds to a replacement ratio of 24%. A replacement ratio of 24% results in about 30% lower spectral accelerations for up to 0.6 second period in comparison to the 40% average reduction for the case with 36% replacement ratio. This indicates that higher replacement ratios result in lower levels of shaking presumably as a result of the increased stiffening of the site.

Conclusion and Future Research

The results indicate that soil-mix panel reinforcement can have a considerable effect on ground motions. This study will further be extended to develop generalized ground motion reduction curves for improved ground. Considering the time required to running nonlinear 3-D finite element analysis, it is necessary to benefit from parallel computing. Since Dynaflow can’t be effectively used in parallel applications, OpenSees is planned to be used with System X, the supercomputer at Virginia Tech.

Athletic Field Characterization

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Sponsors: USDA

Start/Completion Dates: August 2008 / August 2009

Project Background

In competitive sports, athletes understand that injuries are largely unavoidable and consider the potential for injury an acceptable risk. The nature of the player-to-player contact in American Football results in the expectation of impact related injuries. An unexpected result is the large number of impact injuries related to interactions between athletes and the playing surface. A detailed study of American Football fields has not been completed to evaluate the potential for injury as it relates to the engineering properties of the playing surface.

Project Objectives

The purpose of this research is to complete a detailed analysis of the engineering properties of area high school and college football fields. Testing equipment and methods will be evaluated and the most robust techniques will be applied in the field for data collection. Proven test methods using equipment such as the Clegg Hammer, dynamic cone penetrometer (DCP), and tube sampler will provide requisite data that can be correlated with nuclear density gauge, shear wave velocity, Geogauge, and time domain reflectrometry (TDR) data. The engineering properties of interest (density, stiffness, moisture content) are time dependent, and are also related to the environmental conditions and use. Influence of the time dependent parameters requires an extensive testing program to accurately characterize each field and ultimately make recommendations for maintenance to field managers. The results of this study can be compared to injury reports taken by athletic trainers and player surveys to determine the optimum playing conditions for American Football.

Research Accomplished

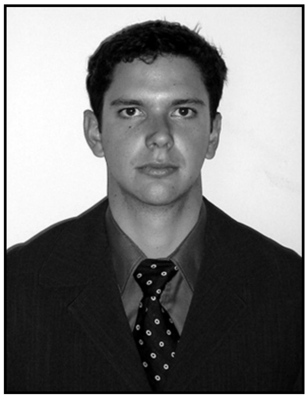
- **Literature Review**

  ASTM's were reviewed to find test methods pertaining to the characterization of athletic fields. Peer reviewed journals were also searched to determine relevant test methods. A staple in the modern practice of characterization of athletic fields is the Clegg Hammer. Prior to the Clegg, instrumented, specially designed weights were dropped from prescribed heights to measure a G_{max} value described by ASTM F 355, "Shock-Absorbing Properties of Playing Surface Systems and Materials." The Clegg measures an impact value (IV) that can be used to calculate G_{max} (McNitt et. al., 2004) and an elastic modulus (Baden Clegg Pty Ltd, 1999). The procedure applicable for Clegg sampling on athletic fields is outlined by ASTM F 1702, "Measuring Shock-Attenuation Characteristics of Natural Playing Surface Systems Using Lightweight Portable Apparatus." A maximum G_{max} value of 200 is recommended for athletic surfaces. The G_{max} maximum value is considered the threshold for life threatening head injuries, adopted from impact tests completed by the auto industry in the 1960's and 1970's.

- **Test Methods and Equipment**

  Preliminary field tests confirm the utility of the Clegg Hammer as a nondestructive test with rapid, reproducible results. The application of the DCP requires a reduction in energy to achieve a target value of approximately 20 blows per 6 inches. Tube samplers are invaluable, providing bulk density and moisture content, but are destructive and labor intensive. The nuclear density gauge is affected by the organic layer of athletic surfaces and may prove to be ineffective. The Geogauge is also affected by the organic layer, and initial test prove that it is not an appropriate tool for playing surfaces. The use of shear wave velocity to determine modulus values for athletic surfaces shows promise but has yet to be field tested. Time domain reflectrometry can be a useful index to measure moisture content in a nondestructive, rapid test. The TDR system output will be compared to moisture contents from tube samples to evaluate reproducibility.

Interaction of Integral Abutment Piling and MSE Walls



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Sponsors: Virginia Transportation Research Council

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

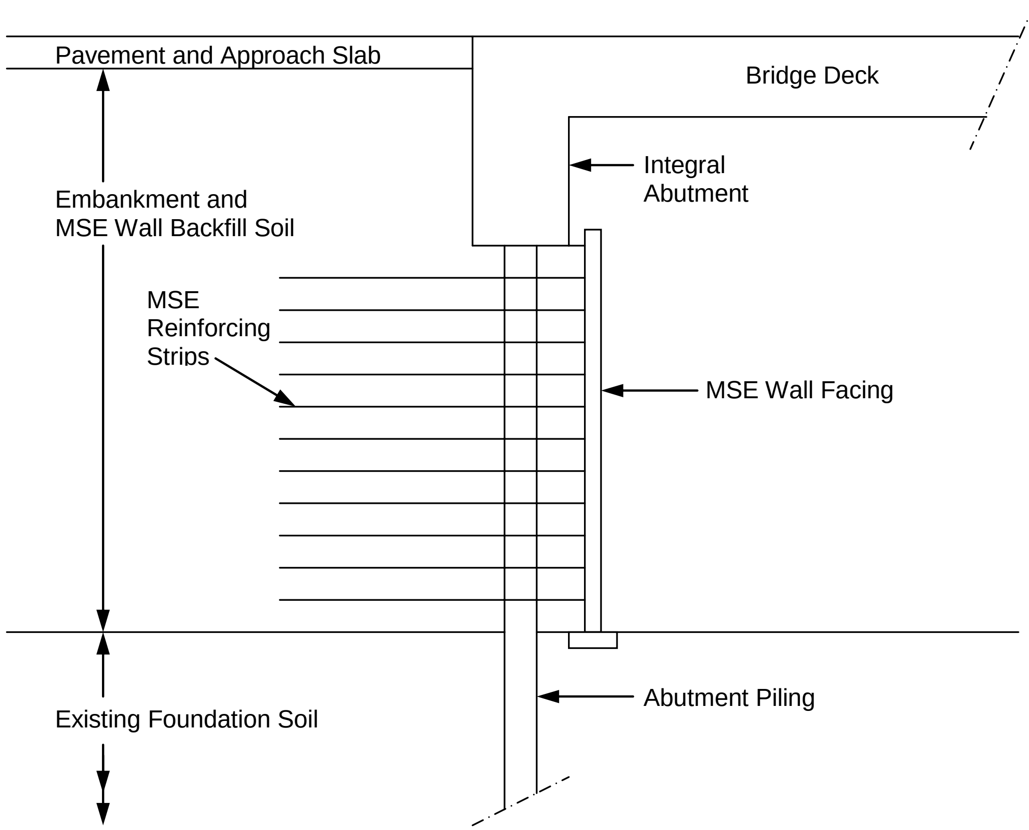


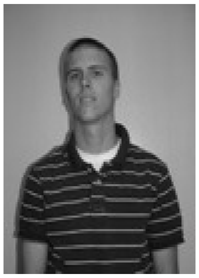
Figure 1. Profile view of MSE system around piling supporting integral bridge abutment.

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.
- VDOT's integral abutment bridge at Telegraph Road, which has abutments in MSE wall backfill, is under construction and instrumentation. The bridge will be analyzed numerically as data become available.
- Calibration of the 3D numerical model is almost completed. The base line for calibration is the instrumented field case described by Hassiotis et al. (2005). Different numerical method and parameters have been tested to match the numerical model response and the field data.
- 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. The recommendations will be developed in 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.

Evaluation of the Clastic Dike Formative Mechanism Using Slurry Trench Filter Cake, Dam Filter, and Landfill Filter Criteria



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Sponsor: National Science Foundation
Start/Completion Dates: May 2007/ongoing

Project Background

The objective of this study presented is to provide insights into the formative mechanisms of the clastic dike features that are located throughout the ancient Glacial Lake Missoula flood sediments in the Pacific Northwest. The dikes are unique in that they are predominantly downward penetrating and have silt sheet linings. Previous studies have hypothesized that these dikes were manifestations of earthquake induced liquefaction/lateral spreading. Although clastic dikes can form as a result of liquefaction, such dikes are almost always upward penetrating, while the dikes analyzed in this study are downward penetrating. Also, silt sheets are uncharacteristic of liquefaction dikes. It has been hypothesized that the dikes resulted from hydraulic fracturing as the hydraulic heads of the rapidly placed, turbid flood water and ground water equilibrated. Central to this proposed mechanism is that silt sheets are actually filter cakes that allowed large seepage forces to develop, and hence, the hydraulic fracturing to occur.

Project Objectives

To test the hydraulic fracture hypothesis, Drs. Stephen Obermeier, Russell Green, and Scott Olson collected numerous samples from the clastic dikes in the Missoula flood sediments, to include samples from host deposits, silt sheets, and dike infill material. Of particular interest are the samples taken from places where the dikes penetrated through layers of finer-grained material, but then abruptly terminated or dissipated in layers of coarser-grained material. The reason for this is because the formation of filter cakes is dependent on the grain size characteristics of the material suspended in the turbid flood waters relative to those of the host sediments. Through analysis of the grain size distribution curves of the collected samples, current filter cake criteria used to design slurry trenches and filter criteria for dam and landfill design will be used to see whether they correctly predict where silt sheets did and did not form in the ancient Glacial Lake Missoula flood deposits. If the filter cake criteria predictions are correct, then the results give additional credence to the hypothesis that the silt sheets are in fact filter cakes and that the clastic dikes were formed by hydraulic fracturing. As a result the earthquake hazard rating of this region would significantly change because some studies hypothesize that the features are the result of earthquake induced liquefaction.

Research Accomplished

• Literary Review

A review of the available literature has been performed to determine current filter cake criteria used to design slurry trenches and filter criteria for dam and landfill design. The most common filter cake formation criteria found in geotechnical literature is based on the effective diameter of the host soil corresponding to 15 percent finer (D_{15}) on its grain size distribution curve and the effective diameter of the filter cake material corresponding to 85 percent finer (d_{85}) on its grain size distribution curve.

Based upon the literary review, the following are the filter cake formation criteria to be used to evaluate whether they correctly predict where silt sheets did and did not form in the ancient Glacial Lake Missoula flood deposits:

1) Main criterion (slurry trench filter cake): $\dfrac{(D_{15})_{HOST}}{(d_{85})_{FILTER\ CAKE}} \leq 5$

2) Supplementary criteria (dam and landfill filter): $(D_{15})_{HOST}$ < 0.5 mm (for clays only)
$C_u < 10$

- **Laboratory Tests**

Currently laboratory tests are being performed on samples collected from several sites in order to develop the respective grain size distribution curves. To analyze the gradations of the soil samples, the samples are being tested by sieve and hydrometer tests in general accordance with ASTM standards. For small sample sizes in which hydrometer test cannot be performed, the soil is being analyzed using a Malvern Mastersizer 2000. This laser diffraction analyzer uses both a blue and red laser light to determine the grain size distribution when the soil is mixed with a 4M sodium hexametaphosphate dispersant.

Key Findings

To assess whether the silt sheets from the clastic dikes are possibly filter cakes, the grain size characteristics of the clastic dikes will be evaluated using the three criteria mentioned above. The results from each analysis will then be compared to visual observations from the various sites.

During evaluation of the grain size characteristics it should noted that the samples were collected post-flood. If prior to the ancient Glacial Lake Missoula flood the sand-gravel-cobble host stratum contained little-to-no fines, as the turbid flood waters flowed into the host stratum no filter cake would form and the suspended silt sheet material would freely disperse in the stratum. As the flood waters receded and evaporated, the dispersed silt sheet material would remain in the sand-gravel-cobble stratum, and consequently, $D_{15\ \text{pre-flood}} > D_{15\ \text{post-flood}}$.

In an attempt to adjust the grain size distributions of the soil samples collected from the sand-gravel-cobble host stratums to pre-flood values, the grain size distribution curves for the host soil samples will be adjusted or "corrected" by scaling the respective silt sheet material samples to each host soil’s percent finer at 0.075 mm.

In order to verify that the silt material contained within the host stratum is the same as that from the “filter cakes” mineralogical studies will be performed.

Additionally, tests should be performed in the laboratory to corroborate the formation (or no formation) of filter cake using the host soil samples collected in the Pacific Northwest. Henry et al. (1998) suggest a procedure for the test involving compaction-mold permeameter attached to a slurry reservoir. Host soil will be placed in the bottom of the mold and then inundated by slowly percolating water up from the bottom of the permeameter. A mixture of slurry and suspended soil particles (filter cake) will then be placed with a deflector to avoid disturbing the host soil. By applying air pressure, a differential head will be created between the slurry surface in the reservoir and the tailwater level at the permeameter outlet. A filter cake will form if slurry and other suspended soil particles are retained on the host soil’s surface, resulting in the flow of water at the permeameter outlet to be reduced to a very small rate.

Load and Resistance Factor Design in Geotechnical Engineering

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Sponsors:	CGPR
Start/Completion Dates:	August 2007 / December 2008

Project Background

AASHTO now requires that load and resistance factor design (LRFD) be used for all new bridge projects. LRFD is a limit state design method that uses load factors and resistance factors instead of factor-of-safety values. This is different from the traditional method of analysis in geotechnical engineering, allowable stress design (ASD), which does use factor-of-safety values.

Project Purpose and 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 focuses on the AASHTO code because it is used most often in U.S. practice. In addition to reviewing the design process, the report summarizes the load and resistance factors specified by AASHTO. Another objective of this report is to help clarify some of the potentially confusing applications of LRFD in geotechnical engineering. LRFD and ASD designs of a 25 ft tall tieback, cantilever, and MSE wall are compared.

Research Performed

A literature search was performed to gain a comprehensive understanding of LRFD and to determine how the LFRD factors were determined. After the literature search was completed, the research focused on the AASHTO code in particular instead of LRFD as a whole. The next phase focused on finding definitive information about how AASHTO deals with earth retaining structures and foundations. Analyses were performed for a tieback, cantilever, and MSE wall of the same geometry in both LRFD and ASD. The goal was 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. In many situations, the LRFD and ASD designs were very comparable. One difference arises from the fact the LRFD does not require an overturning calculation. Instead, overturning is addressed in the eccentricity calculation. In looking at the tieback wall, it was noted that the resistance factors in LRFD varied greatly for calculating the axial capacity of piles, while the factor of safety in ASD remained constant for all methods used. Also in the tieback wall design, one of the biggest differences came in the required flexural capacity of the soldier pile. The ASD design required an HP12x74 while the LRFD design only required an HP 12x53.

A Review of Sustainability in Geotechnical Engineering

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Sponsor: CGPR

Start/Completion Dates: June 2008 / December 2008

Project Background

There is widespread appreciation among CGPR members of the importance of sustainability in current and future geotechnical engineering practice. During the annual CGPR meeting in February 2008, CGPR members discussed and voted in favor of a report on sustainability in geotechnical engineering. An extensive literature search began in June of 2008, and numerous references pertaining to this topic were found. The report was completed in December of 2008.

Contents of Report

The report contains the following main sections:

- *What is Sustainability?*
  - This section provides definitions of sustainability and other terms related to the topic.
- *Benefits of Incorporating Sustainable Practices in Geotechnical Engineering*
  - This section focuses on federal initiatives, economic benefits, and expedited permitting incentives associated with sustainable development.
- *Incorporating Sustainable Practices in Geotechnical Engineering*
  - This section describes several ways that geotechnical engineers can incorporate sustainability into their designs.
- *Reuse of Industrial By-Products and Wastes*
  - This summarizes three key references that were found pertaining to the reuse of industrial by-products. It also provides tables that summarize over 50 additional references.
- *Innovative Sustainable Geotechnical Systems*
  - This section provides an overview of two innovative geotechnical systems.
- *Rating Systems*
  - This provides an overview of three rating systems that judge sustainability of design, construction, and operation of a green building.
- *Sustainable Business Practices*
  - This section provides examples that engineering firms and agencies can use to incorporate sustainable practices into their own businesses.

Engineering Characterization of Earthquake Ground Motions

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Sponsors: National Science Foundation
Start/Completion Dates: Jan. 2005 / Jan. 2009

Project Background

In recent years, geologic and paleoseismic evidence has raised the awareness about the seismic hazard of the stable continental region of central-eastern U.S. (CEUS). The relevance of this topic increased due to the Nation's renewed interest in the construction of new nuclear power plants in the CEUS and due to the occurrence of the M5.2 earthquake in southern Illinois in 2008. However, few ground motion predictive relations suitable for use in engineering design are available for stable continental regions, due to the paucity of strong ground motion recordings in the region. In this regard, McGuire et al. (2001) generated a database of scaled ground motions for stable continental regions for use in detailed engineering analyses.

Project Objectives

The objectives of this study are:

1. To develop empirical correlations (i.e., predictive equations or relationships) for stable continental regions (e.g., CEUS) relating various engineering characteristic parameters of the horizontal components of earthquake ground motions to design earthquake parameters, such as earthquake magnitude, site-to-source distance, and local site conditions (i.e., rock vs. soil).
2. To identify the differences in engineering characteristics of earthquake ground motions from stable continental regions and active seismic regions (e.g., western US: WUS).

Research Accomplished

The ground motion predictive relationships were developed using the non-linear mixed effects (NLME) regression technique of parameters derived from the strong ground motion data set assembled by McGuire et al. (2001). For the purpose of consistent comparisons between CEUS and WUS motions, similar empirical correlations for WUS were developed from recorded strong ground motion data.

- **Engineering Characteristic Parameters**

  The engineering characteristic parameters of earthquake ground motions considered in the study are listed below:

Category	No.	Engineering characteristic parameter
Characteristic periods	1	Predominant spectral period (T_p)
	2	Smoothed spectral predominant period (T_0)

	3	Average spectral period (T_{avg})
	4	Mean period (T_m)
	5	Spectral velocity-acceleration ratio periods ($T_{V/A50}$ and $T_{V/A84}$)
Strong ground motion durations	6	Significant durations ($D_{5\text{-}75}$ and $D_{5\text{-}95}$)
	7	Bracketed durations ($D_{bracket}$)
	8	Effective durations (D_{eff})
Intensity measure	9	Arias intensity (I_a)
Equivalent number of uniform cycles	10	Stress cycles ($n_{eq\tau}$)
	11	Strain cycles ($n_{eq\gamma}$)
Pore pressure generation calibration parameters	12	Pseudo energy capacity (PEC)
	13	α

- **Strong Ground Motion Data**

  The strong ground motion data set for CEUS includes 28 recorded motions and 592 scaled motions. The latter were scaled from the actual earthquake ground motions recorded at active shallow crustal regions worldwide by implementing a stochastic single-corner-frequency point source model (e.g., Boore, 1983; Brune, 1970; 1971; McGuire et al., 2001; Silva and Lee, 1987). The data set for WUS includes a total of 648 recorded motions from 49 earthquakes, with the 1999 Chi-Chi earthquake being the most recent event. These recorded motions were actually the "seed" motions from which the scaled CEUS motions were developed.

- **Regression Method: Non-linear Mixed Effects Regressions**

  The non-linear mixed effects (NLME) regression method produces unbiased fittings of "grouped" data. Specifically, parameters derived from earthquake motions recorded during given earthquakes are grouped together, with the amount of data in groups varying from earthquake to earthquake. This is important in analyzing earthquake ground motion data, otherwise parameters derived from motions from one or two earthquakes will bias the resulting predictive relationship. Furthermore, the NLME modeling allows the functional form of the predictive relationship to be theoretically or empirically based and to be non-linear (the NLME modeling utilizes non-linear regression). Accordingly, the NLME modeling is a robust regression technique suitable for analyzing earthquake ground motion datasets. This study used the statistical analysis program R (version 2.5.0), along with a NLME package.

Key Findings

The comparison showed that the CEUS motions have distinct characteristics from WUS motions. Firstly, the characteristic period of CEUS motions are systematically shorter than those of WUS motions. However, the strong ground motion duration in CEUS tends to be longer than in WUS. Also, CEUS motions had consistently larger intensities than WUS motions. Finally, the number of equivalent stress and strain cycles (Green, 2001; Green and Lee, 2006) for CEUS motions is larger and varies more as a function of depth than WUS motions.

Geotechnical Considerations for Organic Soils and Peats

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Sponsor: CGPR
Start/Completion Dates: May 2007 / January 2009

Project Objectives

The objectives of this study were:

(1) To bring together information regarding the properties of organic soils and peats, the engineering problems that they pose, and methods of dealing with those problems; and

(2) To investigate the accuracy with which the organic content of soil can be determined by test method ASTM Test D 2974, which involves heating the soil sample to 440 degrees C to burn off organic material. Heating at such high temperatures can cause loss of adsorbed water in clays, and this may be wrongly interpreted as indicating that the soil contains organic material.

Characteristics of Organic Soils

This study was concerned with soils that contain organic matter derived from reeds, grasses, or other plant material. In some cases the organic matter retains the fibrous nature of the plants from which it is derived, and in other cases it is decomposed amorphous organic material.

Soil deposits containing 70% or more of organic matter are called peat. Soils containing smaller amounts of organic mater are called silty peat, sandy peat, organic silt or clay, or slightly organic silt or clay.

Peats and organic soils with large amounts of organic matter have poor engineering properties. They can be highly compressible and have low undrained shear strengths. These properties make them undesirable for foundation support or for use in engineered fills.

This manual discusses identification of organic soils and peats, the effects of organic matter on engineering properties, gives typical values of compressibility and strength of organic soils and peat, and reviews methods for mitigating geotechnical engineering problems associated with organic soils and peats.

Engineering Properties of Peats and Other Organic Soils

- **Compressibility**

  Peats and other organic soils that contain large amounts of organic matter are highly compressible.

As a result, embankments placed on these soils settle large amounts. “Weber’s Rule of Thumb” says that a five-foot thick fill placed on peat will settle five feet.

- **Strength and Stability**

  Surprisingly, effective stress friction angles of peat and highly organic soils are usually high, as high as 50 degree, or in some cases even higher. However, large strains are required to mobilize theses strengths.

  Undrained strength ratios (s_u/p) for peats and highly organic soils are also quite high, as high as 0.5 or even higher.

  However, because the unit weights of these soils are low, effective overburden pressures in peats near the ground surface are low, and undrained strengths are also low. As a result, peat deposits near the ground surface have very small bearing capacities, and often cannot support the weight of even low-ground-pressure equipment.

- **Mitigation of Foundation Problems Due to Peat and Highly Organic Soil**

  Three methods are commonly used to mitigate problems associated with peats and highly organic soils:

  (1) Excavation and replacement to remove the problem soils,

  (2) Preloading to reduce settlements, and

  (3) Deep foundations to transfer foundation loads to competent materials.

- **Behavior of Soils with Small Amounts of Organic Matter**

  The properties of soils with less than about 5% organic matter are controlled by the behavior of the inorganic constituents.

  Although some building codes prohibit the use of soils containing any organic matter in foundations or fills, this is not logical, for two reasons:

  (1) Organic content of 5% or less has little or no effect on engineering behavior, and

  (2) The standard method of detecting the presence of organic matter in soils (ASTM D2974), which involves heating the soil at 440 degrees C, may indicate organic content as high as 4.6% for soils that contain <u>no</u> organic matter: heating soils to 440 degrees C may drive off adsorbed water from clay minerals, which is recorded falsely as organic matter.

Seismic Response of Fine Grained Soils

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Sponsor: NSF

Start/Completion Dates: August 2006 / August 2009

Project Background and Objectives

Significant earthquake-induced settlements occurred in saturated fine-grained soils at the Carrefour Shopping Center in Turkey during the 1999 Kocaeli Earthquake (M=7.4). Most of the settlement was due to the undrained cyclic failure of silt/clay (ML/CL) and high-plasticity clay (CH) strata within the subsoil profile. Each suffered about 1-2% vertical strain. Because the CH and ML/CL soils were plastic and did not meet the commonly-used Chinese criteria due to high clay content, they were classified as “non-liquefiable,” and the designers did not anticipate them being a source of significant earthquake-induced deformation. The “non-liquefiable” classification of plastic fine-grained soils has led to the widespread misconception that such soils are somehow immune from pore pressure development and cyclic failure. This has, in turn, led to a widespread underappreciated seismic vulnerability of these soils. Extensive laboratory testing on undisturbed samples from these silty and clayey strata at the site has been performed to investigate this behavior.

Research Accomplished

The laboratory testing included monotonic and cyclic simple shear tests, triaxial tests and conventional 1-D consolidation tests. Considerable pore pressure increases have been measured during cyclic simple shear tests which were later followed by significant reconsolidation settlement. It was found that significant pore pressures begin developing in these soils at cyclic stresses at about 50% of their monotonic shear strength. This transition in behavior with high pore pressure development and subsequent post-cyclic volume changes corresponds to about 0.5% cyclic shear strains. The study demonstrates the limitations of generalized liquefaction screening methods, and dispels the common misconception that high plasticity soils cannot generate high pore pressures and fail under cyclic loading. Test results indicate that the soils at the site can generate significant pore pressures when shaken at levels expected to have occurred during the Kocaeli Earthquake. The findings from this study are in line with the limited number of studies on this topic. Of particular importance, the findings imply that generalized liquefaction screening guidelines are not reliable predictors of seismic vulnerability and, especially, cyclic deformation potential. Fine-grained soils, if shaken hard enough, can suffer strength loss and reconsolidation settlements. The challenge remains to better understand such phenomenon and incorporate this into engineering practice.

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

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Sponsor: National Cooperative Highway Research Program
Strategic Highway Research Program

Project Duration: August 2007 - September 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 facilitate the efficient use of these technologies 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, summarize and develop design and QA/QC procedures, and overcome any identified obstacles that prevent their widespread use in practice.

Results and Work Products

Phase I of the project was completed in the Fall of 2008. The research team identified 47 ground improvement technologies and ranked them according to their level of maturity and contribution to the SHRP2 objectives. Phase I also included a literature review and compiled a database currently containing over 650 documents. The team also collected expert opinion on each of the technologies, and compiled an extensive list of contacts in the field.

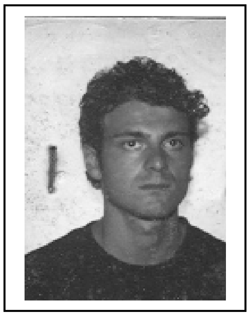
Upon reviewing these resources, the team categorized the technical and non-technical obstacles facing ground improvement technologies. A sampling of the technical obstacles includes the lack of reliable design methods, poorly defined performance criteria, and inadequate QA/QC procedures. Non-technical obstacles were found to include a general lack of knowledge about soil improvement technologies, state DOT structures not always conducive to adopting new technologies, lack of qualified contractors, and proprietary processes.

Current work on the project involves compiling a comprehensive summary for each technology to include: applications and material properties, depth limits, soil types, equipment needs, advantages/disadvantages, design procedures, QA/QC procedures, cost information, specifications, and a case history database. Students at Virginia Tech are currently working on technology summaries for vibro-concrete columns, combined soil stabilization sand cement columns (CSV), drilling/grouting and hollow bar soil nailing, shoot-in/screw-in soil nailing, shored mechanically stabilized earth walls, jet grouting, lightweight fill, and column supported embankments.

Future Research

After completion of the technology summaries, the research team will select technologies for further research based on the current level of technology maturity and the degree to which the technology meets the project objectives. This will include review, refinement, and/or development of 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. Further research will also include development and testing of techniques to mitigate the obstacles impeding widespread use of ground improvement technologies.

Examination of the Applicability of SHANSEP on New Orleans Levee and I-wall Projects



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Start/Completion Dates June 2008/Oct 2010

Project Background

Large scale construction in the New Orleans area requires the assessment of undrained shear strength for stability analyses. In the past, the main tools used for this assessment were unconfined compression tests and unconsolidated-undrained triaxial tests. Since Hurricane Katrina, these tests have been augmented with laboratory and field vane shear tests, direct simple shear tests (DSS), and cone penetration tests (CPT).

In the post-Hurricane Katrina environment, many outspoken geotechnical engineers have vocally suggested that unconfined compression tests and unconsolidated-undrained triaxial tests be completely abandoned, and the strength assessment should be based solely on DSS and SHANSEP procedures (Ladd and Fott, 1974).

Project Objectives

The objective of this research is to assess the applicability of SHANSEP to the New Orleans levee and I-wall projects. The research will determine the differences in shear strength interpretation and the resulting differences in the calculated factor of safety if SHANSEP is used versus conventional methods. The study will also investigate if certain key elements of SHANSEP can be applied beneficially to New Orleans area projects. Laboratory tests of the highest quality, finite element analysis and limit equilibrium analysis are used to achieve this objective.

SHANSEP, as originally outlined by Ladd and Fott, requires that the soil exhibit the ability to be "normalized". Simply put, this means that the same undrained strength ratio S_u/σ'_v, is measured for a given OCR value, regardless of the magnitude of σ'_v. Soils that are sensitive or structured may not possess the ability to be normalized. One of the main goals of the project is to assess whether or not the soils of the study area show normalization properties.

SHANSEP assumes that the initial consolidation stresses are vertical and horizontal and that the soil is consolidated to K_o conditions. On a potential failure plane, the strength of the soil would depend on the magnitude and orientation of the consolidation stresses. In particular it would depend on the major effective stresses during consolidation. For the current New Orleans projects, at many locations, the subsurface clays are fully consolidated under the weight of the existing levee. This means that principal stresses are not vertical and horizontal (except directly below the crest of the levee) due to principal stresses rotation. Also, the soil is not in a K_o consolidated condition since lateral strain would have occurred during consolidation.

Key Findings

(1) UU triaxial tests, if carefully conducted on high-quality test specimens, provide reasonable undrained shear strengths that compare well with field vane shear tests that are corrected for strain rate effects using Bjerrum's correction factor.

(2) For sites that have relatively uniform clay deposits, good agreement can be obtained from UU triaxials, field vane shear tests, and cone penetration tests.

(3) Although DSS apparatuses are still relatively rare in geotechnical testing laboratories, high-quality CKoU-DSS tests can be conducted quicker and with considerably less effort than CKoU-TC and CKoU-TE tests.

(4) DSS tests take about half the time required for CKoU-TC and CKoU-TE tests, but about six to ten times as much time as UU triaxial tests.

(5) The major principal stress during consolidation at the toe of a levee can be about # times greater than the vertical effective stress.

Research to be Accomplished

A large number (>100) undisturbed samples have been obtained from New Orleans area projects. Constant rate of strain (CRS) consolidation tests, as well as CK_oU-TC, CK_oU-DSS, CKoU-TE, laboratory vane shear tests are being conducted on the samples.

Finite element analyses are being conducted using the computer program PHASE2 from Rocsciences, Inc. to determine the initial and final orientation of effective consolidation stresses. Test specimens will be trimmed at various orientations such that the axis of the sample aligns with the direction of the major principal stress. This will allow a determination of the effects of both the principal stress orientation and inherent anisotropy. The computer program SLIDE will be used to conduct limit equilibrium analyses to examine the impact of the method of shear strength interpretation on the factor of safety.

The tests described above, coupled with the finite element and limit equilibrium analyses, will allow the following questions to be answered:

- Do the soils at various sites around New Orleans normalize à la SHANSEP?
- What is the net effect of the rotated consolidation stresses at the toe of the levee? Should corrections be applied to field vane shear tests and Q triaxial tests at the toe of the levee to account for the non-vertical consolidation stresses?
- Can CK_oU-DSS tests be used to any utility on area projects? How do the results of DSS tests compare to conventional UU, UC and field vane tests?
- Is there an appropriate correction factor that should be applied to CK_oU-TC tests to obtain undrained strength ratios representative for conditions on the failure plane?

Investigation of Surface Deformation in Column-Supported Embankments

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Project Background

Geosynthetic-reinforced, column-supported embankments (GRCSEs) 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. This research utilizes a combination of physical and numerical modeling to better understand the mechanisms of surface deformation in column-supported embankments. The ultimate goal of this research is to develop a set of design guidelines that mitigate the risk of this type of surface deformation.

Bench-Scale Physical Modeling

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. Tests can be performed using either a single column or a square array of columns. Single column tests can be performed using 0.75, 1.25, 2, or 3 inch diameter columns. Column arrays consisting of a 5x5 grid of columns with a 3.5 inch center to center spacing can be evaluated using column diameters of 0.75, 1.25 and 2 inches. Also possible is the evaluation of a 2x2 square array of 2 inch columns set on a 7 inch center to center spacing. The apparatus is instrumented to capture the magnitude of relative displacement between the column and the tank base, hereafter referred to as base settlement, as well as the column load for the single 3 inch column setup. Column displacement is controlled by a motorized jack that advances the column(s) into the base of the soil sample at a rate of about 1 inch in 20 minutes. At various increments of penetration, the column 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 draw wire sensor. The laser device measures the distance from the instrument to the sample surface and the draw wire measures the horizontal position of the laser. The profiling system is capable of capturing profiles of the sample surface with a high degree of accuracy and resolution at four orientations around the circular sample tank.

A poorly-graded manufactured sand is used as the sample material and samples ranging in height from about 2 to 10 inches can be prepared dry at selected relative densities using the technique of air pluviation. The relative density of the sample can be selected with a reasonable degree of confidence. 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.

Three types of biaxial polypropylene netting with different tensile stiffnesses were selected for use as the geosynthetic reinforcement. The netting was selected based on 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.

Research Accomplished

To date, over 100 tests have been performed using the bench-scale experimental. Of this total, 48 of the tests were single column tests while the remaining were performed using 5 x 5 square arrays of columns with a 3.5 inch center to center spacing. The results of the single column testing indicate that the magnitude of differential settlement at the sample surface at a given base settlement magnitude decreases linearly with increasing sample height over the range of sample heights evaluated. The orientation of the shear band through the sample resulting from base settlement becomes increasingly inclined from vertical as sample density increases. Loads were measured on the single 3 inch diameter column during testing to allow indirect observation of the stresses developed along the shear band and the vertical component of the tension developed in the reinforcement. For unreinforced samples, the base settlement corresponding to the peak measured load on the column indicates the amount of displacement required to fully mobilize shear strength along the shear band. This magnitude increases when vacuum pressure is applied. As base settlement continues, measured loads decrease to a post-peak value. The post-peak load value is approximately equal to the weight of the cone of displaced soil overlying the column plus any force due to vacuum pressure acting over the displaced sample surface. The inclusion of reinforcement results in an increase in peak measured load on the column when the reinforcement stiffness is high relative to the shear strength along the shear band. The reinforcement also increases the magnitude of the measured post-peak load.

The findings from the testing performed using an array of columns shows that for a given column diameter and spacing, there is a sample height above which base settlement is not expressed on the surface. This transitional height is referred to as the "critical height" and can be found by plotting the ratio of the differential settlement versus base settlement for a range of sample heights. The critical height would be the sample height at which this ratio reaches zero. Differential surface settlement was evaluated along the centerline of a column row and at a 45^o angle to the array. The critical height was found to be about 4.0 inches for both the inline and diagonal directions for the array of 1.25 inch diameter columns. This height is approximately 1.8 times the clear spacing. This is consistent with previously published results. For the array of 2 inch diameter columns, the critical heights in the inline and diagonal direction were found to be 4.0 and 4.6 inches, respectively. This corresponds to critical heights that are 2.7 and 3.0 times the clear spacing, respectively for the inline and diagonal directions. The results from the 2 inch array were unexpected compared to previously published results. This observation suggests that the internal mechanism of deformation is more complex than currently considered in existing design approaches. Using geosynthetic reinforcement in samples tested using the column arrays reduces the magnitude of differential surface displacement. Across the range of reinforcement stiffnesses evaluated, the differential settlement amounted to approximately 40 to 80 percent of the differential settlement measured for an equivalent unreinforced sample. The effectiveness of the geosynthetic increases with increasing tensile stiffness up to a certain value, beyond which higher stiffness has no further effect. The presence of reinforcement did not have an effect on the value of critical height in these experiments.

Future Work

The bench-scale testing will be used to verify and calibrate a 3D numerical model of a GRCSE unit cell develop in FLAC3D. The 3D numerical model will provide a detailed look at the stress distribution within the reinforcement in the vicinity of the pile cap and increase understanding of how reinforcement can be used to mitigate surface deformation in GRCSEs.