AASHTO STANDING COMMITTEE ON RESEARCH
AMERICAN ASSOCIATION OF STATE HIGHWAY AND TRANSPORTATION OFFICIALS

TRB Section AFS00, Soil Mechanics
TRB Committee AFS30, Foundations of Bridges and other Structures
TRB Subcommittee, GeoSiesmic
Top 2006 Research Problem Statement

NCHRP Problem Statement

I. PROBLEM NUMBER

(To be assigned by TRB)

II. PROBLEM TITLE

Performance-Based Design of Foundation Elements and Earth Structures for Extreme Event Loadings

III. RESEARCH PROBLEM STATEMENT

The design of bridges and other highway facilities is often governed by the possibility of loadings or conditions from extreme events including earthquakes, vessel and vehicle collisions, and ice loadings. Current research efforts are also studying the effects of blast loading from terrorist attack and damage to bridge structures in the aftermath of hurricane Katrina. Design methodologies and details for both new construction and retrofit of existing structures for any one of these extreme events often provide increased protection for other extreme events. For example, measures to increase the resistance to seismic loading will likely serve to increase resistance for hurricane and blast loading. Geotechnical design considerations such as transient loading effects, the interaction between the solid and fluid phases in soil, and the nonlinear, plastic behavior of soil are common considerations with respect to development of design analyses for extreme event loadings. These commonalities allow for new developments in geotechnical design for extreme events to “crossover” from one area to another to another, e.g. advances in geotechnical earthquake engineering and seismic design and analysis for foundations and earth structures can often be applied to advance the state-of-the practice with respect to ship collisions, blast loading, and other extreme events. Furthermore, performance criteria for structures subject to extreme loadings are often independent of the event, e.g. allowable deformation for approaches to “lifeline” bridges expected to remain in service and collapse mechanisms for bridges designed to a lifeline safety standard are independent of the event inducing the deformation and/or loads.

Performance-based design is rapidly becoming the norm for modern seismic design of buildings due to the cost savings that can often be achieved through this approach. Levels of performance ranging from “fully operational” to “life safety only” are considered with respect to the cost of achieving these performance levels, the probability of occurrence over the design life of the facility and/or the importance of the facility. However, performance-based design criteria for geotechnical elements (foundations, retaining walls, and earth structures) are not as well established for bridge structures as they are for buildings and for the structural elements of bridges. One of the challenges facing performance-based geotechnical design is the relatively sophisticated level of analysis necessary to describe the performance of a geotechnical system during an extreme event. Performance-based design analyses require the ability to assess ground deformations, pore water pressure development, soil-structure interaction, post-yield behavior of soils and structural elements, and development of collapse mechanism for the extreme event.

Performance-based design and the evaluation of post-yield behavior requires a paradigm shift towards a displacement or deformation-based design as opposed to the traditional force-based design that has been applied to soil mechanics and foundation engineering problems. Designers need to recognize that large deformations may not necessarily represent a life safety risk. For example, a retaining wall or a slope may translate (yield), yet may not pose a life safety risk to users of the highway system. However, consideration must not be restricted to only the impact on the highway system from structure damage, but also to potential collateral damage and life safety impacts for other structures and emergency services that may be affected by the failure of a highway structure, e.g., a facility or structure located directly above or below a retaining structure or slope, damage delaying first-responder access to injured people or to emergency care facilities. These issues are best addressed using a deformation-based approach wherein the post-yield behavior of system components may be evaluated for an upper level (extreme) design event. The recognition that deformation does not necessarily result in structural damage or collapse has led to significant cost savings on many seismic design projects for earth structures. Slopes and embankments are now routinely designed on the basis of “acceptable” or “allowable” seismic deformations such that earth structures considered deficient a decade ago on the basis of a factor of safety of less than 1.0 during the earthquake are now deemed acceptable on this basis. However, this approach has yet to be applied to bridge foundation elements and deformation criteria for embankments containing abutment walls and piles and supporting approach slabs may be quite different from criteria developed for slopes and embankments.

NCHRP Project 12-49, “Comprehensive Specifications for the Seismic Design of Bridges,” was undertaken to develop a new set of seismic design provisions for highway bridges, compatible with the AASHTO *LRFD Bridge Design* Specifications. NCHRP Project 12-49 had as its primary objectives the development of seismic design provisions that reflect the latest design philosophies and design approaches that would result in highway bridges with a high level of seismic performance. Project 12-70, “Seismic Analysis and Design of Retaining Walls, Buried Structures, Slopes and Embankments,” will provide the same products for appurtenant highway structures including retaining walls, buried structures, slopes and embankments. NCHRP Project 12-49 addressed a number of performance-based design issues related to design of bridge foundations and abutments including: (1) capacity of foundation elements exposed to overturning, uplift and plunging; (2) the contribution of the pile cap in lateral capacity and displacement evaluation of deep foundations; (3) implications of liquefaction on the performance of bridge foundations and substructures; and (4) specific guidance for development of spring constants for spread footings and deep foundations. Although these contributions represent advancement over previous guidelines, they are still limited in terms of their ability to consider the impact of transient and permanent deformations inherent to extreme event loadings on the performance of bridge structures.

The past three decades have seen a great upsurge in research in the area of numerical model development, calibration and verification for geotechnical problems. Powerful new constitutive models for soil behavior and sophisticated numerical techniques have been developed. These technologies have advanced to the point where existing powerful numerical modeling computer codes may indeed be used on a personal computer to evaluate the impact of large deformations and the development of collapse mechanisms on geotechnical systems, including the loss of strength and stiffness due to development of pore water pressure leading to liquefaction, soil-structure interaction, and material damping and deformations leading to collapse. These advancements in computer technology and numerical modeling have modernized the way in which extreme event loadings are modeled and the performance of foundations and earth structures subject to these extreme events can be evaluated.

A recent international workshop sponsored by the National Science Foundation held at Johns Hopkins University on “Nonlinear Modeling of Geotechnical Problems: From Theory to Practice” revealed that a wealth of elasto-plastic constitutive models and finite element procedures exist for modeling earth-structure and soil-structure systems subjected to extreme loading. With the aid of these advanced methods and the availability of affordable, powerful personal computers, problems related to extreme event loading can now be solved and failure and deformation mechanisms that were previously unknown or little understood can now be revealed. Consequently, designs can be made more economical yet remain safe. Alternate designs can be pursued and an optimal design developed whereby over-simplified assumptions can be avoided and accuracy and reliability can be significantly increased.

Before advanced numerical techniques can be applied in practice, their ability to accurately predict field performance and their sensitivity to input load and resistance parameters must be established. Case studies are necessary to first “calibrate” the methods against observed performance and subsequently to conduct sensitivity studies and evaluate design alternatives and cost tradeoffs. In some cases, the uncertainty with respect to the extreme event loading may be overwhelming, and the increased sophistication in numerical modeling will not lead to improvements in design. However, in many cases more sophisticated modeling can lead to more reliable (i.e., safer) designs and/or cost significant savings, particularly with respect to extreme events, which apply extreme demands on the geotechnical and structural systems. For instance, numerical models can consider the effect of construction and stress history on soil properties. An example here is the evaluation of the tensile (uplift) capacity of driven pile foundations where traditional methods in which the piles are “wished in place” and the effect of pile driving on the soil properties is ignored may lead to unrealistic predictions for uplift deformation and ultimate capacity.

The use of advanced numerical methods can also provide significant benefits with respect to reliability-based designs for extreme load cases. The impact of variability and uncertainty with respect to both load and resistance parameters can be investigated with these methods. Such analyses may demonstrate that certain parameters, which are difficult to assess have little impact on permanent deformations due to extreme loading, e.g. the elastic, pre-yield stiffness of soil. The scale at which spatial and temporal property variations affect performance, information essential in developing exploration and testing programs, can also be quantified using these methods.

Sometimes advanced constitutive models employ parameters that cannot be well-established based upon correlation with soil type or typical laboratory test results. Performing specialized sampling and testing is expensive and unlikely to be conducted on most projects. The most significant data requirements for performance-based evaluations under extreme loading should be identified and, whenever possible, correlations with index properties and/or default parameters for advanced constitutive models provided. Databases of typical material properties and input parameters for various constitutive models are a valuable resource and can promote more widespread application of these advanced numerical techniques. Properties and parameters inherent to particular rock and soil formations may prevail over large areas and regional databases of appropriate input parameters, including elastic constants, plastic moduli, ultimate strengths, creep model parameters and in-situ stress regimes may be developed from case history analysis and through compilation of results from previous projects and studies. Furthermore, properties for select materials placed and compacted during construction are generally relatively uniform and consistent (compared to in-situ soils) and can often be reliably established based upon soil type from “typical property” tables. The development of correlations between different soil types and relevant material properties is more challenging for sophisticated constitutive models that incorporate many material parameters than for simple “c-ϕ” soil models. However, if the model parameters are kept to a minimum, and each is associated with some physical interpretation, correlations with index properties such as void ratio, water content, Atterberg limits, and fines content are possible and can greatly facilitate the use of these models to evaluate the performance of highway facilities subject to an extreme event.

IV. RESEARCH OBJECTIVE

The objectives of the research are to implement analyses necessary to fully incorporate performance-based design for extreme events in the design of foundations for bridges and other highway structures. The final product will be guidance on the use of advanced numerical methods for performance based geotechnical design, including determination of required input parameters; a database of observations useful for calibration of the models; and descriptions of alternative, simplified methods of analysis for deformation based design. Tasks necessary to achieve these objectives include:

1. Perform a search of the existing literature to collect information on past performance of foundations for bridges and other structures during and after extreme events, and the availability of simplified methods of analysis and advanced numerical methods including sophisticated constitutive models for soils.
2. Develop guidelines for tolerable deformations for foundations during extreme events. Consider both transient and permanent deformations.
3. Select advanced constitutive models and simplified methods of analysis for evaluation and identify the input parameters needed for analysis.
4. Collect existing data on appropriate soils testing and associated parameters and prepare a database correlating soil characteristics and soil behavior to facilitate selection of soils parameters for analysis of extreme event loading.
5. Describe procedures for estimating necessary parameters for analysis using the database described in Task 3 and sampling/testing necessary to utilize or augment existing data.
6. Evaluate and compare modeling errors inherent to use of advanced numerical methods compared to simplified methods of analysis. Where feasible, relate the results of the constitutive model, to a simpler model that is commonly used in routine design.

7. Evaluate the sensitivity of the results to uncertainty on load and resistance parameters for extreme events including earthquakes, vessel and vehicle collisions, ice loading and blast loading.
8. Compare the relative magnitudes of uncertainty with respect to load and resistance.
9. Evaluate the probability of failure, i.e. risk of failure, for various facilities and extreme events.
10. Prepare a recommended practice for analysis of extreme event loadings considering the load deformation response of the soil-structure system and corresponding load path to failure for different foundation elements and earth structures.

Key Words: Blast, Collapse, Collision, Earthquake, Extreme Events, Foundations, Earth Structure, Hurricane, LRFD, Performance-Based Design, Numerical Analysis, Seismic, Soil-Structure Interaction, Wind

Related Work

1. FHWA Project 106 (Completed) – Seismic Vulnerability of Existing Highway Construction.
2. FHWA Project 112 (Completed) – Seismic Vulnerability of New Highway Construction.
3. NCHRP 12-48 (Completed) – Design of Highway Bridges for Extreme Events.
4. NCHRP 12-49 (Completed) – Comprehensive Specifications for the Seismic Design of Bridges.
5. FLPIER, FB-Pier – Florida Pier finite element analysis programs for analysis of bridge substructures including pile foundations subject to ship collision.
6. VELACS Project (completed) – Verification of Liquefaction Analysis by Centrifuge Studies, http://gees.usc.edu/velacs/MainPage.htm
7. Anandarajah, A. (2005). Workshop on "Nonlinear Modeling of Geotechnical Problems: From theory to practice." http://www.ce.jhu.edu/rajah/My%20Web%20Page/NSF%20Workshop%202005/index.htm)
8. NCHRP 12-70 (ongoing) – Seismic Analysis and Design of Retaining Walls, Buried Structures, Slopes and Embankments.
9. NCHRP 12-72 (ongoing) – Blast-Resistant Highway Bridges: Design and Detailing Guidelines.
10. NEES (ongoing) – Network for Earthquake Engineering Simulation

V. ESTIMATE OF PROBLEM FUNDING AND RESEARCH PERIOD

Recommended Funding: It is estimated that the cost to complete the research proposed herein will be approximately $1,500,000.

Research Period: The estimated time needed to complete the research described here will be on the order of 48 months.

VI. URGENCY, PAYOFF POTENTIAL, IMPLEMENTATION AND SUPPORT FOR BUSINESS NEEDS

Initiation of this work is urgent. The extreme event portion of the LRFD design code needs further development to avoid undue conservatism in the design and to provide guidance on assessing the safety of bridges and highway facilities during extreme event loadings. In many cases extreme event loading governs the design.

The current seismic design provisions contained in the AASHTO LRFD Bridge Design Specifications are, for the most part, based on provisions and approaches carried over from Division I-A, “Seismic Design,” of the AASHTO Standard Specifications for Highway Bridges. The Division I-A provisions were originally issued by AASHTO as a Guide Specification in 1983 and were subsequently incorporated with little modification into the Standard Specifications in 1991. The current LRFD provisions are, therefore, based on seismic hazard, and design criteria and detailing provisions, that are now considered at least 10 years and in many cases 20 years out-of-date. There have been many advances in earthquake engineering state-of-the-art since the adoption of AASHTO’s Standard Specifications for Highway Bridges, Division 1A. Many of these advances were incorporated into the recommendations included with the results from NCHRP Project 12-49.

AASHTO’s Technical Committee for Seismic Design (T-3) has been reluctant to adopt the results of research conducted under NCHRP 12-49. This is due to several concerns, most notably: apparent complexity of the proposed guide specifications, the extreme event hazard level, and expansion of the “no analysis” areas beyond what is practice today. Results of the research will more readily facilitate acceptance of the LRFD Specifications by the engineering community in that the goal of achieving more consistency between different agencies recommending seismic design standards including the IBC, FEMA, and the ATC will be realized.

This problem statement addresses three topics in the 2005 AASHTO Highway Subcommittee on Bridges and Structures “Grand Challenges: *A Strategic Plan for Bridge Engineering”:*

- Grand Challenge 1: Extending Service Life
- Grand Challenge 2: Optimizing Structural Systems
- Grand Challenge 4: Advancing The AASHTO Specifications

This project should be implemented through NCHRP.

VII. PERSONS DEVELOPING THE PROBLEM

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VIII. PROBLEM MONITOR

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IX. DATE AND SUBMITTED BY

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