Highway Bridge Seismic Design: Summary of FHWA/MCEER Project on Seismic Vulnerability of New Highway Construction

by Ian M. Friedland

Research Objectives

The FHWA-sponsored project titled Seismic Vulnerability of New Highway Construction (MCEER Project 112), which was completed in 1998, performed studies on the seismic design and vulnerability analysis of highway bridges, tunnels, and retaining structures. Extensive research was conducted to provide revisions and improvements to current design and detailing approaches and national design specifications for highway bridges. The program included both analytical and experimental studies, and addressed seismic hazard exposure and ground motion input for the U.S. highway system; foundation design and soil behavior; structural importance, analysis, and response; structural design issues and details; and structural design criteria.

In the fall of 1992, MCEER commenced work on a comprehensive research program sponsored by the Federal Highway Administration to evaluate the seismic vulnerability of new and existing highway construction. One part of this two-contract program, Seismic Vulnerability of New Highway Construction (Project 112), resulted in a series of special studies related to seismic design of highway bridges, tunnels, and retaining structures, in order to develop technical information upon which new seismic design approaches and details, and future specifications, could be based. The project was prompted in part because significant progress had been made over the last two decades in several key areas, including improved knowledge of: (1) seismic hazard and risk throughout the United States, (2) geotechnical earthquake engineering, and (3) seismically resistant design. At the time Project 112 was initiated, however, there were still many gaps in basic knowledge, and some of the recently-developed information and data required additional study before they could be applied directly to highway engineering applications nationwide. Consequently, Project 112 resulted in a series of analytical and experimental studies related to the seismic analysis, design, and performance of bridges, tunnels, and foundations.

Sponsors

Federal Highway Administration

Research Team

Project Management

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Key Subcontract Institutions

- *University at Buffalo*
- *Applied Technology Council*
- *Brigham Young University*
- *Dynamic Isolation Systems Inc.*
- *Earth Mechanics Inc.*
- *Geomatrix Consultants Inc.*
- *Imbsen & Associates Inc.*
- *Modjeski and Masters Consulting Engineers*
- *Princeton University*
- *Rensselaer Polytechnic Institute*
- *University of Nevada, Reno*
- *University of Southern California*

The research conducted under Project 112 had a national focus and was intended, in large part, to address differences in seismicity, bridge types, and typical design details between eastern or central U.S. bridges, and those that had been previously studied in California and the western U.S. In particular, unlike the western U.S., design strategies used in the eastern and central U.S. need to reflect the statistical probability that an earthquake significantly larger than the "design" earthquake can occur. In many cases, it was noted that California design practice required significant modification before being implemented in the eastern and central U.S. due to these differences in seismicity and bridge construction type.

A range of special studies were carried out that encompassed research on: seismic hazard; foundation properties, soil properties, and soil response; and the response of structures and systems (see Figure 1). These studies were conducted by a consortium of researchers, coordinated by MCEER. The consortium included a variety of academic institutions and consulting engineering firms, bringing together more than 20 earthquake and bridge engineers and scientists. This consortium provided a balance between researchers and practicing professionals from the eastern, central, and western U.S.

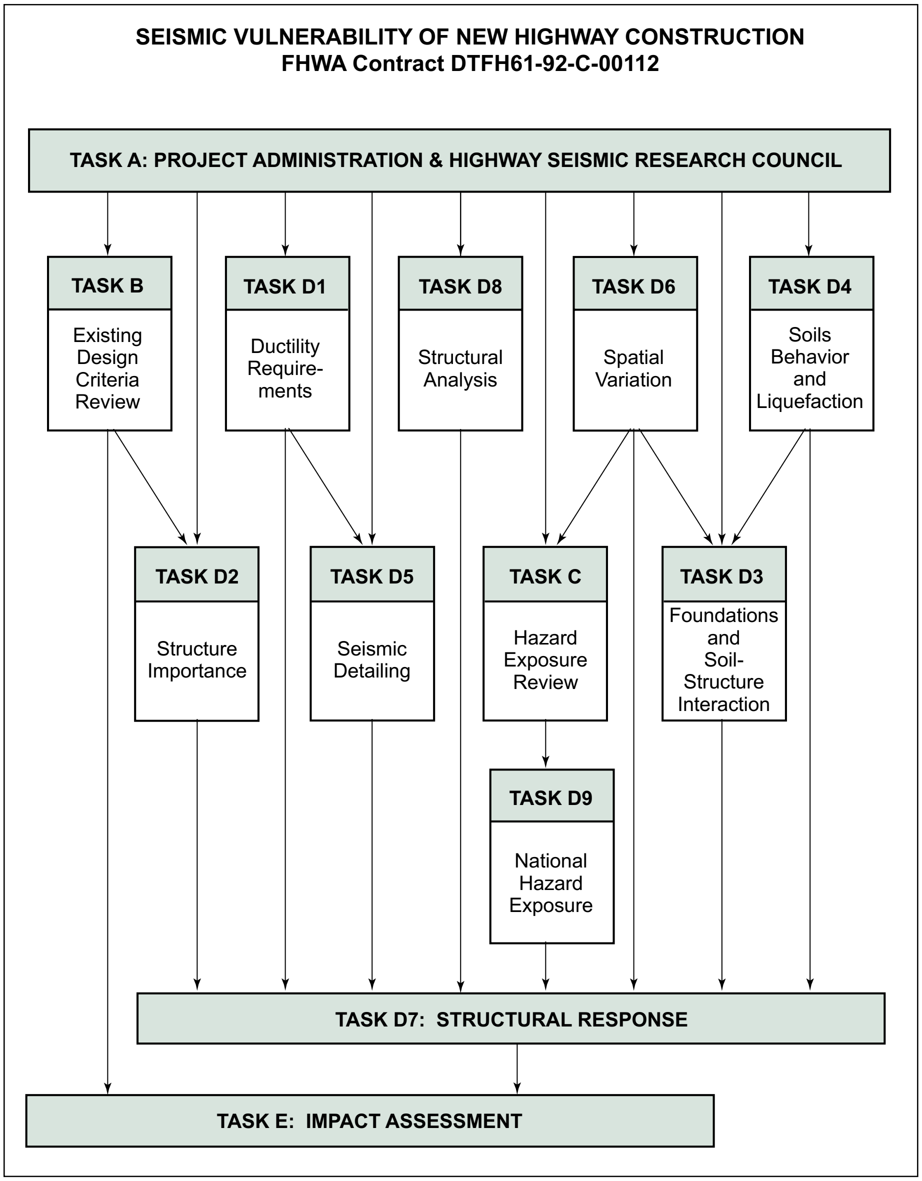
It is anticipated that current specifications for the seismic design of bridges will be revised, and that new seismic design guidelines will be prepared for other highway system components, in part on the basis of this work.

This paper summarizes some of the important results of the research conducted under the program. It draws heavily from a review of the program's research results and expected impacts (Rojahn et al., 1999) and discusses issues raised in the report.

Seismic Hazard Exposure and Ground Motion Input

The research in the area of seismic hazard exposure focused on the evaluation of alternative approaches for portraying and representing the national seismic hazard exposure in the U.S., quantifying and developing an understanding of the effects of spatial variation of ground motion

It is anticipated that the results of this program will be considered in future design specification development work. Specifically, the AASHTO-sponsored National Cooperative Highway Research Program (NCHRP) initiated NCHRP Project 12-49, "Development of Comprehensive Bridge Specifications and Commentary" in the fall of 1998. The objective of NCHRP Project 12-49, which is being conducted by a joint venture between MCEER and the Applied Technology Council, is to develop new bridge seismic design specifications, commentary, and design examples, which can be incorporated into the AASHTO *LRFD Bridge Design Specifications* in the near future. Much of the basis for the specification changes that will be recommended under NCHRP Project 12-49 are expected to be drawn from the results of the work conducted under this FHWA contract.



■ Figure 1. Special Studies Conducted by MCEER under Project 112

Links to Current Research

- *Seismic Vulnerability of Existing Construction (Project 106)*
- *Seismic Vulnerability of the National Highway System (TEA-21 Project)*
- *National Cooperative Highway Research Program (NCHRP) Project 12-49*

on the performance of highway structures, and the development of inelastic design spectra for assessing inelastic deformation demands.

Representation of Seismic Hazard Exposure

Research in the area of seismic hazard exposure representation was conducted in order to:

- explore a number of important issues involved in national representations of seismic ground motions for design of highway facilities;
- recommend future directions for national seismic ground motion representation, especially for use in nationally applicable guidelines and specifications such as the AASHTO seismic design provisions for bridges; and
- identify areas where further development and/or research are needed to define ground motion

Collaborative Partners

Design and Performance Criteria

- *Review Existing Design Criteria and Philosophies,* ***C. Rojahn, R. Mayes, I. Buckle***
- *Impact Assessment and Strawman Guidelines for the Seismic Design of Highway Bridges,* ***C. Rojahn, R. Mayes, I. Buckle***

Seismic Hazard and Exposure

- *Compile and Evaluate Maps and Other Representations, and Summarize Alternative Strategies for Portraying the National Hazard Exposure of the Highway System,* ***M. Power***
- *Recommended Approach for Portraying the National Hazard Exposure,* ***M. Power***

Ductility Requirements

- *Establish Representative Pier Types for Comprehensive Study – Eastern & Western U.S.,* ***J. Kulicki, R. Imbsen***
- *Physical and Analytical Modeling to Derive Overall Inelastic Response of Bridge Piers,* ***J. Mander***
- *Derive Inelastic Design Spectra,* ***R. Imbsen***

Structure Importance

- *Evaluation of Structure Importance,* ***J. Kulicki***

representation for the design of guidelines and specifications.

The ground motion issues that have emerged in recent years as potentially important to the design of highway facilities and that were considered in this work included consideration of the following:

- What should be the basis for the national seismic hazard portrayal of highway facilities, and how should this be implemented in terms of design values?
- Can or should energy or duration be used in a design procedure?
- How should site effects be characterized for design?
- Should vertical ground motions be specified for design?
- Should near-source ground motions be specified for design?

The following summarize the key elements of each issue and conclusions of the research.

Seismic Hazard Portrayal

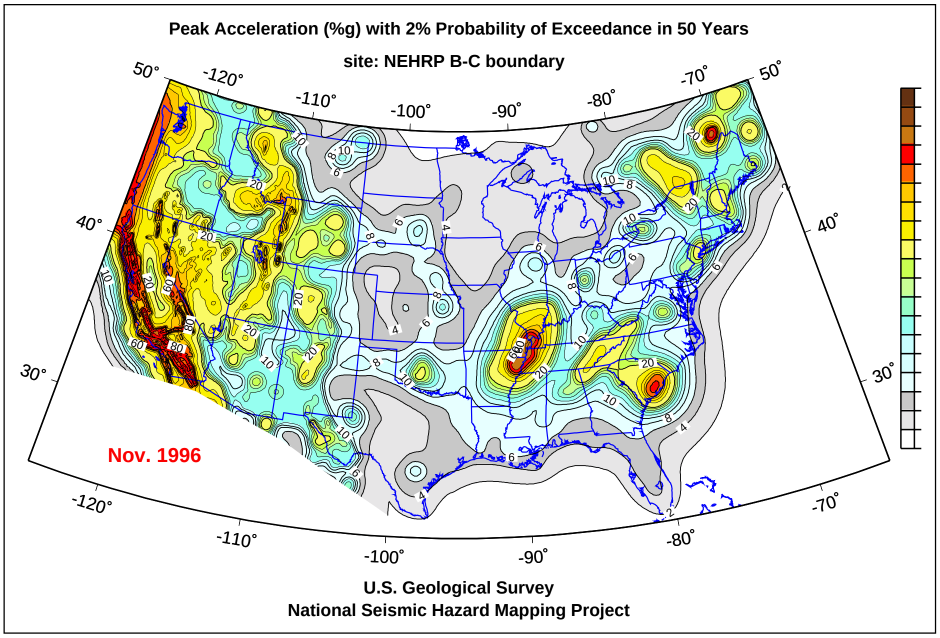
In 1996, the U.S. Geological Survey (USGS) developed new seismic ground shaking maps for the contiguous U.S. These maps depict contours of peak ground acceleration (PGA) and spectral accelerations (SA) at 0.2, 0.3, and 1.0 second (for 5% critical damping) of ground motions on rock for probabilities of exceedance (PE) of 10%, 5%, and 2% in 50 years, corresponding to return periods of approximately 500, 1000, and 2500 years, respectively.

The research considered whether the new USGS maps should replace or update the maps currently in AASHTO, which were developed by the USGS in 1988. The key issue regarding whether the new USGS maps should provide a basis for the national seismic hazard portrayal for highway facilities is the degree to which they provide a scientifically improved representation of seismic ground motion. Based on an analysis of the process of developing the maps, the inputs to the mapping, and the resulting map values, it was concluded that these new maps represent a major step forward in the characterization of national seismic ground motion. The maps are in substantially better agreement with current scientific understanding of seismic sources and ground motion attenuation throughout the U.S. than the current AASHTO maps. It was therefore concluded that the new USGS maps should provide the basis for a new national seismic hazard portrayal for highway facilities.

The issue of an appropriate probability level or return period for design ground motions based on the new USGS maps was also examined. Analyses were presented showing the effect of probability level or return period on ground motions and comparisons of ground motions from the new USGS maps and the current AASHTO maps. The research recommended that, for design of highway facilities against collapse, consideration should be

Technical Report: Seismic Hazard Exposure

- **Proceedings of the FHWA/MCEER Workshop on the National Representation of Seismic Ground Motion for New and Existing Highway Facilities, edited by I.M. Friedland, M.S. Power and R.L. Mayes, NCEER-97-0010.**



U.S. Geological Survey

■ Figure 2. Peak ground accelerations represented as a percentage of g with a 2% probability of exceedance in 50 years

given to adopting probability levels for design ground motions that are lower than the 10% probability of exceedance in 50 years that is currently in AASHTO. This is consistent with proposed revisions to the 1997 NEHRP provisions for buildings, in which the new USGS maps for a probability of exceedance of 2% in 50 years (2,500 year return period) have been adopted as a collapse-prevention design basis. It was determined that, from a deterministic standpoint, the 2%/50 year maps provided a good representation of the acceleration and force levels that had occurred in the 1800s in both the New Madrid seismic zone and in Charleston, South Carolina.

Consideration of Energy or Duration

At the present time, the energy or duration of ground motions is not explicitly recognized in the design process for bridges or buildings, yet many engineers are of the opinion that the performance of a structure may be significantly affected by these parameters, in addition to the response spectral characteristics of the ground motion. As a result, it was concluded that some measure of the energy of ground motions is important to the response of a bridge, but, at present, there is no accepted design procedure to account for energy. It was recommended that research in this area should be continued to develop energy-based design methods that can supplement current elastic-response-spectrum-based design methods. It was also concluded that energy rather than duration is the fundamental parameter affecting structural behavior.

Characterization of Site Effects

At a Site Effects Workshop held in 1992 at the University of Southern California (USC), a revised quantification of site effects on response spectra and revised definitions of

Collaborative Partners (cont.)

Foundations and Soil-Structure Interaction

- *Compile Data and Identify Key Issues,* ***I.P. Lam***
- *Abutment and Pile Footing Studies by Centrifuge Testing,* ***R. Dobry***
- *Develop Analysis and Design Procedures for Abutments,* ***I.P. Lam, G. Martin***
- *Develop Analysis and Design Procedures for Retaining Structures,* ***R. Richards, K. Fishman***
- *Develop Analysis and Design Procedures for Pile Footings,* ***I.P. Lam, G. Martin***
- *Develop Analysis and Design Procedures for Drilled Shafts,* ***I.P. Lam, G. Martin***
- *Develop Analysis and Design Procedures for Spread Footings,* ***G. Gazetas***
- *Performance and Sensitivity Evaluation, and Guideline Development,* ***P. Lam, R. Dobry, G. Martin***

Soil Behavior and Liquefaction

- *Site Response Effects,* ***R. Dobry***
- *Identification of Liquefaction Potential,* ***T.L. Youd***
- *Development of Liquefaction Mitigation Methodologies,* ***G. Martin***
- *Design Recommendations for Site Response and Liquefaction Mitigation,* ***G. Martin***

Collaborative Partners (cont.)

Special Seismic Detailing

- *Capacity Detailing of Columns, Walls, and Piers for Ductility and Shear,* ***J. Mander, R. Imbsen, J. Kulicki, M. Saiidi***
- *Capacity Detailing of Members to Ensure Elastic Behavior,* ***J. Mander, R. Imbsen, J. Kulicki***
- *Detailing for Structural Movements - Bridges,* ***R. Imbsen, J. Kulicki***
- *Detailing for Structural Movements - Tunnels,* ***M. Power***
- *Structural Steel and Steel/ Concrete Interface Details,* ***J. Kulicki***

Spatial Variation of Ground Motion

- *Spatial Variation of Ground Motion,* ***M. Shinozuka, G. Deodatis***

Structural Response

- *Effects of Vertical Acceleration on Structural Response,* ***M. Button***

Structural Analysis

- *Review Existing Analytical Methods, and Identify and Recommend Analytical Procedures Appropriate for Each Structure Category and Hazard Exposure,* ***I. Buckle, J. Mander***

site categories were proposed. Subsequently, these revised site factors and site categories were adopted into the 1994 NEHRP provisions and the 1997 Uniform Building Code (UBC). Since the development of these revised site factors, two significant earthquakes occurred (the 1994 Northridge and 1995 Kobe earthquakes) which provided substantial additional data for evaluating site effects on ground motions, and research using these data has been conducted.

The site factors and site categories in the current AASHTO specifications are those that were superseded by the USC Workshop recommendations in the NEHRP Provisions and the UBC. Under this research, the question was whether the USC Workshop recommendations should be utilized in characterizing ground motions for highway facilities design and whether they should be modified to reflect new data and new knowledge since the 1992 Workshop. The most significant differences between the USC Workshop recommendations and the previous site factors (those currently in AASHTO) are: (1) the revised site factors include separate sets of factors for the short-period and long-period parts of the response spectrum, whereas the previous site factors were only for the long-period part; (2) the revised site factors are dependent on rather than independent of intensity of ground shaking, reflecting soil nonlinear response; and (3) the revised site factors are larger (i.e., show a greater soil response amplification) than the previous factors at low levels of shaking, and are appropriate to the lower-seismicity regions in the U.S.

It was found that the post-Northridge and post-Kobe earthquake research conducted to date was supportive of the site factors derived in the 1992 USC Workshop, although revisions to these factors might be considered as further research findings on site effects become available.

Vertical Ground Motions

At present, the AASHTO specifications do not contain explicit requirements to design for vertical accelerations. Ground motion data from many earthquakes in the past 20 years have shown that, in the near-source region, very high short-period vertical spectral accelerations can occur. For near-source moderate-to-large magnitude earthquakes, the rule-of-thumb ratio of 2/3 between vertical and horizontal spectra is a poor descriptor of vertical ground motions. At short periods, the vertical-to-horizontal spectral ratios can substantially exceed unity, whereas at long periods, a ratio of two-thirds may be conservative. It was demonstrated that the profession's current understanding and ability to characterize near-source vertical ground motions is good, especially in the western U.S. where the near-source region is better defined (i.e., near mapped-active faults). It was also demonstrated that high vertical accelerations as may be experienced in the near-source region can significantly impact bridge response and design requirements in some cases. On the basis of these findings, it was concluded that vertical ground motions should be considered in bridge design in higher seismic zones for certain types of bridge construction. However, specific design criteria and procedures still need to be developed for certain bridge types.

Near-source Ground Motions

The characteristics and the effects of near-source ground motions on bridge response were examined. As the distance to an earthquake source decreases, the intensity of ground motions increases, and this increase in ground motion intensity is incorporated in new USGS maps. However, in addition to their higher intensity, near-source ground motions have certain unique characteristics that are not found at greater distances. The most significant characteristic appears to be a large pulse of long-period ground motions when an earthquake rupture propagates toward a site. Furthermore, this pulse is larger in the direction perpendicular to the strike of the fault than in the direction parallel to the strike. This characteristic of near-source ground motions has been observed in many earthquakes, including most recently in the Northridge, Kobe, Turkey and Taiwan earthquakes. Preliminary analyses of bridge response indicate that near-source ground motions may impose unusually large displacement demands on bridge structures. It was therefore concluded that traditional ground motion characterizations (i.e., response spectra) may not be adequate in describing near-source ground motions, because the pulsive character of these motions may be more damaging than indicated by the response spectra of the motions. Recommendations include the need for additional research to evaluate more fully the effects of near-source ground motions on bridge response and to incorporate these effects in code design procedures. Until adequate procedures are developed, consideration should be given to evaluating bridge response using site-specific analyses with representative near-source acceleration time histories.

Spatial Variation of Ground Motion

The objective of the research in this area was to develop procedures for determining spectrum compatible time histories that adequately represent spatial variations in ground motion including the effects of different soil conditions. The procedures were then used to examine the effects of spatial variability on critical response quantities for typical structures.

The methodology used a spectral representation to simulate stochastic vector processes having components corresponding to different locations on the ground surface. An iterative scheme was used to generate time histories compatible with prescribed response spectra, coherency, and duration of motion. Analysis results for eight example bridges were tabulated, showing the relative ductility demand ratio for column flexure due to seismic wave propagation spatial effects. In general, there was about a 10% maximum increase when using

Summary Report: Spatial Variation of Ground Motion

- **Effect of Spatial Variation of Ground Motion on Highway Structures, by M. Shinozuka and G. Deodatis, Agency Final Report.**

Photographs courtesy of I.G. Buckle

■ Figure 3. Research in spatial variation of ground motion included case studies of the SR14/I-5 interchange and other bridges damaged during the Northridge, California earthquake. Further research is needed to define the importance of these effects and to develop simplified design procedures for a broad range of bridge configurations.

linear analysis, and a 25% maximum increase when using nonlinear analysis for bridges up to 1000 feet in length. Results were also tabulated for relative opening and closing at expansion joints for bridges with superstructure hinges. In general, the relative joint opening movement was up to two times when using either linear or nonlinear analysis for bridges up to 1000 feet in length. However, the conducted analyses were too limited in scope on which to base specific guidance for a large variety of bridge types and conditions at this time, and it was recommended that further studies are required before code language could be developed.

Inelastic Design Spectrum

The research in this area had the objective of developing inelastic response spectrum which would allow designers to assess the inelastic deformation demands, ultimately leading to improved seismic performance for new bridge construction. The spectrum are being derived for nationwide use, accommodating different seismic environments and site soil conditions. They are also being developed for design applications, by accounting for scattering and variabilities that exist in real earthquake ground motions and for nonlinear structural response.

Under the current program, the research has not progressed to the point where its results are ready for implementation. When complete, it is likely to have a major impact on seismic design code requirements for bridges, as inelastic spectra will be one of the key elements in a displacement-based or energy-based design procedure. Future work in this area should include procedures for determining inelastic spectra at a specific site. The current state of research provides an approximate method that starts with an elastic spectrum rather than time history; as time histories for the eastern U.S. are currently lacking, this approach will have an obvious appeal.

Foundation Design and Soil Behavior

Research tasks in this area investigated and improved criteria for the design and analysis of major foundation elements including abutments, retaining walls, pile and spread footings, and drilled shafts. In addition, work was performed on soil liquefaction and lateral spread identification and mitigation.

Abutments and Retaining Walls

Research on bridge abutments and retaining walls focused on modeling alternatives, clarifying the process of design for service loads versus seismic loading, and providing simplified approaches for design that incorporate key issues affecting seismic response. The research also attempted to provide a new procedure for determining the seismic displacements of abutments and retaining walls founded on spread footings, which differ from current procedures by addressing mixed-mode behavior (i.e., including rotation due to bearing capacity movement and sliding response). Both experimental and analytical studies were conducted; the experimental studies included sand-box experiments on a shaking table and centrifuge models. Results of this research included:

- Development of a simplified procedure for estimating abutment stiffness. A key element of this approach is determining the portion of the wall that can be relied on to mobilize backfill resistance.
- Extending current AASHTO design procedures to the more general case of translation and rotation of walls and abutments. The results are presented in a manner that will allow the methods to be easily introduced into a future code revision. The new procedures will be of greatest use for free-standing gravity walls and for active mode abutment and wall movements.
- Consideration of passive loading conditions for walls and abutments. Current AASHTO provisions only address active loading conditions. Since passive loading can result in forces that are up to 30 times those for active conditions, there is a strong possibility that many bridges will not develop passive resistance without abutment damage.

Pile and Spread Footings, and Pile Groups

Studies on pile footings, spread footings, and pile groups included experimental and analytical research which was intended to: (a) provide improved understanding of

Web Sites

MCEER Highway Project
http://mceer.buffalo.edu/research/HighwayPrj/default.html

MCEER Publications
http://mceer.buffalo.edu/publications/default.asp

Technical and Summary Reports: Foundation Design and Soil Behavior

- **Foundations and Soils - Compile Data and Identify Key Issues, by I.P. Lam, Agency Final Report.**
- **Centrifuge Modeling of Cyclic Lateral Response of Pile-Cap Systems and Seat-Type Abutments in Dry Sands, by A. Gadre and R. Dobry, MCEER-98-0010.**
- **Modeling of Bridge Abutments in Seismic Response Analysis of Highway Bridges, I.P. Lam and M. Kapuskar, Agency Final Report.**
- **Seismic Analysis and Design of Bridge Abutments Considering Sliding and Rotation, by K.L. Fishman and R. Richards, Jr., NCEER-97-0009.**
- **Modeling of Pile Footings and Drilled Shafts for Seismic Design, by I.P. Lam, M. Kapuskar and D. Chaudhuri, MCEER-98-0018.**
- **Development of Analysis and Design Procedures for Spread Footings, by G. Gazetas, G. Milonakis and A. Nikolaou, Agency Final Report.**
- **Synthesis Report on Foundation Stiffness and Sensitivity Evaluation on Bridge Response, by I. P. Lam, G.R. Martin, and M. Kapuskar, Agency Final Report.**

"Among the major studies conducted under this project was a review, synthesis, and improvement to recent developments in simplified procedures for evaluating the liquefaction resistance of soils, and the compilation and evaluation of case studies and procedures for ground liquefaction mitigation."

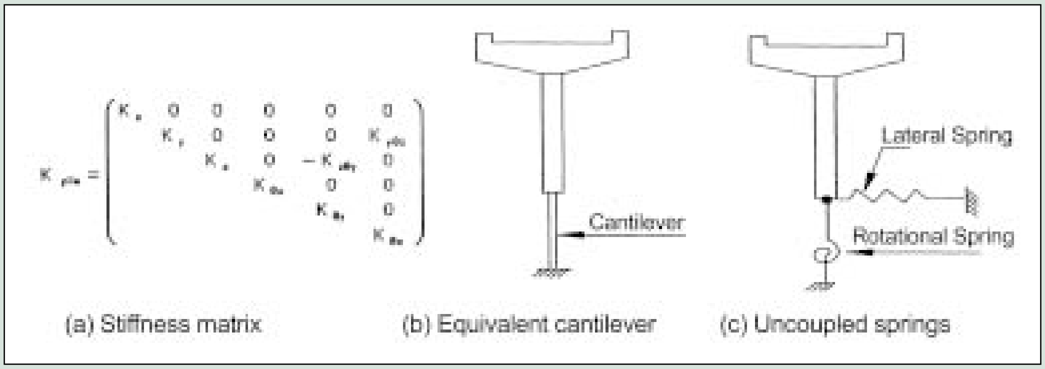
the lateral response of pile-cap foundations; (b) evaluate the influence of modeling parameters on estimated displacement and force demands; (c) recommend methods for characterizing the stiffness of pile footings; (d) quantify the importance of radiation damping and kinematic interaction on response; and (e) evaluate conditions under which uplift becomes significant and how best to model uplift in a design procedure. Results from these studies included the following:

- For pile-cap systems, the research demonstrated that design procedures should use simple additions for the contribution from the base, side and active/passive ends when estimating the lateral capacity of embedded spread footings in dense sand, along with elastic solutions with an equivalent linear soil shear modulus at shallow depths to estimate the secant stiffness of the footing. This effectively confirms that existing procedures can be used to obtain reasonable approximations of pile-cap foundation response, as long as consideration is given to the levels of deformation and embedment for the system.
- Axial and lateral loading response and stiffness characteristics are important parameters for the design of single piles and pile groups, although such information is not currently addressed in the AASHTO provisions. Axial response often controls rocking response of a pile group. New procedures and simplified stiffness charts are provided for determining the lateral load-deflection characteristics of single piles and groups.
- Nonlinear load-deflection analyses illustrate the sensitivity of results to uncertainties in p-y stiffness, gapping, pile-head fixity, bending stiffness parameters, and embedment effects. The analyses have demonstrated that load-deformation response is more affected by input variations than by the moment within the pile.
- For spread footings without uplift, the research demonstrated that (a) ignoring soil-structure interaction reduces the fundamental period of the system, resulting in higher accelerations; (b) increasing the effectiveness of embedment increases radiation damping and reduces the fundamental period of the system; and (c) neglecting radiation damping has only a minor effect on the system. Uplift of the spread footing results in a softer mode of vibration for the system, with increasing fundamental period as the amount of uplift increases.

Drilled Shafts

Research on drilled shafts was conducted in order to provide information on the influence of modeling procedures on the response of the structure, evaluate the effects of modeling on estimated displacement and force demands on the foundation, and to summarize methods for characterizing the response of drilled shaft foundations, including their limitations. Results of this work included the following:

- Foundation stiffness has been shown as a key parameter and contributor to the dynamic response of the structure, necessitating realistic estimates and appropriate integration into a



■ Figure 4. Researchers reviewed three procedures for representing foundation stiffness in the modeling process: (a) coupled foundation stiffness matrix, (b) equivalent cantilever approach; and (c) uncoupled base-spring model.

detailed structural analysis. The response of a soil-foundation system to load is nonlinear; however, for practical purposes, an equivalent linear representation is normally used.

- Guidance is provided on the development of equivalent linear and nonlinear stiffness values, and the importance and sensitivity of foundation geometry and boundary conditions at the shaft head are identified. A key conclusion is that realistic representation of pile-head fixity can lead to a much more economical design.
- The p-y approach is recognized as the most common method of analyzing the nonlinear response of the shaft to lateral load. Parameters that must be considered include the effects of soil property variation, degradation effects, embedment, gapping, and scour effects.

Liquefaction Processes and Liquefaction Mitigation Methodologies

A significant amount of research was conducted under the MCEER Highway Project on liquefaction processes, screening for liquefaction potential, and the development and/ or improvement of liquefaction mitigation methodologies. Much of this work was conducted under a companion FHWA contract on the seismic vulnerability of existing transportation infrastructure (FHWA Contract DTFH61-92-C-00106), but much of it is appropriate for both new design and existing structure evaluation. Among the major studies conducted under this project was a review, synthesis, and improvement to recent developments in simplified procedures for evaluating the liquefaction resistance of soils, and the compilation and evaluation of case studies and procedures for ground liquefaction mitigation. Results of this research included:

- Identification of a consensus simplified procedure for evaluating liquefaction resistance. Minor modifications for the determination of the stress reduction factor used in the calculation of the cyclic stress ratio were recommended, which allow the stress reduction factor to be

> *"Structural importance, analysis, and response studies provided a synthesis of current systems and details commonly used to provide acceptable seismic performance in various states and regions."*

Technical and Summary Reports: Soil Behavior and Liquefaction

- **Site Factors and Site Categories in Seismic Codes, by R. Dobry, R. Ramos and M. Power, MCEER-99-0010.**
- **Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils, edited by T.L. Youd and I.M. Idriss, NCEER-97-0022.**
- **Development of Liquefaction Mitigation Methodologies/Ground Densification Methods, by G. Martin, Agency Final Report.**
- **Design Recommendations for Site Response and Liquefaction, by G. Martin, Agency Final Report.**

calculated to depths greater than 30 meters.

- Identification of the latest procedures for determining cyclic resistance ratios (CRR) using cone penetration test (CPT) procedures. One of the primary advantages of CPT is the consistency and repeatability of the method. Plots for determining the liquefaction resistance directly from CPT data, rather than converting to an equivalent standard penetration test (SPT) N-value, are presented. Procedures are also provided for correcting CPT data based on overburden pressures, fines contents, and for thin layers.
- Plots for determining CRR from shear wave velocity data have been prepared, and procedures for correcting shear wave velocity data due to overburden stress and fines content are explicitly given.
- Methods which have been employed successfully for liquefaction mitigation include deep dynamic compaction, deep vibratory densification, gravel drains, permeation grouting, replacement grouting, soil mixing, and micro blasting. Parameters and limitations for each of these approaches are summarized, including typical treatment depths and applicable soil types.
- Flow charts for assessing ground deformations for pre- and post-treatment conditions were developed. These are accompanied by recommendations for preferred ground improvements methods based on differing site conditions.
- Development of rapid screening procedures for liquefaction susceptibility of soils and foundations.

Structural Importance, Analysis and Response

Studies were conducted in order to provide a definition of structural importance, which is necessary in the development of design and performance criteria, and to evaluate methods of analysis and structural response. Structural importance analysis response studies also provided a synthesis of current systems and details commonly used to provide acceptable seismic performance in various states and regions. Among the findings of these studies were the following:

- Provisions employed by the California Department of Transportation (Caltrans) were generally more rigorous than those used by the majority of states (who primarily used current AASHTO provisions). However, adoption of Caltrans' design provisions nationwide would likely complicate designs and add to construction cost; this may be unjustified for many low-to-moderate seismic hazard states. In addition, if Caltrans' experience is to be adopted nationally, some adjustments are required in order to accommodate bridge types and details commonly used elsewhere.

- Studies that were conducted on the application of advanced modeling methods for concrete bridge components provided a computer program which determines moment-curvature and force-deflection characteristics for reinforced concrete columns; excellent correlation was obtained between analytical and experimental test results for these components.
- A refined model to simulate the hysteretic behavior of confined and unconfined concrete in both cyclic compression and tension was developed. The model includes consideration of the nature of degradation within partial hysteresis looping and the transition between opening and closing cracks.
- A study on energy and fatigue demands on bridge columns resulted in design recommendations for the assessment of fatigue failure in reinforcing steel, based on the results of nonlinear dynamic analyses. This methodology incorporates traditional strength and ductility considerations with the fatigue demands. Based on parametric studies, it was concluded that low cycle fatigue demand is both earthquake and hysteretic model dependent.
- Based on an examination of existing and proposed methods for quantifying bridge importance, a specific method was selected and tested against a database of bridge information commonly available within the FHWA's National Bridge Inventory. One limitation of the study is that it deliberately avoided addressing political and economic issues related to bridge seismic design criteria and highway network considerations.
- Following the Northridge earthquake, concerns were raised as to the role vertical accelerations may have played in causing damage to one or more bridges. In a study conducted to investigate the effects of vertical acceleration on bridge response, preliminary results indicate that vertical components of ground motion could have a significant effect on bridge response for structures within 10 km of the fault, and even within 20 – 30 km for certain conditions. The results of this study will be controversial when publicized; however, a far too limited study was conducted (only six example

Technical Reports: Structural Importance, Analysis and Response

- **Effect of Vertical Ground Motions on the Structural Response of Highway Bridges, by M. Button, C. Cronin and R. Mayes, MCEER-99-0007.**
- **Methodologies for Evaluating the Importance of Highway Bridges, by A. Thomas, S. Eshenaur and J. Kulicki, MCEER-98-0002.**

bridges were analyzed) in order to provide definitive guidance at this time.

- In a study which investigated the applicability of simplified analysis methods to various types and configurations of bridges, a number of design and analysis limitations were identified. Parameters evaluated included curvature, span length ratio, pier height, skew and span connectivity. Based on the analyses, a definition for "regular" bridges and for which simplified methods are appropriate was developed. In general, regular bridges must have three or fewer spans, variation of mass distribution between adjacent spans varying by less than 50%, a maximum ratio between adjacent pier stiffnesses in the longitudinal and transverse directions not greater than 4.0, and a subtended angle in plan not greater than 90°.

Structural Design Issues and Details

A number of studies were conducted in order to improve design procedures and structural detailing for highway structures, but the focus was primarily on bridges; one study also examined movement detailing for tunnels. These studies looked at issues of capacity detailing for ductility, elastic behavior, and movements. Among the results of this research were the following:

- A design concept termed Damage Avoidance Design (DAD) was developed which attempts to avoid plastic hinging in columns, thereby avoiding loss of service for important bridges following a major earthquake. The concept evaluated details which provide for rocking of columns and piers, which rotate about their ends but are restrained from collapse through gravity and the optional

Undamaged specimen (prior to testing) *Damaged specimen (after testing)*

Photographs courtesy of J. Mander

Figure 5. Researchers developed a new design concept called Control and Repairability of Damage (CARD) for bridge column hinges. The CARD method controls damage while accommodating large earthquake-induced deformations.

use of central unbonded post tensioning in the column core.

- A second design concept termed Control and Repairability of Damage (CARD) was also developed, which provided structural and construction details for reinforced concrete columns that provide replaceable or renewable sacrificial plastic hinge zone components. In this concept, the hinge zones are deliberately weakened and regions outside the hinge zones are detailed to be stronger than the sacrificial (fuse) zone; the remaining elements of the structure then remain elastic during strong earthquakes.
- In a study on transverse reinforcing requirements for concrete bridge columns and pier walls, it was found that the current AASHTO requirements could be lowered by up to 50% while still achieving displacement ductilities of 4 to 7 for bridges in low to moderate seismic zones. An

"Studies in structural design issues and details looked at capacity detailing for ductility, elastic behavior, and movements."

Technical and Summary Reports: Structural Design Issues and Details

- **Application of Simplified Methods of Analysis to the Seismic Design of Bridges, by J.H. Kim, M.R. Button, J.B. Mander and I.G. Buckle, Agency Final Report.**
- **Establish Representative Pier Types for Comprehensive Study: Eastern U.S., by J. Kulicki and Z. Prucz, NCEER-96-0005.**
- **Establish Representative Pier Types for Comprehensive Study: Western U.S., by R.A. Imbsen, R.A. Schamber, and T.A. Osterkamp, NCEER-96-0006.**
- **Seismic Resistance of Bridge Piers Based on Damage Avoidance Design, by J.B. Mander and C.T. Cheng, NCEER-97-0014.**
- **Seismic Design of Bridge Columns Based on Control and Repairability of Damage, by C.T. Cheng and J.B. Mander, NCEER-97-0013.**
- **Capacity Design and Fatigue Analysis of Confined Concrete Columns, by A. Dutta and J.B. Mander, MCEER-98-0007.**
- **Capacity Design of Bridge Piers and the Analysis of Overstrength, by J.B. Mander, A. Dutta, and P. Goel, MCEER-98-0003.**
- **Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part I – Evaluation of Seismic Capacity, by G.A. Chang and J.B. Mander, NCEER-94-0006.**
- **Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part II – Evaluation of Seismic Demand, by G.A. Chang and J.B. Mander, NCEER-94-0013.**
- **Ductility of Rectangular Reinforced Concrete Bridge Columns with Moderate Confinement, by N. Wehbe, M. Saiidi, D. Sanders and B. Douglas, NCEER-96-0003.**
- **Capacity Detailing of Members to Ensure Elastic Behavior, by R.A. Imbsen, R.A. Schamber, and M. Quest, Agency Final Report.**
- **Capacity Detailing of Members to Ensure Elastic Behavior - Steel Pile-to-Cap Connections, by P. Ritchie and J. M. Kulicki, Agency Final Report.**
- **Structural Steel and Steel/Concrete Interface Details for Bridges, by P. Ritchie, N. Kauhl and J. Kulicki, MCEER-98-0006.**
- **Structural Details to Accommodate Seismic Movements of Highway Bridges and Retaining Walls, R.A. Imbsen, R.A. Schamber, E. Thorkildsen, A. Kartoum, B.T. Martin, T.N. Rosser and J.M. Kulicki, NCEER-97-0007.**
- **Derivation of Inelastic Design Spectrum, by W. D. Liu, R. Imbsen, X. D. Chen and A. Neuenhofer, Agency Final Report.**
- **Summary and Evaluation of Procedures for the Seismic Design of Tunnels., by M. S. Power, D. Rosidi, J. Kaneshiro, S. D. Gilstrap, and S.-J. Chiou, Agency Final Report.**

important aspect of this work was that the end anchorages for transverse steel hoops must be maintained for the reinforcing to be effective; 90° bends on J-hooks were found to be inadequate.

- Research was conducted on moment overstrength capacity in reinforced concrete bridge columns, and a simplified method for determining column overstrength was developed. The upper-bound overstrength factors developed in this task validate prescriptive overstrength factors recommended in ATC-32, but also indicate that some factors in current Caltrans and AASHTO provisions may be too low.
- A synthesis was conducted on details commonly used to accommodate expected movements on bridges and retaining walls in the eastern and western U.S. Based on the synthesis, design and detailing recommendations were made in order to provided the basis for improved bridge design standards. The specific elements considered in this effort included restraining devices, sacrificial elements, passive energy dissipation devices, and isolation bearings. A similar effort was conducted on movement criteria and detailing for tunnels.
- For steel superstructures, a number of issues were considered, including ductility based on cross-section configuration, applicability of eccentrically-braced frames, details which allow for easy repair of steel sections following a moderate to large earthquake, anchor bolt performance under lateral uplift loads, and economical moment connection details between steel superstructures and concrete substructures.

Implementation of Research Results

In the case of highway bridges, seismic design provisions are contained in the two AASHTO bridge specifications: *LRFD Bridge Design Specifications* (2nd Edition, 1998) and Division I-A, Seismic Design, of the *Standard Specifications for Highway Bridges* (16th Edition, 1996). In 1997, AASHTO recognized that there had been many important advances in the knowledge of earthquake hazard, bridge seismic performance, and design and detailing. As a result, AASHTO charged the Transportation Research Board's AASHTO-sponsored National Cooperative Highway Research Program (NCHRP) with conducting a project to update and revise the bridge seismic design specifications contained in the *LRFD Bridge Design Specifications*.

NCHRP Project 12-49, "Comprehensive Specification for the Seismic Design of Bridges," was initiated in

Technical Reports: Implementation of Research Results

- **Impact Assessment of Selected MCEER Highway Project Research on the Seismic Design of Highway Structures, by C. Rojahn, R. Mayes, D.G. Anderson, J.H. Clark, D'Appolonia Engineering, S. Gloyd and R.V. Nutt, MCEER-99-0009.**
- **Seismic Design Criteria for Bridges and Other Structures, by C. Rojahn, R. Mayes, D.G. Anderson, J. Clark, J.H. Hom, R.V. Nutt and M.J. O'Rourke, NCEER-97-0002.**

August 1998. The objective of NCHRP Project 12-49 is to develop new specifications for the seismic design of highway bridges, which can be incorporated into the *LRFD Bridge Design Specifications*. These new specifications will be nationally applicable with provisions for all seismic zones. The results of research currently in progress or recently completed, along with current demonstrated practice, are the principal resources for this project, especially with respect to the research conducted under the FHWA-sponsored MCEER Highway Project.

The design criteria being developed under NCHRP Project 12-49 will address the following: (1) strength-based and displacement-based design philosophies; (2) single- and dual-level performance criteria; (3) acceleration hazard maps and spectral ordinate maps; (4) spatial variation effects; (5) effects of vertical acceleration; (6) site amplification factors; (7) inelastic spectra and use of response modification factors; (8) equivalent static nonlinear analysis methods; (9) modeling of soil-structure interaction and structural discontinuities at expansion joints; (10) duration of the seismic event; and (11) design and detailing requirements for both steel and concrete super- and substructures.

A joint venture of the Applied Technology Council and MCEER was selected by the NCHRP to conduct Project 12-49. In the first phase of the project, the basic philosophy for the new specifications has been developed, along with recommendations regarding representation of seismic hazard for design, and minimum design and performance criteria for typical highway bridges and bridge components. The work conducted previously by MCEER, Caltrans, and others lead directly to the development of this new specification's philosophical framework.

The time schedule for NCHRP Project calls for the completion of a first draft of the specification and commentary by the end of 1999, and subsequent drafts and revisions completed during 2000. The target date for submission of a recommended specification to AASHTO by NCHRP is early 2001.

Conclusion

As a result of a research program sponsored by the Federal Highway Administration, researchers working for the Multidisciplinary Center for Earthquake Engineering Research have developed a number of analytical tools, methods of analysis, structural design details, and specification recommendations appropriate for seismic design of highway systems and structures. The primary focus of this work has been on highway bridges, but some research on tunnels and retaining structures was also performed. The program has also resulted in recommendations regarding the representation of seismic hazard in future design codes, the performance and improvement of soils under seismic shaking, and an improved understanding of the behavior of structural systems and components under seismically-induced forces and displacements. In addition, it is likely that additional recommendations regarding the use of a performance-based design philosophy and dual-level design and performance criteria will be made to AASHTO as a result of this work.

"MCEER has developed a number of analytical tools, methods of analysis, structural design details, and specification recommendations appropriate for seismic design of highway systems and structures."

References

Rojahn, C., Mayes, R., Anderson, D.G., Clark, J.H., D'Appolonia Engineering, Goyd, S. and Nutt, R.V., 1999, *Impact Assessment of Selected MCEER Highway Project Research on the Seismic Design of Highway Structures*, MCEER-99-0009, April.

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Friedland, I.M., Mayes, Ronald L., Yen, Phillip and O'Fallon, John, 2000, "Highway Bridge Seismic Design: How Current Research May Affect Future Design Practice," TRB Bridge Conference, Paper Number 5B0042.