Seismic Vulnerability of New Highway Construction, Executive Summary

FHWA-RD-99-098

MARCH 2002

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Research, Development, and Technology
Turner-Fairbank Highway Research Center
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FOREWORD

This executive summary gives a succinct report on the results of the Federal Highway Administration's study titled "Seismic Research Program," which was conducted at the National Center for Earthquake Engineering Research (NCEER) in Buffalo, NY. The objective of this study was to obtain state-of-the-art technical information to be used in developing new specifications for the seismic design of bridges. This research has taken a national viewpoint and tried to address the issues faced by the central and eastern States as well as those on the west coast.

Since the results of this research will be evaluated and incorporated into future American Association of State Highway and Transportation Officials bridge specifications, there will not be a comprehensive final report. For those interested in more detailed information on the results of this study, there are a number of NCEER or Multidisciplinary Center for Earthquake Engineering Research (MCEER) reports on specific tasks. These documents, as well as the working reports on the others tasks, will be available through MCEER (formerly NCEER). This executive summary will be of interest primarily to researchers, educators, and engineers who wish to look beneath the surface of specifications.

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Director, Office of Infrastructure
Research and Development

NOTICE

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16. Abstract

This executive summary gives an overview of the results of FHWA Contract DTFH61-92-C-00112, Seismic Research Program, which performed a series of special studies addressing the seismic design of new construction. The objectives of this project were to perform a series of special studies pertaining to the seismic vulnerability of highway structures, and to develop technical information on which future specifications for the seismic design of bridges could be based.

This project divided the work into 5 areas and 13 tasks, focussing on the following elements: review of current seismic design criteria, the seismic hazard exposure of the American highway system, foundation design and soil behavior, structural design, structural analysis and response, the relative importance of specific bridges and an assessment of the impact of current and recently completed research.

The Seismic Research Program had a national focus, and aimed in part to address the differences in seismicity, bridge types, and typical design details between the central and eastern United States (CEUS) and those previously studied in California and the western United States. In many cases, west coast design practices required considerable modification before implementation in the CEUS.

The project resulted in 34 research reports, of which 31 are summarized in this document. Seventeen of the reports have been published as National Center for Earthquake Engineering Research (NCEER) or Multidisciplinary Center for Earthquake Engineering Research (MCEER) reports. The research agencies' final reports for the other tasks are available from MCEER upon request.

An independent assessment of the results and potential impact of this project was performed under Task E of this contract. This impact assessment report, to be published by FHWA (or MCEER), has identified critical topics that should be addressed in seismic bridge design specifications and contains a "straw man" for a set of bridge design guidelines. This impact assessment is contained in Report No. MCEER 99-0009.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yards	0.836	square meters	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³
NOTE: Volumes greater than 1000 l shall be shown in m³.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m²	cd/m²
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in²	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	yd²
ha	hectares	2.47	acres	ac
km²	square kilometers	0.386	square miles	mi²
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m³	cubic meters	35.71	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in²

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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Introduction

In 1992, the Multidisciplinary Center for Earthquake Engineering Research (MCEER), formerly the National Center for Earthquake Engineering Research (NCEER), commenced work on FHWA contract DTFH61-92-C-00112. The objectives of this project (known as Project 112 within the MCEER Highway Project) were to perform a series of special studies related to the seismic vulnerability of highway bridges, tunnels, and retaining structures, and to develop technical information on which new seismic design specifications could be based in the future. It is anticipated that current specifications for the seismic design of bridges will be revised, and new seismic design guidelines will be prepared for other highway system components, in part on the basis of this work.

An independent assessment of the results and potential impacts of these studies was also performed under this contract. In a report that will be disseminated by the FHWA and MCEER in the near future, Task E (see tables 1 and 2, and figure 1) identified critical topics that should be addressed in future highway bridge seismic design specifications, and prepared a set of "strawman" bridge seismic design guidelines.

This project was one of two initiated around the same time under the MCEER Highway Project. The second project under this effort (known as Project 106) was also sponsored by the FHWA under contract DTFH61-92-C-00106. That project consisted of studies focussed on reducing the seismic vulnerability of the existing national highway system.

The project on new highway construction was prompted in part because significant progress had been made over the last two decades in several key areas, including: (1) knowledge on seismic risk data 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 it could be applied directly to highway engineering applications. Consequently, Project 112 included a series of analytical and experimental studies related to the seismic design and performance of bridges, tunnels, and foundations. The project focused on the following elements:

- Review of current national and international seismic design criteria.
- Seismic hazard exposure of the U.S. highway system.
- Foundation design and soil behavior.
- Structural design.
- Structural analysis and response.
- Determining the relative importance of specific bridges.
- Assessment of the impact of current and recently completed research.

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 United States. In particular, unlike the western United States, design strategies used in the eastern and central United States need to reflect the statistical probability that an earthquake significantly larger than the "design" earthquake could occur. In many cases, it was noted that

California design practice required significant modification before being implemented in the eastern and central United States because of these differences in seismicity and bridge type.

A range of special studies was therefore carried out that encompassed research on seismic hazard; foundation properties, soil properties, and soil response; and the response of structures and systems. 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 United States.

Research Areas and Tasks

Technical issues addressed under Project 112 were grouped into several primary subject areas, as shown in table 1 and figure 1. Table 2 contains a list of all tasks that were conducted under the project.

The results of the research from this project are intended to provide the basis for developing new design criteria and specifications, particularly for highway bridges. Secondary products resulting from this work include task and synthesis reports describing the advances made in design for bridges and other highway transportation systems and components. Table 3 provides a summary of all reports produced under this project.

Research Summary and Expected Impacts

The research conducted under FHWA contract DTFH61-92-C-00112 covered a range of topics as shown in table 2. Many of the resulting research reports address important issues that should be considered during the development of future seismic design codes; some provide design procedures and discuss computer programs that will be useful as design aids to the profession; and others provide background information and research documentation. For this Executive Summary, research reports have been grouped into four main categories:

I. <u>Seismic Hazard, Exposure, Bridge Performance, and Structural Importance</u>

- *Proceedings of the FHWA/NCEER 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. These proceedings document the findings of a forum of more than 50 researchers and design professionals who met to present papers and discuss issues relating to national representation of seismic ground motion for new and existing highway facilities. Consensus recommendations were developed on six issues. The report is a valuable resource for design code developers, because it covers several issues in depth and presents consensus recommendations derived after discussion by the entire group. Specific recommendations are given regarding seismic mapping and site factors, and clear positions are stated supporting the implementation of provisions that cover vertical motion, near-source effects, and spatial effects to highway facility seismic codes.

- *Site Factors and Site Categories in Seismic Codes,* by R. Dobry, R. Ramos and M. Power. This study addresses the amplification of earthquake ground motion by local soil conditions and provides new definitions of site categories and site coefficients. These recommendations were incorporated in the 1994 *NEHRP Recommended Provisions for Seismic Regulations for New Buildings* (BSSC, 1995) and, more recently, in the 1997 *Uniform Building Code* (ICBO, 1997). The site categories and site coefficients are compared with those in previous codes, including the current American Association of State Highway and Transportation Officials (AASHTO) provisions. Ground-motion recordings from the 1994 Northridge and the 1995 Kobe earthquakes generally validate the recommended values. The site factors discussed in this report are recommended for incorporation into the AASHTO seismic design provisions simultaneously with a change in the shape of the long-period segment of the response spectra from a $1/T^{2/3}$ to a $1/T$ relationship.

- *Effect of Spatial Variation of Ground Motion on Highway Structures,* by M. Shinozuka and G. Deodatis. A method for generating spectrum-compatible time histories is introduced, which accounts for traveling seismic waves, loss of coherency with distance, and differing soil conditions. The method reproduces complicated motion such as the 1964 Niigata earthquake ground motion recording, which showed an abrupt change in frequency content at the onset of liquefaction. The method is used to examine the response of several realistic bridges with total lengths varying from 34 to 483 m. The number of spans varied from 3 to 10, and the longest span ranged from 13 to 63 m. Both linear and nonlinear time-history analyses were conducted. The results are expressed as the ratio of response quantities considering spatial variation to the same quantities with no spatial variation, i.e., identical support motions. The ratio of maximum moment to yield moment of the columns, displacement values, and joint openings and closings were considered. The angle of incidence of the seismic waves and vertical acceleration were less important parameters. Identical support motion is recommended for representing unskewed bridges under 305 m in length with at least two spans and uniform soil conditions; more conservatively, the seismic response coefficient is increased by 10 percent or the *R* factor decreased by 20 percent. The report recommends that time-history analyses be performed using spatial variation, with several scenario earthquakes, and several different values of wave velocity when any of the following are true: the bridge is over 305 m in length, the bridge has supports on different local soil conditions, or the bridge is severely skewed.

- *Effects of Vertical Ground Motions on the Structural Response of Highway Bridges*, by M. Button, C. Cronin, and R. Mayes. This study addresses the question: How critical is the vertical component of seismic ground motion in determining the demands placed on key components of highway structures? Current bridge design codes do not require consideration of vertical motion effects, and few bridges have been designed considering this effect. Available ground motion records show that vertical acceleration can exceed horizontal acceleration. This study considers important issues affecting the design, thus providing new insight into design considerations that have up to now been handled by assumption or approximation, or overlooked due to lack of information. The major impact of the report is that vertical acceleration can be a critically significant factor in the seismic response of highway bridges, and should be appropriately covered by design codes and practices. The report contains data and guidance that are practical and can be readily put into practice. It will help designers of structures close to major faults by showing what structural and foundation factors are of most significance with respect to vertical motion, aiding the optimization of structure configuration. The report also offers simple design procedures for most cases. It will aid the development of codes for bridge design, as it offers many recommendations that can be used in a design-specification format.

- *Evaluation of Structural Importance,* by A. Thomas, S. Eshenaur, and J. Kulicki. This investigation used a number of existing and proposed numerical screening and ranking methods to evaluate the importance of bridges. The methods were evaluated by taking a representative sample of bridges, having a group of qualified persons independently select the 20 most important bridges from this group, averaging the opinions, and comparing the averaged results with the results generated from the various numerical ranking methods. The best numerical methods were selected and further modified to give better correlation. Based on this, a modified version of an approach developed in Montana, known as MTN5, was developed. This method uses National Bridge Inventory (NBI) data on both the route carried and the route crossed. The method seems suited for making retrofitting decisions for existing bridges but also has application to bridge rehabilitation and design decision-making. Calculation of a numerical importance rating may be useful, but it alone should not dictate the decision of whether or not a bridge should be designed for a higher level of seismic performance, as such a subjective decision is influenced by the incremental cost increase of strengthening a bridge.

II. <u>Structural Analysis, Design and Response</u>

- *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. This study addresses simplified methods that may be used to develop limitations and recommendations for design. The uniform-load method, the single-mode method, and multi-mode spectral analysis are compared. Curvature, span-length ratios, pier height, skew, and span connectivity are discussed as they relate to the use of the simplified methods. A set of 27 continuous bridges with integral abutments defined the characteristics of regular bridges for which the simplified methods of analysis are applicable. The current AASHTO definitions for "regular" bridges are based on the recommendations contained in this report.

- *Establish Representative Pier Types for Comprehensive Study: Eastern United States*, by J. Kulicki and Z. Prucz and *Establish Representative Pier Types for Comprehensive Study: Western United States,* by R.A. Imbsen, R.A. Schamber, and T.A. Osterkamp. These studies identify pier designs and detailing currently in use in the eastern and western United States on the basis of State surveys. They were conducted at the beginning of the contract in order to assist in identifying details susceptible to earthquake damage, and on which to base future work under the contract.

- *Seismic Resistance of Bridge Piers Based on Damage Avoidance Design,* by J.B. Mander and C.T. Cheng. This is the first of two reports that developed new pier design concepts. The Damage Avoidance Design (DAD) approach ensures that plastic hinges do not develop in the columns, thereby avoiding loss of service after a significant earthquake. Rocking piers are forced to rotate at their ends, but are restrained from toppling through gravity and the optional use of central, unbonded, post-tensioned reinforcement in the core of the columns. This design procedure could be incorporated in the commentary to a code for designers who wish to explore it. Once some of the identified limitations in the design approach have been resolved, it will need to be compared with others, such as seismic isolation, to establish its cost-effectiveness. One advantage of the concept is that prefabricated columns can be used, reducing total construction time and costs. From a constructibility perspective, the concept may be attractive in areas where prefabricated construction minimizes the traffic disruption that would be associated with conventional construction.

- *Seismic Design of Bridge Columns Based on Control and Repairability of Damage*, by C.T. Cheng and J.B. Mander. This report documents a second new design concept called Control and Repairability of Damage (CARD). The research developed and tested construction details in reinforced concrete columns that are intended to provide a replaceable or renewable sacrificial plastic hinge zone or fuse. Hinge zones are deliberately weakened with respect to the adjoining components; all regions outside a hinge zone are detailed to be stronger than the hinge zone and to remain elastic during seismic loading. The special detailing of the hinge zone permits relatively quick repair of the earthquake damage. Repair of the damaged hinge zones permits use of the bridge for at least minimum levels of traffic after a major earthquake. This work will not have a direct impact on code provisions, although it is an important design concept that will reduce the downtime of bridges after an earthquake. The design concept should be recognized in the commentary of any future performance-based code. Compared with conventional construction, the hinge zone construction will have a higher initial cost. Repair costs following a major earthquake will be less. Moreover, in the event of a large damaging earthquake that would render a conventionally built structure irreparable, a structure designed with hinge zones might still be repaired with its service life extended indefinitely.

- *Capacity Design and Fatigue Analysis of Confined Concrete Sections*, by A. Dutta and J.B. Mander. In this study, transverse hoop fracture is explicitly predicted, based on energy balance principles. The objective was to develop a complete design procedure for columns to eliminate all undesirable modes of failure, including buckling of the longitudinal bars. Transverse reinforcement requirements will either increase or decrease relative to current requirements depending on the axial load and the longitudinal steel reinforcement ratio. These recommendations will be useful additions to the current requirements.

- *Capacity Design of Bridge Piers and the Analysis of Overstrength*, by J.B. Mander, A. Dutta, and P. Goel. This report determines the moment overstrength capacity of reinforced bridge columns for use in capacity design procedures. The upper-bound overstrength factors tend to validate some prescriptive overstrength factors such as those in the ATC-32 report (ATC, 1996) and to indicate that such factors in other specifications, (e.g., the California Department of Transportation and AASHTO) may sometimes be too low. These prescriptive factors can be overly conservative for some columns. The moment-curvature method developed in this study could also be used for design. It would aid in the development of design specifications. The effect of uncertainty in material and geometric properties needs to be evaluated so that the appropriate load and resistance factors can be developed for reliability-based seismic design codes.

- *Seismic-Energy-Based Fatigue-Damage Analysis of Bridge Columns: Part I – Evaluation of Seismic Capacity,* by G.A. Chang and J.B. Mander. Part I of this study resulted in a computer program, UB-COLA, which is capable of accurately predicting the behavior of reinforced concrete columns subjected to inelastic cyclic deformations. The axial, flexural, and shear cyclic behaviors are modeled as well as the low-cycle fatigue properties of reinforcing bars and high-strength, prestressing steel bars. The program was capable of predicting the failure mode of either low axial-load columns (low-cycle fatigue of longitudinal reinforcement) or high axial-load columns (fracture of confining reinforcement and crushing of concrete). For shear-critical columns, the cyclic inelastic behavior was simulated through the cyclic inelastic strut and tie-modeling technique. Although this work will not have a direct impact on codes, it forms a key element in the implementation of the pushover method of analysis. The computer program UB-COLA, developed as part of this research, will become a valuable tool for design offices.

- *Seismic-Energy-Based Fatigue-Damage Analysis of Bridge Columns: Part II – Evaluation of Seismic Demand,* by G.A. Chang and J.B. Mander. A smooth, asymmetric, degrading, hysteretic model (Takeda) is presented that is capable of accurately simulating the behavior of bridge columns. The parameters for the analytical model are determined automatically by using a system-identification routine. The model was integrated into a single-degree-of-freedom (SDOF) inelastic dynamic analysis program, and a significant number of nonlinear analyses were performed, which resulted in design recommendations regarding the assessment of fatigue failure in reinforcing steel. The report includes a proposed methodology for the seismic evaluation of bridge structures that incorporates the traditional strength and ductility aspects plus the fatigue demand on reinforcing steel. The current code use of force-reduction factors that are independent of natural period are not conservative for short-period stiff structures and may lead to fatigue failure of the reinforcement. Recommendations are made for minimum values of force-reduction factors that prevent fatigue failure in the reinforcement. The design procedure would, as a minimum, be appropriate for inclusion in a code commentary to indicate how energy, and in particular low-cycle fatigue effects, can be accounted for in the design process.

- *Ductility of Rectangular Reinforced Concrete Bridge Columns with Moderate Confinement*, by N. Webbe, M. Saiidi, D. Sanders, and B. Douglas. Detailing guidelines are developed for reinforced concrete bridge columns and wall piers in areas of moderate seismicity. The report suggests that current AASHTO confinement requirements may be relaxed in areas of moderate and low seismicity because of the adequate performance of analytical and experimental test columns. This will greatly simplify the construction of such columns and wall piers due to reduced congestion in rebar detailing and placement.

- *Capacity Detailing of Members to Ensure Elastic Behavior,* by R.A. Imbsen, R.A. Schamber, and M. Quest. This report provides a compendium of Caltrans design practices that have been shown to perform well in earthquakes. Four areas for which new or recent design changes have been implemented by Caltrans are covered. They are joint shear in the connection of cap beam to column, superstructure flexural capacities that force plastic hinging in the columns, footing detailing, and outrigger and knee joint connections.

- *Capacity Detailing of Members to Ensure Elastic Behavior – Steel Pile-to-Cap Connection,* by P. Ritchie and J. M. Kulicki. This report discusses the connections between steel piles and concrete pile caps that are required to remain elastic during earthquakes. Both axial-load and moment-resisting connections are explored. Limited, common sense, design guidelines are presented for the cases covered. The connections could well be standardized when the work is complete, and therefore not add to design costs. For the achievement of desirable performance, it is important to avoid brittle failures in these underground connections.

- *Structural Steel and Steel/Concrete Interface Details,* by P. Ritchie, N. Kauhl, and J. Kulicki. This report assesses the seismic performance of details associated with steel bridge towers extending from a massive concrete substructure to the superstructure, as well as the seismic performance of other steel substructure and superstructure details for new construction. Seismic research related to steel bridges has lagged that of concrete bridges, so this report assists in advancing design practice. The report summarizes available information and discusses potential mechanisms within a steel bridge that can act as energy-dissipating components.

- *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. This report addresses details for bridges and retaining structures in the eastern and western United States and develops seismic design recommendations for these details based on the need to accommodate structural movements. These recommendations and details can be used as a basis for developing improved bridge design standards. The report includes many illustrations of the devices used to accommodate structural movements. Advantages and disadvantages of some of the devices are noted. Examples of approaches used in specific States are also given.

- *Derivation of Inelastic Design Spectrum,* by W. D. Liu, R. Imbsen, X. D. Chen, and A. Neuenhofer. The objective of this research was to develop inelastic response spectra for nationwide use, allowing engineers to assess inelastic deformations and thereby design for improved seismic performance. The report provides an approach and methodology for the derivation of inelastic spectra. There is a need for the use of such methodologies in future design specification development projects, but additional work will be required before the methodology developed under this task can be applied in practice.

- *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. This report reviews the seismic evaluation and design of three types of tunnels: bored, cut-and-cover and submerged. The report provides guidance that can be readily applied in practice, and could be used in the future as the basis for the development of a specification for tunnel design. Several analysis issues have been identified in the report as requiring additional research. In terms of tunnel performance, the racking behavior of cut-and-cover tunnels appears to be the seismic response most in need of careful attention.

III. Foundations and Soil Structure Interaction

- *Foundations and Soils – Compile Data and Identify Key Issues, by I.P. Lam.* This report on soils, abutment, and foundation issues provides results of a survey of State transportation agencies regarding typical foundations and abutments in their existing bridge inventories. The primary purpose of the survey was to identify foundation systems commonly used in bridge design within the United States. This information provided background information for other research studies being conducted as part of the FHWA-sponsored research program. While the primary focus of the survey was to identify typical foundation systems, the survey also had two secondary objectives. The first of these was to provide a preliminary assessment of procedures that might be used for screening the seismic vulnerability of existing bridges. The second was to identify major foundation design issues that warrant consideration during the remainder of the FHWA-sponsored research program.

- *Centrifuge and Numerical Modeling of Lateral Response of Pile-Cap Systems and Seat-Type Abutments in Dry Sand,* by A. Gadre and R. Dobry. The translational response of pile-cap foundations and seat-type abutment walls during seismic loading was investigated. The two primary objectives project were to (1) understand the lateral response of pile-cap foundations and seat-type abutments and (2) verify current design procedures used to estimate stiffness and capacity of these elements. Of specific interest was the contribution of the cap to the lateral-load capacity of a pile-cap foundation system, and whether additional rules can be used to account for lateral-load resistance contributions from the pile and footing. A second area of interest was the effective damping of pile-cap systems and abutment foundations. Results from this test program were interpreted to provide valuable guidance involving the relative contributions of a single pile and the pile cap to lateral-load resistance of the structure. Methods for determining abutment wall capacity and stiffness are also discussed.

- *Modeling of Abutments for Seismic Design,* by I.P. Lam and G. Martin. The objectives of the report were limited to (1) clarifying the process of design for service loads versus design for seismic loading, (2) reviewing abutment modeling alternatives, and (3) providing a simplified approach for design that still incorporates key issues affecting abutment response. The report addresses the task objectives by investigating the relevant abutment design issues that affect seismic performance. The primary focus of the investigation was passive loading. The research effort included numerical modeling using simplified and rigorous methods. The research showed that calculated abutment forces may differ significantly, as a function of the modeling methods. The period of a bridge model is affected by the abutment model, with the potential to result in longer periods of vibration, more displacement, and reduced forces. The current AASHTO seismic design provisions provide guidance for the design of abutment walls under active loading conditions. In some situations, passive loading conditions will be more critical for abutment design. New AASHTO seismic design provisions should be expanded to address passive loading. Considering the complexity of the passive loading case, a detailed commentary covering methods for determining passive capacity and stiffness is needed.

- *Seismic Analysis and Design of Bridge Abutments Considering Sliding and Rotation,* by K.L. Fishman and R. Richards, Jr. This report provides a new procedure for determining the earthquake-induced displacement of retaining walls and bridge abutments founded on spread footings. The new procedure differs from existing displacement-based procedures for determining the sliding response of bridge abutments by addressing mixed-mode behavior, which includes both rotation due to bearing capacity movement and sliding response. The procedure also extends existing methods for estimating sliding and rotation by introducing a pinned-restraint condition at the top of the retaining wall and by accounting for reductions in bearing capacity caused by seismic loading. The procedure for predicting permanent (mixed-mode) displacements was calibrated against test cases that were modeled in the laboratory. The boundary conditions at the top of the abutment were varied during the test program to include sliding, rotation-about-the-top, and mixed sliding and tilting. Procedures for using this new approach in seismic design are described. A computer program for estimating sliding and rotational displacements is included in an appendix. Information developed as a result of this work is in a form that could be easily integrated into new AASHTO seismic design provisions. However, conclusions from independent numerical analyses by other researchers were sufficiently different from those reached in this report that some type of resolution on the appropriate approach should be reached before the method is adopted.

- *Modeling of Pile Footings for Seismic Design,* by I.P. Lam and M. Kapuskar. Seismic design methods used to represent pile foundations for bridge structures were evaluated. The project had the following objectives: (1) evaluate the influence of modeling methods on response of the pile footings; (2) establish the influence of modeling methods on the estimated displacement and force demand; (3) summarize methods for characterizing the stiffness of pile footings and discuss their limitations; and (4) provide guidelines on seismic design practice. The focus of the report is on pile-group foundations rather than single-pile extensions. Information in this report gives a practical summary covering the state of the practice for the seismic design of pile foundations. A primary feature of the report is that it attempts to provide the interface between the structural and geotechnical design processes. The current AASHTO seismic design provisions do not cover most of the topics included in this report.

- *Modeling of Drilled Shafts for Seismic Design,* by I.P. Lam and D. Choudhuri. There were four objectives to this research task: (1) provide information regarding the influence of the modeling procedure on the response of the structure; (2) evaluate the effects of modeling procedures on the estimated displacement of and force demand on the foundation; (3) summarize methods of characterizing the response of drilled-shaft foundations, including their limitations; and (4) give guidelines on seismic design practice. The primary focus is on lateral loading. The contents of the report provide a practical summary of the state of the practice. A key contribution is that the report addresses differences in design procedures relative to those used for driven piles. These differences are related to the installation procedure, drilled shaft versus driven pile diameter, the length-to-diameter ratio, and the structural configuration. An important feature of the report is that it attempts to provide an interface between the structural and geotechnical design processes. Information in this report provides important documentation regarding the seismic design of drilled-shaft foundations.

The current AASHTO seismic design provisions do not cover most of the topics included in this report.

- *Development of Analysis and Design Procedures for Spread Footings,* by G. Gazetas, G. Milonakis, and A. Nikolaou. Five issues are addressed in this report: (1) when to incorporate foundation stiffness in the dynamic analysis of bridge piers; (2) the significance of properly modeling the effect of embedment on the dynamic stiffness of the foundation; (3) the importance of radiation damping and kinematic interaction in response; (4) conditions under which uplift becomes significant, including how it is modeled in design and analysis; and (5) the significance of local soil nonlinearities under the edges of a rocking foundation and methods to account for it in the analysis. The report includes interesting observations regarding the response of a spread footing foundation system during seismic loading. These observations deal with the importance of soil-structure interaction, embedment, and radiation damping to the overall system response. Observations are also made regarding seismic bearing capacity and footing uplift. However, the results, as currently developed and presented, cannot be easily adapted into code provisions. The parametric study of the seismic response of footings without uplift essentially covers a single combination of soil, structural type, and earthquake loading. The validity of these results for other combinations of soils, structures, and earthquake characteristics needs to be assessed. Some results regarding the seismic effects on bearing capacity differ from those of other researchers. The differences should be documented and reconciled. With additional evaluation and further documentation of the method of analysis, the results of this task could be adopted into new codes.

- *Synthesis Report on Foundation Stiffness and Sensitivity Evaluation on Bridge Response,* by I. P. Lam, G. R. Martin, G. R., and M. Kapuskar. This report discusses bridge response for different values of abutment stiffness and bent foundation stiffness. The sensitivity study considered a typical two-span bridge with the center bent supported by four different foundation systems: piles, spread footings, pier wall, and drilled shafts. The examples of foundation stiffness developed here will be useful in commentary on future codes, even though some California consultants are already using the design procedures. The procedures call for close coordination between the design and geotechnical engineers, especially for flexible-base conditions.

IV. <u>Liquefaction and Soil Behavior</u>

- *Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils,* edited by T.L. Youd and I.M. Idriss. The objectives of the workshop were to review recent developments in the simplified procedure for evaluating the liquefaction resistance of soils and to gain consensus on further improvements and additions that should be incorporated in the simplified procedure. A workshop on this subject had not been held since the National Research Council (NRC) sponsored a workshop in 1985. Emphasis was placed on developments that had been published after the 1985 NRC workshop. Workshop participants focused their review and discussions on procedures used to predict the triggering of liquefaction. They further limited their discussions to shallow soil deposits on level or nearly level ground. From these discussions the workshop participants developed consensus recommendations on (1) use of standard and cone penetration tests; (2) use of shear-wave velocity measurements; (3) use of the Becker penetration test for gravelly soils; (4) magnitude scaling factors; and (5) correction factors $K\sigma$ and $K\alpha$. The workshop participants also addressed issues relating to earthquake magnitude and peak ground acceleration. Liquefaction criteria based on probabilistic and seismic energy methods were also considered.

- *Development of Liquefaction Mitigation Methodologies / Ground Densification Methods*, by G. Martin. Densification procedures currently being used to mitigate the potential for ground liquefaction and the associated hazard were evaluated. The objective of this task was to compile the results of a number of liquefaction remediation-related tasks performed as part of the MCEER Highway Project into a form that could be used for the development of codes and guidelines. The work included in this compilation can assist in the selection of optimum available liquefaction mitigation or ground improvement methods using ground densification. The methods addressed in this compilation can be used at bridge sites where a high potential for liquefaction is identified during site investigations. The report is useful for identifying more efficient design methods, which will lead to lower unit costs for ground improvement. Furthermore, the information on the mechanisms governing the mitigation process should lead to better efficiency and higher reliability in design. Key components of the information presented in this report could either be incorporated in the new AASHTO seismic design provisions or included as a provisional commentary in an appendix.

- *Design Recommendations for Site Response and Liquefaction*, by G. Martin. The research conducted under this task provided a synthesis of results from MCEER Highway Project studies and from studies performed by others, in order to develop seismic design guidelines on topics related to: (1) the influence of site soils on earthquake ground motion or site response; (2) the evaluation of liquefaction hazards; and (3) the mitigation of liquefaction hazards. The influence of site soil stratigraphy on earthquake ground response is discussed in two ways, namely via an empirical approach using seismic hazard maps and the site specific response analysis approach using representative input ground motions. The use of the revised Universal Building Code/National Earthquake Hazard Reduction Program (UBC/NEHRP) site factors are recommended for a revised AASHTO mapping approach. Design approaches using one- or two-dimensional site specific methods are also described. Revised simplified empirical liquefaction assessment procedures (with associated commentary on field investigations) are recommended for use in future specifications and guidelines. Commentaries on analytical approaches to liquefaction evaluation and lateral spreads are also provided. Design models for the vibro-replacement and ground densification methods of liquefaction mitigation are provided, together with an overview of other methods of liquefaction mitigation.

Future Work and Research Implementation

It is anticipated that much of this work 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 is to develop new bridge seismic design specifications, commentary, and design examples, which will be incorporated into the AASHTO *LRFD Bridge Design Specifications* in the near future. Much of the basis for the specification changes that will be made in NCHRP Project 12-49 are expected to be drawn from the results of the work conducted under this FHWA contract.

Acknowledgments

The work on this contract was conducted by the Multidisciplinary Center for Earthquake Engineering Research (MCEER). Ian G. Buckle was the project principal investigator and Ian M. Friedland was the project manager. MCEER was assisted by the following key subcontract institutions: the 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 at Reno; and the University of Southern California.

Much of the material contained in this technical summary was extracted from the Task 112-E report, *Impact Assessment of MCEER Highway Project Research on a National Bridge Seismic Design Code*, which was prepared by the Applied Technology Council. Authors of that report include Christopher Rojahn, Ronald Mayes, Donald Anderson, John Clark, Stewart Gloyd, and Richard Nutt, with assistance provided by geotechnical consultant D'Appolonia Associates.

Table 1. Project Subject Areas and Tasks

Subject Areas	Research Tasks
Seismic Hazard and Ground Motion	C, D6, D9
Design Issues • foundations and soils • structures and special issues • design issues and details	 D3, D4 D2, D7, D8 D1, D5
Design and Performance Criteria	B, E
Project Management and Administration	A, F

Table 2. Research Tasks Initiated Under MCEER Project 112.

Area/Task No.	Task Description	Principal Investigator(s)
Project Administration and Reporting		
112-A	Project Administration & Support for the Highway Seismic Research Council	I. Buckle/ I. Friedland
112-F	Project Reporting	I. Friedland
Design and Performance Criteria		
112-B	Review Existing Design Criteria and Philosophies	C. Rojahn/ R. Mayes/ I. Buckle
112-E	Impact Assessment and Strawman Guidelines for the Seismic Design of Highway Bridges	C. Rojahn/ R. Mayes/ I. Buckle
Seismic Hazard and Exposure		
112-C	Compile and Evaluate Maps and Other Representations, and Summarize Alternative Strategies for Portraying the National Hazard Exposure of the Highway System	M. Power
112-D-9	Recommended Approach for Portraying the National Hazard Exposure	M. Power
Ductility Requirements		
112-D-1.1	Establish Representative Pier Types for Comprehensive Study – Eastern & Western U.S.	J. Kulicki/ R. Imbsen
112-D-1.2	Physical and Analytical Modeling to Derive Overall Inelastic Response of Bridge Piers	J. Mander
112-D-1.3	Derive Inelastic Design Spectra	R. Imbsen
Structure Importance		
112-D-2	Evaluation of Structure Importance	J. Kulicki
Foundations and Soil-Structure Interaction		
112-D-3.1	Compile Data and Identify Key Issues	I. P. Lam
112-D-3.2	Abutment and Pile Footing Studies by Centrifuge Testing	R. Dobry
112-D-3.3	Develop Analysis and Design Procedures for Abutments	I. P. Lam/ G. Martin
112-D-3.4	Develop Analysis and Design Procedures for Retaining Structures	R. Richards/ K. Fishman
112-D-3.5	Develop Analysis and Design Procedures for Pile Footings	I. P. Lam/ G. Martin
112-D-3.6	Develop Analysis and Design Procedures for Drilled Shafts	I. P. Lam/ G. Martin

Table 2. Research Tasks Initiated Under MCEER Project 112. (continued)

Area/Task No.	Task Description	Principal Investigator(s)
112-D-3.7	Develop Analysis and Design Procedures for Spread Footings	G. Gazetas
112-D-3.8	Performance and Sensitivity Evaluation, and Guideline Development	P. Lam/R. Dobry/ G. Martin
Soil Behavior and Liquefaction		
112-D-4.1	Site Response Effects	R. Dobry
112-D-4.2	Identification of Liquefaction Potential	T. L. Youd
112-D-4.3	Development of Liquefaction Mitigation Methodologies	G. Martin
112-D-4.4	Design Recommendations for Site Response and Liquefaction Mitigation	G. Martin
Special Seismic Detailing		
112-D-5.1	Capacity Detailing of Columns, Walls, and Piers for Ductility and Shear	J. Mander/ R. Imbsen/ J. Kulicki/ M. Saiidi
112-D-5.2	Capacity Detailing of Members to Ensure Elastic Behavior	J. Mander/ R. Imbsen/ J. Kulicki
112-D-5.3(a&b)	Detailing for Structural Movements - Bridges	R. Imbsen/ J. Kulicki
112-D-5.3(c)	Detailing for Structural Movements - Tunnels	M. Power
112-D-5.4	Structural Steel and Steel/Concrete Interface Details	J. Kulicki
Spatial Variation of Ground Motion		
112-D-6	Spatial Variation of Ground Motion	M. Shinozuka/ G. Deodatis
Structural Response		
112-D-7	Effects of Vertical Acceleration on Structural Response	M. Button
Structural Analysis		
112-D-8	Review Existing Analytical Methods, and Identify and Recommend Analytical Procedures Appropriate for Each Structure Category and Hazard Exposure	I. Buckle/ J. Mander

Table 3. Project 112 Report Summary

Author(s)	Title	Task(s)	Status/ Disposition
Rojahn, et al	Seismic Design Criteria for Bridges and Other Structures	112-B	NCEER 97-0002 and ATC-18
Friedland, Power & Mayes (ed.)	Proceedings of the FHWA/NCEER Workshop on the National Representation of Seismic Ground Motion for New and Existing Highway Facilities	112-C 112-D-9	NCEER 97-0010
Kulicki & Prucz	Establish Representative Pier Types for Comprehensive Study B East	112-D-1.1(a)	NCEER 96-0005
Imbsen, Schamber & Osterkamp	Establish Representative Pier Types for Comprehensive Study B West	112-D-1.1(b)	NCEER 96-0006
Chang & Mander	Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part I – Evaluation of Seismic Capacity	112-D-1.2	NCEER 94-0006
Chang & Mander	Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part II – Evaluation of Seismic Demand	112-D-1.2	NCEER 94-0013
Liu, Neuenhofer, Chen & Imbsen	Derivation of Inelastic Design Spectrum	112-D-1.3	Agency Final Report
Thomas, Eshenaur & Kulicki	Methodologies for Evaluating the Importance of Highway Bridges	112-D-2	NCEER 98-0002
Lam	Foundations and Soils B Compile Data and Identify Key Issues	112-D-3.1	Agency Final Report
Gadre & Dobry	Centrifuge Modeling of Cyclic Lateral Response of Pile-Cap Systems and Seat-type Abutments in Dry Sand	112-D-3.2	MCEER 98-0010
Lam & Kapuskar	Modeling of Bridge Abutments in Seismic Response Analysis of Highway Bridges	112-D-3.3	Agency Final Report
Fishman & Richards	Seismic Analysis and Design of Bridge Abutments Considering Sliding and Rotation	112-D-3.4	NCEER 97-0009
Lam & Kapuskar	Modeling of Pile Footings for Seismic Design	112-D-3.5	Agency Final Report

Table 3. Project 112 Report Summary. (continued)

Author(s)	Title	Task(s)	Status/ Disposition
Lam & Chaudhuri	Modeling of Drilled Shafts for Seismic Design	112-D-3.6	Agency Final Report
Gazetas, Mylonakis & Nikolaou	Development of Analysis and Design Procedures for Spread Footings	112-D-3.7	Agency Final Report
Lam, Martin & Kapuskar	Synthesis Report on Foundation Stiffness and Sensitivity Evaluation on Bridge Response	112-D-3.8	Agency Final Report
Dobry, Ramos & Power	Site Factors and Site Categories in Seismic Codes	112-D-4.1	Agency Final Report
Youd (ed.)	Proceedings of the NCEER Workshop on Evaluation of Liquefaction Resistance of Soils	112-D-4.2	NCEER 97-0022
Martin	Development of Liquefaction Mitigation Methodologies: Ground Densification Methods	112-D-4.3	Agency Final Report
Martin	Design Recommendations: Site Response and Liquefaction	112-D-4.4	Agency Final Report
Mander & Cheng	Seismic Resistance of Bridge Piers Based on Damage Avoidance Design	112-D-5.1(a) 112-D-5.2(a)	NCEER 97-0014
Cheng & Mander	Seismic Design of Bridge Columns Based on Control and Repairability of Damage	112-D-1.2 112-D-5.1(a) 112-D-5.2(a)	NCEER 97-0013
Dutta & Mander	Capacity Design and Fatigue Analysis of Confined Concrete Columns	112-D-5.1(a)	MCEER 98-0007
Wehbe, Saiidi, Sanders & Douglas	Ductility of Rectangular Reinforced Concrete Bridge Columns with Moderate Confinement	112-D-5.1(d)	NCEER 96-0003
Mander, Dutta & Goel	Capacity Design of Bridge Piers and the Analysis of Overstrength	112-D-5.2(a)	NCEER 98-0003
Imbsen, Schamber & Quest	Capacity Detailing of Members to Ensure Elastic Behavior	112-D-5.2(b)	Agency Final Report
Ritchie & Kulicki	Capacity Detailing of Members to Ensure Elastic Behavior B Steel Pile-to-Cap Connections	112-D-5.2(c)	Agency Final Report

Table 3. Project 112 Report Summary. (continued)

Author(s)	Title	Task(s)	Status/ Disposition
Imbsen, Schamber, Thorkildsen, Kartoum, Martin, Rosser & Kulicki	Structural Details to Accommodate Seismic Movements in Highway Bridges and Retaining Walls	112-D-5.3(a&b)	NCEER 97-0007
Power, Rosidi, Kaneshiro, Gilstrap & Chiou	Summary and Evaluation of Procedures for the Seismic Design of Tunnels	112-D-5.3(c)	Agency Final Report
Ritchie, Kauhl & Kulicki	Structural Steel and Steel/Concrete Interface Details	112-D-5.4	NCEER 98-0006
Shinozuka & Deodatis	Effect of Spatial Variation of Ground Motion on Highway Structures	112-D-6	Agency Final Report
Button, Cronin & Mayes	Effect of Vertical Ground Motions on the Structural Response of Highway Bridges	112-D-7	Agency Final Report
Kim, Button, Mander & Buckle	Application of Simplified Methods of Analysis to the Seismic Design of Bridges	112-D-8	Agency Final Report
Rojahn, Mayes, et al	Impact Assessment of MCEER Highway Project Research on a National Bridge Seismic Design Code	112-E ATC-18-1	Agency Final Report

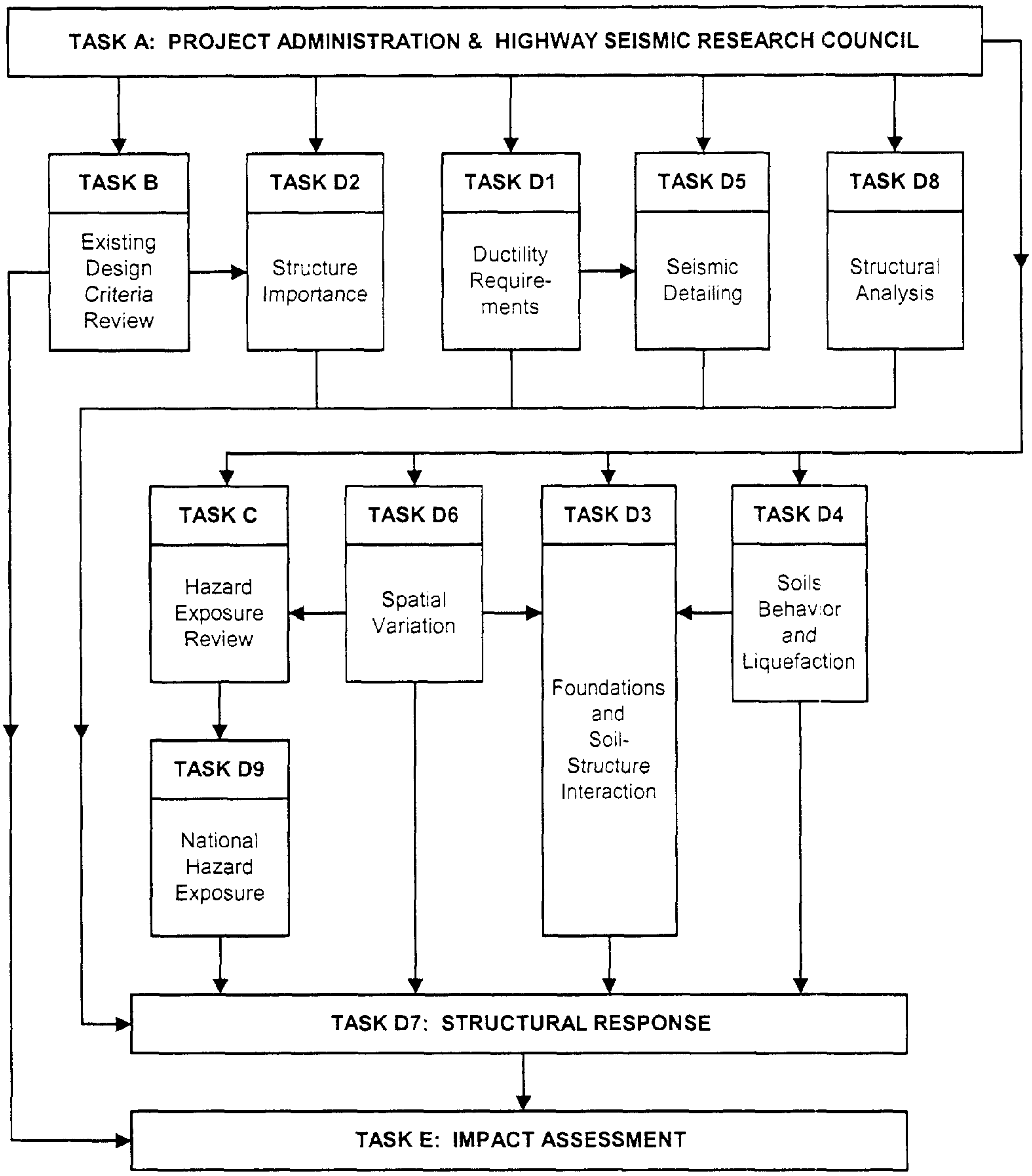

Figure 1. Project Subject Areas

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