The New FHWA/MCEER Seismic Vulnerability Study of Highway Systems: Loss Estimation Methodology and the Seismic Design and Retrofitting of Long Span Bridges

by

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ABSTRACT

In the fall of 1998, the Multidisciplinary Center for Earthquake Engineering Research was awarded a 6-year, $10.8 million contract by the Federal Highway Administration of the U.S. Department of Transportation to conduct a series of studies related to the seismic performance of the U.S. national highway system. The research being conducted under this contract is intended to provide improved tools for evaluating and assessing the societal impacts of earthquakes on highway systems and bridges, and to reduce the amount of damage that may occur to existing and future highway structures from a moderate-to-significant seismic event. The focus of this paper is on two aspects of this comprehensive program: (1) development of formal loss estimation methodologies for highway systems subject to damaging earthquakes, and (2) the development of a manual for the seismic design and retrofitting of long span bridges.

KEYWORDS: earthquake engineering; seismic vulnerability; loss estimation; seismic risk assessment; seismic design; seismic retrofitting

1. INTRODUCTION

Surface transportation is a critical component of the infrastructure that society relies on. Surface transportation systems act as key links within and between population centers and business sectors, and provide for the movement of people and goods throughout a region, nationally, and globally. This transportation network must continue to function during and after the occurrence of a natural disaster such as an earthquake so that the lifelines of our society can continue to function and emergency services can be provided to minimize the loss of life and economic distress.

Of all the components of the surface transportation system, bridges have been shown to be among the most vulnerable to earthquake damage. About 70 percent of the approximately 500,000 highway bridges in the U.S. were constructed prior to 1971, with little or no consideration given to seismic resistance. Recent earthquakes, such as the 1989 Loma Prieta, 1994 Northridge, and 1995 Kobe earthquakes, have demonstrated the need to find new and improved ways to design and construct bridges and highways which can withstand the force and displacement demands placed on them, and to cost-effectively retrofit existing seismically-vulnerable structures.

Recognizing the shortcomings evident in both existing highway bridges and current design specifications for new bridges, the Federal Highway Administration (FHWA) initiated a comprehensive seismic research program for

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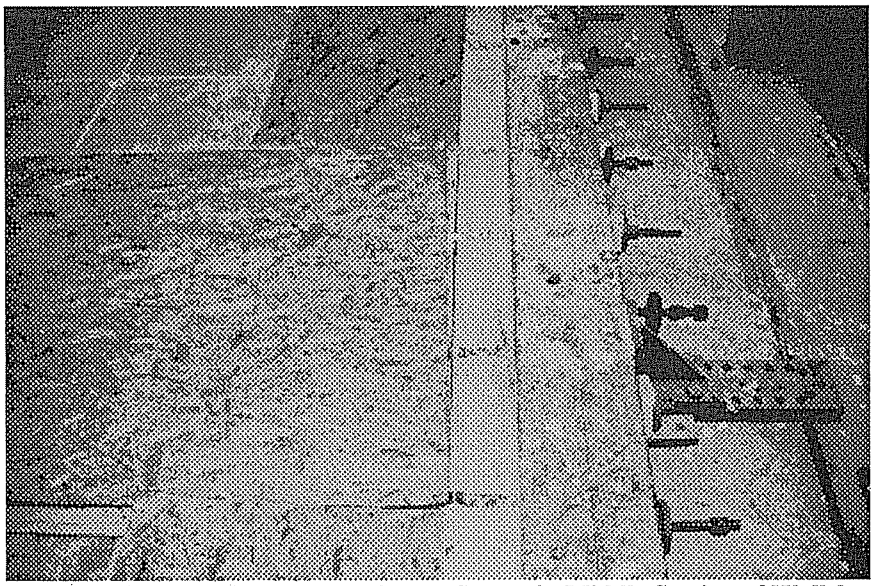

Photo 2: Compression and Tension on Straps in Middle Section of Wall 8

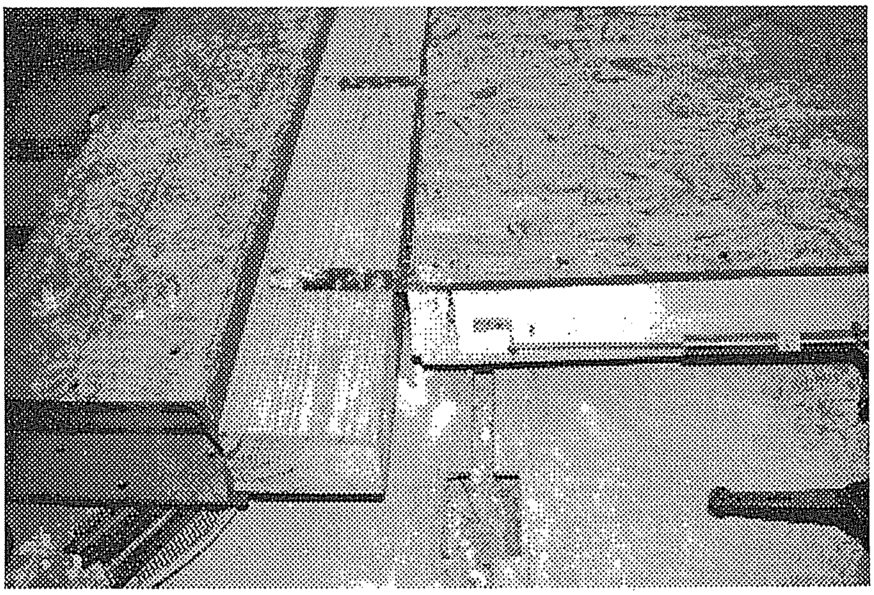

Photo 3: Load on First Two Straps of Wall 8

bridges and highways in 1992. That program was comprised of two contracts: Seismic Vulnerability of Existing Highway Construction, FHWA contract DTFH61-92-C-00106 (a six year study) and Seismic Vulnerability of New Highway Construction, FHWA contract DTFH61-92-C-00112 (a four year project). Both studies were initiated in cooperation with the Multidisciplinary Center for Earthquake Engineering Research (MCEER) [formerly the National Center for Earthquake Engineering Research]. Final products of these two studies will include a 3-volume seismic retrofitting manual for highway systems, and recommendations for improving future seismic bridge design specifications.

Despite these gains in knowledge, there is still some distance to go before seismic resistant highway systems are a reality. Some classes of bridges have yet to be studied in any systematic manner, such as long span bridges, and structures on or crossing difficult sites continue to be a problem. Some of these structures are very old and have piers constructed of unreinforced masonry and members assembled from non-ductile steels and cast iron. Many are located on unknown foundations or, if the foundations are known, they are usually massive underground lightly reinforced concrete structures, often constructed in weak soils. Their seismic resistance is difficult, if not impossible, to quantify given the current state of knowledge. This is a major concern because these structures are usually critically important to the region they serve. Any loss of access will have a major impact on emergency services following an earthquake and impede post-earthquake recovery. Society expects a higher level of performance from these structures than for more conventional highway structures. Yet little is known about their capacity for extreme loads, such as earthquake loads, and assurances of unrestricted access following an earthquake cannot be given at this time.

The high cost of retrofitting the nation's bridges is a major disincentive to owner agencies who are faced with extensive upgrade programs. A more intelligent way of prioritizing a bridge inventory, and selecting bridges to be retrofitted, is necessary to ensure that scarce resources are used in the most cost-effective manner. For this purpose, a seismic risk assessment procedure has been developed by MCEER under one of the earlier FHWA contracts. This procedure allows for the determination of traffic flow impacts due to bridge-related damage caused by various scenario earthquakes. To reach its full potential however, the methodology must be extended to assess the direct and indirect costs of this damage and include the effects of damage to other components of a highway system such as tunnels, slopes, pavements, and retaining structures. But in order for the bridge engineering community to have confidence in this refined loss estimation methodology, it must be calibrated against actual earthquake experience-data and validated by independent consultants against data sets from both large and small earthquakes. It is noted that such a tool, once developed, will not only be invaluable for bridge engineers, but will also allow emergency response personnel to plan ahead using earthquake scenarios, perform rapid damage assessments following an actual earthquake, and manage recovery in an optimal way.

To address these and other related needs, the Multidisciplinary Center for Earthquake Engineering Research (MCEER) was awarded a 6-year, $10.8 million contract in the fall of 1998 by the Federal Highway Administration (FHWA) of the U.S. Department of Transportation. This contract, which was authorized under the 1998 Transportation Efficiency Act for the 21st Century (TEA-21), is addressing research on the seismic vulnerability of the U.S. national highway system. This contract is intended to draw on and extend the work that has been conducted under the prior two FHWA research projects being conducted by MCEER.

2. SEISMIC VULNERABILITY OF THE HIGHWAY SYSTEM

The earlier FHWA contracts are primarily focussed on the seismic design and retrofitting of typical highway bridges found throughout the U.S. The TEA-21 contract focuses on several special issues considered as critical to the future of the Nation's highway transportation infrastructure. The TEA-21 research addresses:

- Development of formal loss estimation methodologies for highway systems. This research is intended to draw on and extend the work being conducted by MCEER on the development of a seismic risk assessment methodology for highway systems.

- Development of a seismic design and retrofitting manual for long span bridges. The earlier FHWA-sponsored research is developing a series of seismic retrofitting manuals for application to typical highway bridges and highway structures (retaining structures, slopes, tunnels, culverts, and pavements). The new manual will address long span bridges which are typically critical lifeline structures, including long span trusses, suspension, and cable stayed bridges.

- Development or improvements for "smart" or "intelligent" earthquake protective systems, including bearings and dampers, specialty materials, and other passive and hybrid semi-active systems.

- Studies related to foundation design and soil behavior and response, including large pile group behavior, long period ground motions, and improvements in ground remediation technologies.

The project will also address a series of special studies, including the development of post-earthquake non-destructive assessment technologies for retrofitted bridge components, support for NCHRP Project 12-49 which is developing a new seismic design specification for highway bridges, and designing and implementing a seismic instrumentation system for the Cape Girardeau cable-stayed bridge, which is currently under construction across the Mississippi River between Missouri and Illinois and is within the New Madrid seismic hazard zone, to record seismic free field and structural response data.

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This six-year research program will study the seismic vulnerability of highway systems and components, and will develop cost-effective methods of retrofitting system components and facilitate the implementation of these methods in the field. The program has a national focus and addresses structure types and issues not currently being addressed in other research programs or projects. The program includes a mix of analytical and experimental studies, and will result in a number of manuals, guides, and design and retrofitting recommendations for evaluating and improving the seismic vulnerability of highway systems and their components. Some of the new and improved knowledge and technologies may have applicability to other modes of transportation and opportunities for the transfer of this information to these other modes will be pursued.

The program is comprised of eight primary tasks, as follows:

Task A – Project Administration and Highway Seismic Research Council
Task B – Loss Estimation Methods for Highway Systems
Task C – Seismic Design and Retrofit Manual for Long Span Bridges
Task D – Earthquake Protective Systems
Task E – Foundation and Geotechnical Studies
Task F – Special Studies
Task G – Technology Exchange and Transfer
Task H – Reports

The objective and focus of the research being conducted under Tasks B and C are detailed in the following.

3. LOSS ESTIMATION METHODS FOR HIGHWAY SYSTEMS

Loss estimation methods have moved to the forefront as earthquake hazard reduction tools. As a result of technological advances in data collection and management, relational data analysis, and software development, loss estimation methodologies are now packaged in user-friendly platforms and are capable of performing calculations in a matter of minutes. This is in contrast to studies a decade ago that were largely static (that are performed for single scenarios) and performed essentially on paper maps.

In addition to these advances in computer hardware and software, our understanding of the performance of a wide range of systems, including highways, has been improved considerably. Much of this advancement in the highway field has been as a result of the seismic risk assessment (SRA) methodology developments under the FHWA-sponsored MCEER Highway Project. Due in large part to the occurrence of several recent events, our ability to model in more depth and in more detail the impacts of large earthquakes has grown significantly.

Acknowledging that the assessment of socioeconomic impacts caused by the failure and disruption of transportation systems was essentially absent until roughly five years ago, the current state of knowledge in this area is ripe for continued rapid advancement. Researchers in the U.S., Japan, and New Zealand now consider the assessment of impacts beyond direct losses critical in justifying future seismic mitigation programs.

The role of loss estimation methods in the present study is three-fold. First, loss estimation methods will be used in the estimate of seismic vulnerability for existing transportation systems, in particular highway networks. Second, based on this analysis, loss estimation methods will be used to project future benefits, in terms of reduced losses, from the execution of retrofit programs. Like most policy-related studies, it is important to identify and understand fully the impact of suggested changes in policy: will this program result in long-term savings? does the implementation of the program have ancillary benefits that help to improve other factors beyond earthquakes? is there an optimal schedule for retrofitting that takes into consideration the age of the structure, the regional variation of seismicity, and ongoing maintenance programs? These are all questions that can be answered in part by loss estimation methods. Finally, loss estimation can be effectively applied in a post-earthquake environment.

When a major earthquake hits a metropolitan area, one of the first priorities for emergency response officials is to determine the extent of damage; that is, identify which areas have been hardest hit and will therefore require the most resources in order to restore service or minimize loss of life and economic hardship. By knowing this information, reconnaissance efforts and emergency repairs can be prioritized, thus eliminating the possibility of over-committing resources for relatively insignificant events. In addition, loss estimation methods can be used to help assess optimal recovery strategies. Is it better to repair a particular structure or just replace it? An analysis of future seismic hazards and risks could allow a comparison of the relative benefits associated with each strategy or action.

The research being conducted by MCEER is focused on the development and application of loss estimation methods for a broad range of purposes. The approach is structured to maximize the potential for achieving each of the above objectives. It must be understood, however, that in order to develop a tool that is implementable, considerable effort must be spent in designing the methodology, incorporating state-of-the-art models, calibrating and validating the methodology, and eventually testing the methodology using potential users.

The approach for integrating loss estimation methods into the current overall program is to build on what has been accomplished previously under the MCEER Highway Project, by enhancing that model and expanding the types of losses are that estimated (including indirect losses), incorporating new developments and data where appropriate, ensuring the usability of the methodology so that it is presented as a flexible and user-friendly software tool with ample documentation, and expanding the methodology to address other highway system components and other transportation systems, where appropriate.

The research for this task is comprised of three major components:

Task B1 – Loss Estimation Methodology Development, Additional Refinement of the Current Project SRA; System Calibration and Validation
Task B2 – Other Highway Components
Task B3 – Other Transportation Systems

Task B1 is comprised of five parts: (1) validation, calibration, and refinement of the current seismic risk assessment (SRA) methodology; (2) development of direct and indirect loss modules for incorporation into the SRA system; (3) calibration of the complete system and validation by independent testing; (4) completion of the system software and documentation; and (5) demonstration and workshops.

Under the earlier FHWA project, a major focus has been on bridge damage state modeling and traffic state analysis, with limited additional work in direct loss modeling and other highway system elements. While significant progress was made in that study, there are still important gaps in several areas. These include applicability of models outside of the demonstration city, i.e., Memphis, Tennessee; more accurate modeling of impaired traffic states; continued enhancements in network analysis uncertainties; and more rigorous treatment of site-specific assessments of certain seismic hazards (e.g., lateral spread damage is currently being evaluated under that project but may not be fully characterized). As part of Task B1-1, refinements in the current methodology will be made to address these and other limitations and provide needed enhancements.

In order to extend the current SRA methodology to incorporate a more rigorous assessment of direct and indirect economic losses, further model development will take place in Task B1-2. In this task, a comprehensive set of measures will be identified that will address direct and indirect losses. Some measures will focus on the impacts on the highway system itself, such as repair costs and debris removal; other measures will concentrate on the impacts to surrounding exposures (e.g., populations and businesses). To insure the credibility of these new models, calibration and validation studies of the complete integrated system, including the incorporation of other highway system components and transportation modes and discussed under Tasks B2 and B3, will be performed in Task B1-3 using data from a series of actual large and small earthquakes.

To expand the current SRA methodology to other highway components, damage models will be developed for retaining structures, slopes, tunnels, culverts, approach fills, and pavements under Task B2. These models will be incorporated into the current methodology, as they may have significant impact on the traffic flow analyses. Specific model development will include damage state fragility modeling, including uncertainty analysis, restoration modeling, and traffic flow impact modeling based on different levels and types of damage. The goal of this task is to improve the overall modeling of damage and impacts to highway networks by including all key components.

Finally, in order to adapt the methodology to other transportation systems, a series of studies under Task B3 that address freight and urban mass transit (UMT) rail systems may be conducted, if time and project funds permit. Past experience in the U.S. and Japan has shown that, in the presence of earthquake damage to highway systems, freight and UMT rail systems can greatly facilitate the return of workers to their jobs, and the transport of essential materials and goods into and out of the region. This, in turn, can effectively reduce overall economic losses due to earthquake damage, and can also enhance the region's emergency response and recovery operations. Accordingly, the objective of Task B3 is to integrate freight and UMT rail transportation systems models with the highway system models above. The end result of this integration will be a multimodal land-transportation SRA methodology.

There is a tremendous opportunity to also facilitate cross-disciplinary research to improve particular loss estimation modules. For example, the work that will be completed on long span bridges under Task C (as described below) will necessarily feed into the fragility and damage/loss modeling in this part of the program. By incorporating the results from this related research, we can be assured that the most logical set of parameters and data needed to represent or characterize the performance of long span bridges are incorporated in the overall SRA methodology. By the same token, the loss estimation methodology might also identify the relative importance of long span bridges with regard to overall system performance. This kind of information could be valuable in explaining the need for retrofitting such structures. In addition to the long span bridge task, the advanced bridge earthquake protective system task may provide important insights and information in the application of the methodology. By understanding what new measures might improve the specific performance of a particular bridge, we can identify more effective ways of improving the overall performance of the system. Similarly, we can use loss estimation tools to estimate the relative benefits associated with these new and advanced technologies. Relative benefits could be extended to include the larger system benefits associated with this implementation.

4. SEISMIC DESIGN AND RETROFIT MANUAL FOR LONG SPAN BRIDGES

In 1983, the FHWA published the *Seismic Retrofitting Guidelines for Highway Bridges*, the first attempt at providing nationally-applicable guidance on screening, evaluating, and retrofitting seismically vulnerable highway bridges. That report (and its 1995 update, *Seismic Retrofitting Manual for Highway Bridges*, which was developed under the FHWA-sponsored MCEER Highway Project) are intended to address the vast majority of typical short-to-medium span structures contained in the U.S. National Bridge Inventory. However, very limited information is available on a national basis concerning evaluating the seismic vulnerability or retrofitting of long span bridges. At the current time, long span bridges are evaluated on a case-by-case basis and are usually considered as "special studies." However, there are a number of similarities between the structural systems and components of many long span bridges, and the development of a manual with recommended guidance on their evaluation and retrofitting could provide some uniformity and technical assistance in their evaluations nationwide.

Some long span bridges are very old and have piers of unreinforced masonry, or members fabricated from non-ductile steels and cast iron. Some are located on unknown foundations or, if known, they are usually massive lightly reinforced concrete pedestals in weak soils. Their seismic resistance is difficult, if not impossible, to quantify given the current state of engineering knowledge. This is a major concern because these structures are usually critically important to the region they serve, and any loss of access will have a major impact on emergency services following an earthquake, with the potential to impede post-earthquake response and recovery. Society expects a higher level of performance from these structures than for the more conventional highway structures; yet little is known about their capacity to accommodate or resist extreme loads, such as those experienced during an earthquake, and assurances of unrestricted access following an earthquake cannot be given at this time. This part of the TEA-21 project will address this problem in a consistent and transparent manner, drawing on experience from recent earthquakes and the expertise of a team of skilled researchers and practitioners.

For the purpose of this project, long span bridges have been defined as those structures where the main span exceeds 120 m. In contrast with short-to-medium span bridges that are generally comprised of simply-supported or continuous girders, long span bridges are generally made up of an assemblage of elements in the form of trusses, arches, cables, or a combination thereof. Most long span bridges can be classified into the following superstructure types:

- Steel Trusses – through trusses, deck trusses; articulation defined as simple span, cantilever, continuous, gerber, or combination

- Steel and Concrete Arches – through arches, deck arches; articulation defined as full arch, two or three hinged arch, or tied arch (single or multi-spans)

- Steel and Concrete Cable Stayed – single and double towers, single and multi-planes of cables; varied articulation
- Steel Suspension Spans – earth anchored, self anchored; typically three spans of articulation

The most prolific of all long span bridges in the U.S. is the truss-type of structure. Therefore it is planned to primarily, but not exclusively, focus on the truss-type of long span bridge in this research. In addition, most substructures for long-span bridges can be classified into the following types: spread footings, timber piles, concrete piles, steel piles, or caissons.

Long span bridges, especially those of the truss type, can be quite old. Therefore the nature, integrity, and seismic performance of the substructure and foundation systems are generally unknown.

For this project, a *Seismic Design and Retrofitting Manual for Long Span Bridges* will be developed. This manual will be complementary to but distinct from the 1995 *Seismic Retrofitting Manual* and the revision of that manual that is currently underway via the MCEER Highway Project. Some of the issues to be covered in the proposed long span manual are discussed in the following. A number of these issues were identified during a Long Span Bridge Workshop, which was conducted under the MCEER Highway Project in 1994.

4.1 Structural Issues

One of the distinctions between short span and long span bridges is in the definition of importance. Long span bridges generally cross waterways at locations where there is little, if any, redundancy in the highway network. The operational demands on such bridges are therefore considerably greater, and it is of paramount importance to ensure that a long span bridge remains open following a large earthquake. This dictates that long span bridges should behave in a "mostly elastic" fashion. This performance objective raises difficulty in determining the extent of permitted inelastic behavior of the main structural elements.

Retrofitting measures for such bridges are also challenging. Schemes that have been proposed to date are largely untested and therefore unproven. It is necessary to conduct experimental studies on critical subassemblages that are representative of typical long span bridge structures in order to gain an understanding of their expected performance and behavior under dynamic loading. Of particular importance are braced and unbraced sway frames, bearing-pedestal seating systems, and the strength and ductility of bridge piers and foundations. Retrofit measures for these critical elements and subassemblages are also considered to be important and will be addressed during the life of the project. However, prior to conducting research on retrofitting measures, a series of analytical studies will be performed to ascertain the most critical elements along with the need for retrofitting. This analytical phase of work will take place over the first two years of the project, whereas studies on retrofit measures will commence in the third year.

Experience in California has shown that many of their long span bridge piers and towers require some form of retrofitting. Although this experience is useful in identifying research needs, the extent of their applicability to national guidelines is unknown. For example, in low-to-moderate seismic zones, it may be neither expedient nor feasible to seismically retrofit a long span bridge that only has modest seismic demands imposed upon it. Some limited form of retrofitting (for example, bearings and seats) or the " do-nothing" option may be more economically justified. This option is rather attractive considering the exceedingly expensive retrofit measures that may be required if these bridges are retrofitted for long return period earthquakes. Research is therefore needed to in order to provide owners guidance on assessing the vulnerability of long span structures and the expected outcome if the "do-nothing" option is adopted.

4.2 Geotechnical and Foundation Issues

There are a number of important geotechnical and foundation considerations for long span bridges that must be addressed. These include the need for studies on improved evaluation of long-period ground motion characteristics in existing earthquake records, developing methods for estimating liquefaction-induced lateral spreading loads on caissons and pile supported piers, consideration of soil-foundation interaction from large pile groups and caissons, and characterization of the site response at soft soil sites.

Ground acceleration characteristics and related spectral accelerations have historically formed the basis for seismic design. However, in the case of long span bridges, natural periods of vibration may be in the range of 3 to 10 seconds. In this period range, the signal-to-noise ratio of recorded accelerograms require the use of high pass filters to eliminate the noise. Consequently, the accuracy of spectral ordinates in the 3 to 10 second range is questionable. As peak ground displacements occur in this range and spectral displacement ordinates provide essential design criteria, research is needed to clarify the nature and magnitude of displacement spectra and peak ground displacements associated with design earthquakes.

In the case of large caissons and pile-supported bridge piers where current retrofit analyses indicate the potential for liquefaction-induced lateral displacements, ground remediation options are often impractical, particularly where foundations are located in river channels. Consequently, the need to assess whether the load and displacement demands on the foundations are of concern becomes a critical need, as does the option of developing an economical structural retrofit, if required.

The typical input to a soil-structure interaction analysis relies on free field site response results. Recent sensitivity studies on soil-structure interaction indicate that the resultant overall bridge solution is very sensitive to the site response analysis results. For large pile groups and caisson foundations, excitation to the structure comes from input ground motions at various depths along the pile group and caisson length. In addition to the overall level of shaking, phase differences in depth-varying ground motions will introduce rotational excitation on the structure. The depth-varying input ground motion will introduce a tilting motion in addition to horizontal and translational motions in the structure. This effect can be very significant for cantilevered foundation systems; i.e., when the pile cap or cross-bracing is cantilevered a big distance above the mudline. Whereas available site response analyses have been verified to some degree by comparing surface motion to recordings, some of the subtleties in phase change with depth (i.e., the apparent propagation speed with depth) have not been verified resulting in drastic changes in shaking of the structure as implied by the tilting mode of the input to the structure. This aspect can be addressed by examining some of the available down-hole strong-motion recordings, e.g., at Port Island from the Kobe earthquake and the SMART-1 array. Also, some sensitivity studies can be conducted to compare the phase angle change between nonlinear and equivalent linear site response analyses and 2-D site response analyses, which inherently decompose 1-D shear waves at reflecting boundaries to compressional and shear waves. Some guidance on this issue can improve the level of confidence in the state-of-practice for soil-structure interaction analyses and in design practice.

Extremely large pile groups (involving hundreds of piles) are very common for long span bridges and group effects for such systems are believed to be extremely important. However, available pile group test data is limited to mostly 3 x 3 pile groups. The University of Florida had developed some data on a 4 x 4 pile group and these data have been used to compare with the elasticity pile group theory, which was found to be somewhat misleading as it over-predicts group effects. This lack of experimental data has left designers to make subjective judgements, usually by modifying p-y curves. Completely ignoring group effects can lead to very serious errors for very large pile groups, while relying on the elasticity approach has been found to be deficient even for small pile groups. Research in this area is needed and the advance of constitutive modeling and 3-D finite element programs can tremendously improve our ability to account for group effects by analytical approaches.

5. CONCLUSIONS

The FHWA-sponsored research program recently initiated by MCEER will address a number of important aspects related to the seismic vulnerability of the national highway system. Two of four major research thrust areas, loss estimation methodologies for highway systems and seismic design and retrofitting of long span bridges, have been described in this paper. Other thrust areas, including advancing the state of practice with respect to the development of intelligent earthquake protective systems, and geotechnical studies on soils and foundation behavior, will be discussed in subsequent papers and presentations.

The results of this work are expected to have significant short- and long-term impacts on the performance and economics associated with earthquake impacts on highway systems, and it is expected that some of the advances made in this program will have direct application to other surface transportation modes. As the research is still in its initial stages, the first set of results and products will not be available for approximately 3 or more years.