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Chapter 8

FE Based Vulnerability Assessment of Highway Bridges Exposed to Moderate Seismic Hazard

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Additional information is available at the end of the chapter

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1. Introduction

The assessment of seismic vulnerability in regions where the risk from earthquake shaking is considered moderate poses special problems in terms of establishing critical conditions for failure and the importance and urgency for taking action. Research studies sponsored at the University of Mississippi (UM) over a period of about 10 years by the Mississippi Emergency Management Agency (MEMA) and Mississippi Department of Transportation (MDOT), respectively, have been aimed at identifying the vulnerability of select critical highway bridges subject to significant ground shaking from the New Madrid Seismic Zone (NMSZ).

The historical occurrence of multiple but infrequent major seismic events in the NMSZ exceeding seismic moment of *M* 7 has been established by geophysicists and seismologists through numerous surveys of surface rupture features and paleoseismological excavations conducted throughout the region (for example, see [10, 18]). Planners in both state and federal agencies are concerned about the consequences of both physical and economic damage posed by the next major recurrence of a potentially catastrophic earthquake along the fault. The United States (US) Federal Emergency Management Agency (FEMA) sponsored a major research study [3] to investigate the multi-state regional consequences of a hypothetical event of *M* 7.7 on both buildings and bridges. The bridges in Mississippi discussed in this chapter represent critical lifelines exposed to the earthquake threat that are located along the evacuation routes and economic supply chains for communities in the northern part of the state as well as the tri-state metropolitan area of the city of Memphis, Tennessee, having population of about 1.3 million.

A myriad of uncertainties exist for both the rare but potentially catastrophic seismic events and the multiple factors affecting the response of these soil-foundation-structure systems. In the absence of ground motion records for the severe historical events in the seismic zone under

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consideration, a simulation based approach is adopted to highlight the salient features of both the input and response at the site. The vulnerability assessment requires that reasonable behavioral response and multiple failure limit states be examined under a range of possible ground motion intensities. While a probabilistic approach is desirable overall, a deterministic approach enables the examination of the key response characteristics and the detailed information needed to establish relative importance of different limit states including soil capacity, pile/column axial and flexural strength, and member/system instability.

The bridge seismic vulnerability studies in this chapter highlight the challenges posed by the need to balance the level of sophistication of the finite element (FE) simulation with the:

1. state of knowledge of the bridge facilities, their seismic exposure, and local site conditions
2. project objectives in order to provide safe and economic decision making for hazard mitigation and emergency response and mobilization planning

Lessons learned and discussed herein are the result of over a decade of research at UM sponsored at the multidisciplinary Center for Community Earthquake Preparedness (CCEP) and graduate level studies by a number of students supported by the Department of Civil Engineering.

2. Seismic hazard and inventory characterization for the study region

In [10] the 1811, 1812 sequence of three distinct earthquakes corresponding to rupture along separate segments of the irregular shaped New Madrid fault is described. More recently, in the FEMA study [3], a scenario established for emergency planning purposes comprising a single M7.7 event consisting of sequential rupture along all three segments. Seismicity of smaller events recorded using a strong motion instrument array during an almost 30 year span is plotted in Figure 1 to which the approximate location of the study region has been added.

According to the 2012 data compiled for the National Bridge Inventory (NBI) [6] in the US by the Federal Highway Administration (FHWA), a total of 18,459 highway bridges are found in the 82 counties in the state of Mississippi (MS). The study region contains only a small subset of this inventory and may be approximately characterized as the counties located in north MS most likely to experience moderate ground shaking from a major event in the NMSZ. Based on default inventory data contained in the GIS-based software, Hazards US-Multihazard (HAZUS-MH) [5] created under sponsorship by FEMA for use in emergency management planning, 1133 bridges are exposed to the moderate seismic hazard.

The seismic vulnerability of all bridges in MS has been examined from a risk or loss estimation point of view in both [3] and [13]. In each study, the HAZUS-MH methodology has been implemented which depends on use of fragility curves assigned to bridge classes included in the NBI system. No study has yet been performed to assess seismic vulnerability using FE as the basis of the loss estimation. The present study provides a first step toward such a more comprehensive study and focuses on five bridges at a variety of sites in the study region

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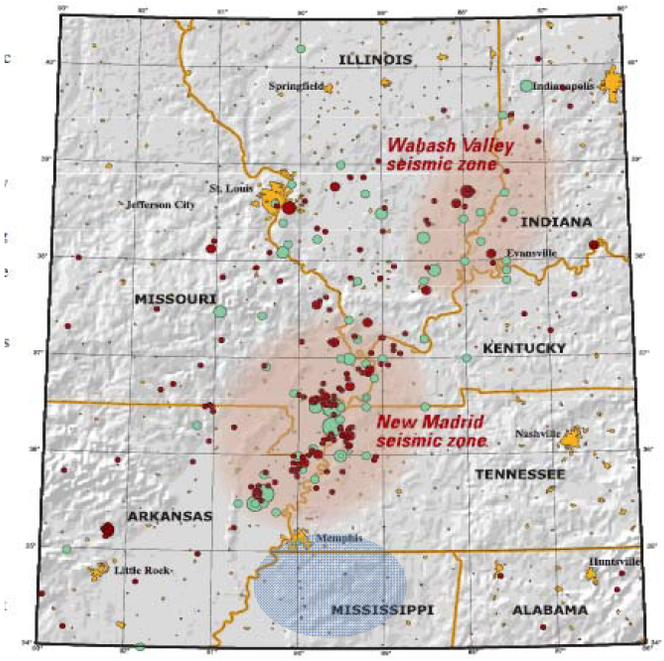


Figure 1. Recent seismicity in NMSZ and surrounding multi-state region exposed to risk of a repeat of historic catastrophic events (M7-M8); red circles give epicenters for events > M2.5 during the period, 1974-2002 [from 19]; the study region is represented by the blue shaded area

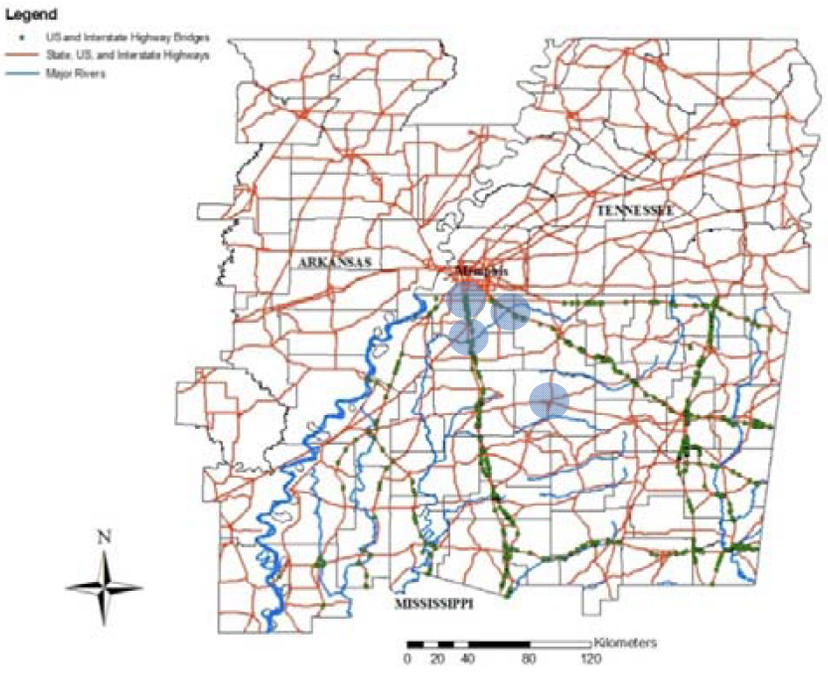


Figure 2. NBI bridge inventory in study region shown by open circles; green circles show bridges located in north Mississippi on the major access routes for the Memphis metropolitan area, those investigated using FE based seismic vulnerability analysis lie within shaded areas; red lines indicate highways on federal and state system; blue lines represent major rivers to show critical water crossings

investigated during three separate projects. Figure 2 shows the locations of the sites in relation to the NBI inventory supplied in HAZUS-MH and federal and state highway system.

The select bridges studied have been modeled to varying degrees of complexity with both two-dimensional (2D) and three-dimensional (3D) computational simulations including eigenvalue, linear dynamic, nonlinear static, and nonlinear dynamic. Earthquake time histories have been generated to capture a range of intensities from M6 to M8 and peak ground accelerations (PGA) in the approximate range, PGA=5-50% g, depending on the site, study objectives, and methodology. It is noteworthy that, over the period of the studies, significant changes have occurred in the understanding of the earthquake risk and level of ground shaking to be expected. Each study used the best available knowledge at the time.

The earliest study was performed for MEMA in the context of a broader study of the seismic vulnerability of facilities located on the UM campus [17]. The motivation for the study was the belief that the University was and remains a key to economic development in the state as well as a place of both historic value and a population center of relatively high density. The study included an approximately 70 year old bridge that serves as a major entrance as seen in Figure 3. The bridge was designed by MDOT prior to any recognition of a significant seismic threat in the applicable design code. This bridge served as the first attempt at a detailed 3D FE-based evaluation of seismic response and vulnerability assessment [12]. The evaluation was performed with both fixed base and soil-foundation-substructure interaction boundary conditions to capture the influence of high embankments on the response of the structural components with emphasis on the pier columns.



Figure 3. East Gate Bridge carrying traffic from University Avenue in the City of Oxford at the entrance to the UM main campus [17]; present day bridge, old private railroad tracks, and right-of-way have been replaced by a modern city roadway

A second study [14] was performed for MDOT for what the Bridge Division deemed a critical facility that provides access from a major interstate highway to a vital economic development region in the state. The region is located within the fastest growing county in the state and one of the fastest growing in the nation due to its proximity to the metropolitan area of the city of Memphis, Tennessee. Approximately 30 years old, this bridge shown in Figure 4 was built to low seismic standards. The code recognized by MDOT was and remains the one published by the American Association of State Highway and Transportation Officials (AASHTO). Even when the first edition of the AASHTO Bridge Load and Resistance Factor Design (LRFD)

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Specifications appeared in 1994, the ground motion demand at the site was only about PGA=0.15g.

The third and most recent study was performed for MEMA to investigate findings of the FEMA sponsored NMSZ catastrophic earthquake study [3] on the impact of an *M* 7.7 event on bridges in MS. Using a HAZUS-MH fragility curve based analysis which estimated conditional probabilities of damage at four basic limit states (slight, moderate, extensive, and complete), the study found that only six bridges in the entire state would have a significant probability exceeding slight damage. The purpose of the FEMA study was to provide states affected by the NMSZ a basis for establishing earthquake components of their federally mandated mitigation plans. The MEMA study used an FE based approach to establish vulnerability considering more site and facility specific information. In consultation with MDOT personnel, three bridges shown in Figure 5 were identified for study. All are located on major evacuation/mobilization routes which crossed the Coldwater River. The bridges were deemed near the edge of significant ground shaking based on the FEMA study. The rationale was that if these showed evidence of significant vulnerability then bridges closer to the NMSZ would then be at similar or higher risk.



Figure 4. Bridge carrying *MS* 302 over Interstate highway *I* 55; (left) looking toward Southaven, MS, a fast growing city forming part of the metropolitan area of the City of Memphis; (right) view of the intermediate bents and girders of the two closely spaced bridges



Figure 5. Three bridges crossing the Coldwater River on lifelines serving the study area; (left) view of southbound *I* 55 bridge; (middle) nearby *US* 51 bridge showing piled bents carrying simple spans; (right) view of northbound *US* 78 bridge

3. Ground motion simulation for the study sites

The lack of seismic records of significant earthquake events in the NMSZ makes the task of selecting ground motion excitation for response analysis a challenge. The state of knowledge of the causative features of the fault and the expected attenuation of motions from the source has changed over time and remains an area of significant debate and research. Spectral physics-based parametric source and attenuation models have provided a rational basis for the case studies presented here.

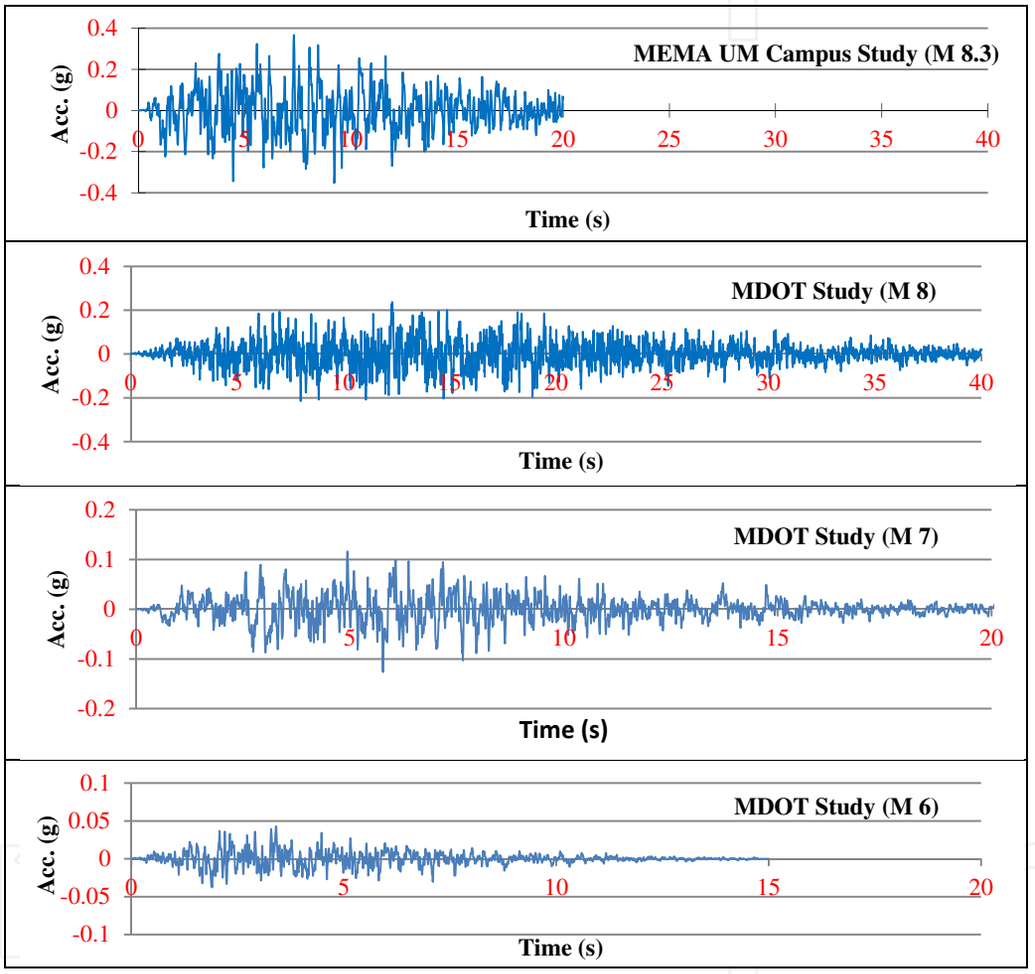


Figure 6. resultant horizontal ground acceleration time histories used in FE model analyses; MEMA UM campus study [17]; MDOT study [14]; MEMA Coldwater River bridges study [16]

Figure 6 shows resultant horizontal ground motion realizations generated for the various studies assuming 2D propagation from an assumed epicenter usually taken as Marked Tree, Arkansas, the town nearest to the southernmost position of the New Madrid fault. In the MEMA campus and MDOT bridge studies, orientation of the bridge was considered and component motions were then extracted for application to the FE models. In the absence of a 3D propagation model, requiring definition of layered media in a spherical coordinate system,

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vertical motion was obtained by uniformly scaling the resultant horizontal motion by the commonly assumed factor of 2/3.

In the MEMA UM campus study [17], the input horizontal motion realization for the UM campus was generated by others for M6.3 and *M* 8.3 events having source along the nearest (southernmost) segment of the NMSZ. In the MDOT bridge study [14], software was obtained from the US Geological Survey (USGS) and source model parameters and attenuation relations were identified in consultation with USGS and the University of Memphis enabling simulation of multiple realizations at arbitrary intensities. Events of nominal *M* 6, 7, and 8 were selected in order to capture different response levels. In the MEMA Coldwater River bridges study [16], a FEMA scenario of *M* 7.7 was adopted to be consistent with their results for the multi-state NMSZ region which were based on a distributed source model involving slip along the entire southern segment of the New Madrid fault. Since the study provided only PGA contours, not time histories, the MDOT study realization for the *M* 8 scenario case (Fig. 6) was scaled to achieve an input motion with PGA corresponding to that of the *M* 7.7 scenario at the bridge site locations (approximately PGA=0.25g).

Source spectral models for the very large intensity events were such that all ground motions have significant energy in the 1-2 Hz range coinciding with fundamental and low natural frequencies of the bridges.

4. FE modeling options

When using FE as the basis of vulnerability assessments, it is important to make several basic decisions regarding modeling approach including probabilistic versus deterministic and simple versus complex. These choices influence at the most general level, the software to be used, and at the most specific level, the key modeling assumptions such as system scope, boundary conditions, incorporation of soil-structure interaction (SSI), and focus on lumped parameter, 2D structural, or 3D continuum finite elements. Rather than propose a comprehensive view on the proper choices for all possible objectives, the select bridge study cases are offered as the possible range one might consider.

In the MEMA UM campus study [17], no prior knowledge existed. As a result of this uncertainty about what might be expected as well as a strong desire to ensure the safety of the many thousands of students, employees, and visitors to the campus and a major concern about the impact of significant losses to the future functioning of the university enterprise and consequential economic impacts on the state, the sponsors sought the most realistic view possible given the state of the art at the time. In response to this objective, the analysts committed to full 3D nonlinear dynamic FE simulation including SSI in cases where it might have a significant influence on the response. The project was initiated in the mid-1990s when the software ABAQUS [7] provided many desirable features including 3D nonlinear beam-column (structural) elements (B33) with user input moment-curvature relations and 3D continuum (solid) "infinite" elements (CIN3D8) with shape functions capturing radiation damping, in effect

providing non-reflecting boundaries which allow dissipation of wave energy propagating radially away from the FE model.

There was little experience with the modeling approach at the time of the study and no experience with the nonlinear beam-column and radiation damping elements, so validation analyses were performed [9]. Detailed drawings were available from the bridge designer (MDOT), and a series of detailed models were developed to establish confidence in each subsequent level of complexity. Static self-weight analysis was first performed using a so-called fixed-based model (no soil stiffness included) to represent structural connectivity and weight and stiffness characteristics. Basic features of the fixed base model are shown in Fig. 7.

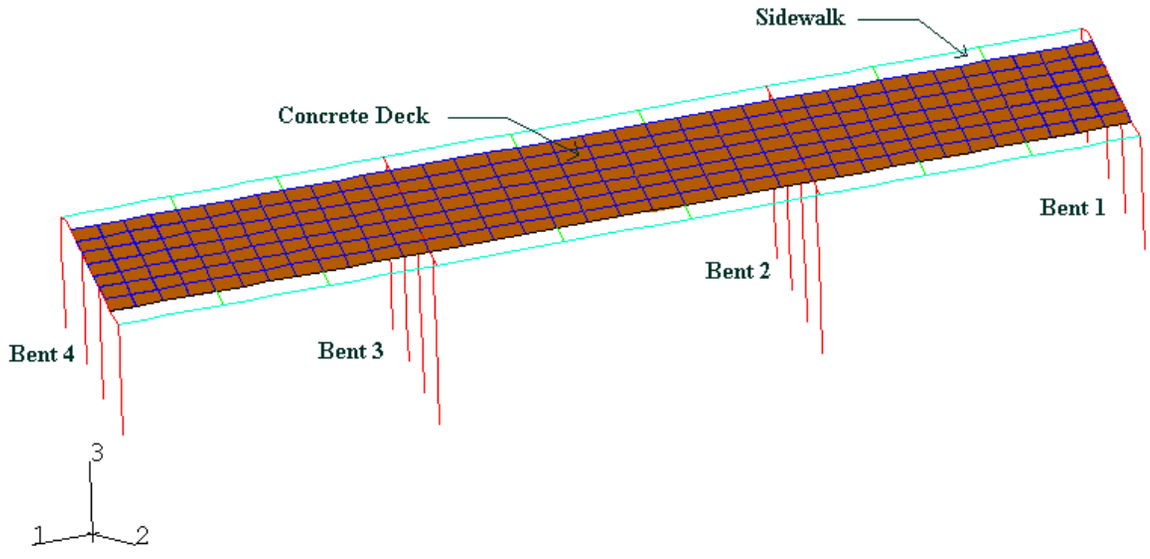


Figure 7. Fixed-base FE model of East Gate Bridge for MEMA UM campus study[17]; bents modeled with nonlinear beam-column elements; composite concrete deck-steel girder superstructure modeled using concrete plate elements for deck and linear beam elements for steel girders; no soil degrees-of-freedom

Once an acceptable result was obtained from the static analysis, an eigenvalue analysis was performed to estimate structural mass distribution characteristics and associated mode shapes and frequencies. Since the ground motions shown in Figure 6 accounted primarily for propagation through the earth's crust, modification and possible amplification as the seismic waves propagated through soil at the bridge site was not considered. To account for this limitation, a one-dimensional (1D) vertical wave propagation analysis [12, 17] was performed using a model of the top 100 ft of soil layers based on data obtained from soil borings. The analysis incorporated nonlinear softening of dynamic shear moduli at high strains and enabled generation of input motions to all fixed degrees-of-freedom (DOF) in the FE model regardless of elevation, in this case, at both the base of the columns of the intermediate bents and the level of the end abutment pile caps.

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As Figure 3 shows, there is a significant difference (over 30 ft) in elevation between the abutments and the intermediate bents. Furthermore, the deck girders are built into concrete end walls where fill material is placed beneath the roadway. Between the abutments and what is now a roadway, steep embankments are found. To incorporate the interaction between the soil immediately below the footings of the intermediate piers, the embankments, and the structural system, the significantly more elaborate model shown in Figure 8 was developed [12,17].

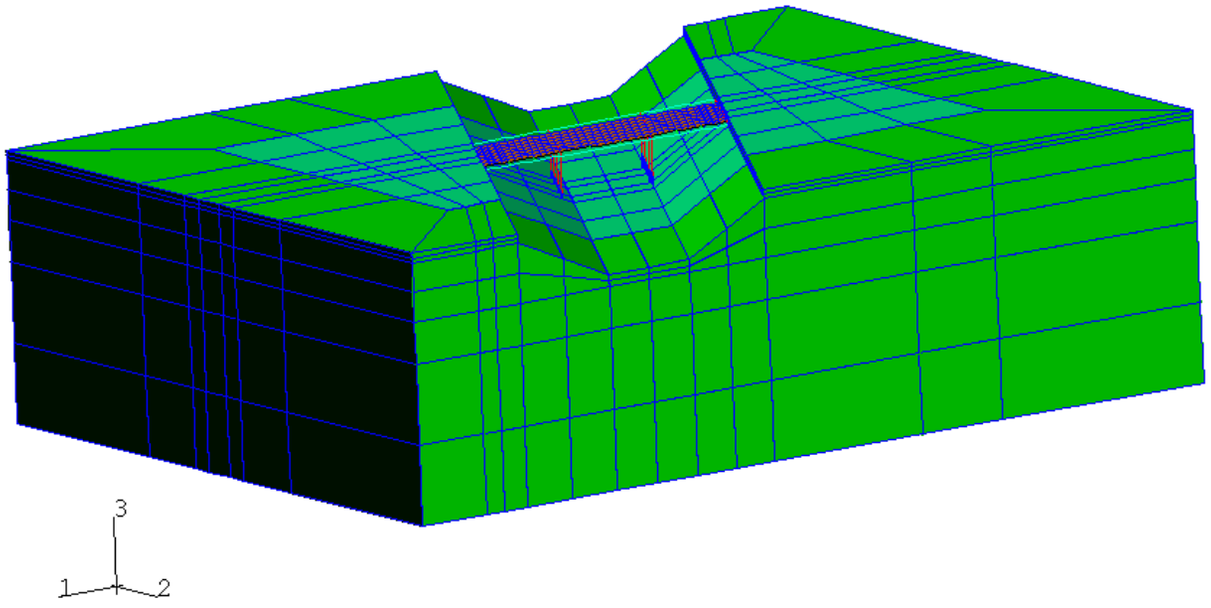


Figure 8. Subsurface geology and embankment interaction FE model of East Gate Bridge for MEMA UM campus study [12, 17]; end walls modeled with shell elements; active/passive soil pressure resistance modeled with nonlinear springs connecting end wall and back fill soil elements; embankment soil and subsurface geology modeled with elastic 3D solid elements; radiation damping at absorbing boundaries modeled with 3D solid infinite elements

The MDOT study was the first earthquake vulnerability study performed in the state for its Bridge Division. Again because of the many uncertainties, a 3D detailed FE based simulation approach [15] was adopted to provide the most accurate estimate of likely response. The bridge system was much larger than the one in the UM campus study due to the overcrossing of an interstate highway which now carries three lanes of traffic in each direction and the presence of two bridge frame substructures separated by a only a small gap between bents (see Fig. 4). The servicing of a large commercial center and a rapidly growing residential community required the bridge to carry a total of nine lanes of traffic, each substructure carrying traffic in one of the two directions. Embankments again created a significant difference in elevation of approximately 20 ft between soil beneath respective roadway pavements, but here the embankments were sloped to accommodate access to/from the interstate highway.

As shown in Figure 9, there were four continuous deck spans totaling approximately 350 ft. The substructures now included both piled footings at the end abutments and central inter-

mediate bent and spread footings at the two other intermediate bents. A low-rise building SSI study [9] had demonstrated the importance of including a refined mesh locally around spread footings to account for soil softening under large seismic shaking. The detail view in Figure 9 shows the refinement pattern used around the bridge footings.

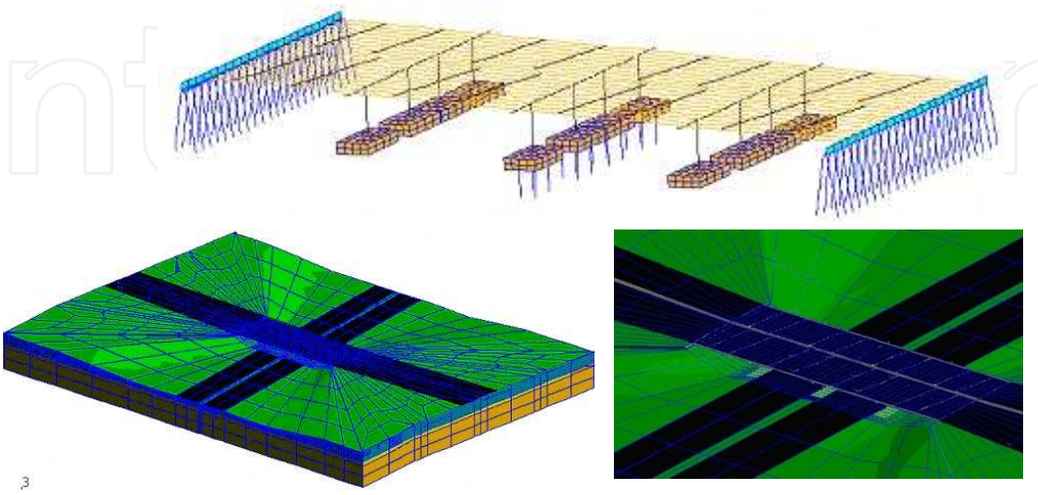


Figure 9. Subsurface geology and embankment SSI FE model of I55/*MS*302 Goodman Road Overcrossing for MDOT study [14]; concrete girders and bent frame members modeled with 3D nonlinear beam elements; concrete deck and footing modeled with shell elements (top figure shows soil elements connecting to footing shell elements); soil modeled using 3D solid elements with a Drucker-Prager cap material model for nonlinear response at high strains; radiation damping at absorbing boundaries modeled with 3D solid infinite elements

The MEMA Coldwater River bridges study [16] was originally intended to support a multi-state regional (National Level) earthquake Exercise (NLE) sponsored by FEMA with participation by MEMA. A major flood along the MS River threatened to overtop the levees protecting the farming communities in the Delta region, so MEMA personnel were called away from the exercise, and the input from the bridge study was not required as planned. The long term objective of the study to assess the bridge vulnerability was nonetheless pursued but without as much urgency.

The three Coldwater River bridges consisted of multiple intermediate bents (up to 42 in one case) supporting composite concrete deck slabs over short simple spans (40-50 ft) and a longer central span (100-120 ft) over the main navigable channel. The deck in the central span was usually continuous over several adjacent spans and consisted of a multi-cell concrete box girder or a composite concrete steel girder section. With a limited budget and time frame, a 3D model of the entire bridge with SSI was not attempted. A simpler approach was taken that focused on characterizing the main perceived sources of vulnerability.

Again, design drawings were available from MDOT along with soil borings and test pile logs. The drawings indicated the structures had been built in the 1950s and 1960s, and lacked any consideration of seismic loading in the design. The location of the bents in the flood plain of the river with, in several cases, soil in the top layer permanently saturated, allowed the possibility of weak lateral resistance of the soil and liquefaction under strong ground shaking.

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The modeling approach thus focused on 2D representation of lateral resistance of the typical intermediate bents in each bridge and 3D representation of the continuous span box girders.

Figure 5 shows that the intermediate bents consist of 4-5 relatively short concrete piles with batters on the outer piles tied together by a concrete pile cap that support bearings for the deck girders. Figure 10 shows the representation of this structural system as modeled in the SAP2000 software [1]. The piles in this system were designed for vertical (deck weight and vehicle live) loads primarily, so the potential vulnerability is from lateral inertial load generated by seismic shaking. Under lateral forces, the piles have a tendency to bend under the lateral resistance from the soil. Furthermore, the overturning moment associated with the deck lateral load develops increased compressive axial loads in the outer (batter) piles far in excess of their design assumptions.

Key aspects of the modeling are the axial and bending capacity of the concrete pile section, the lateral stiffness of the soil, the unsupported length of the pile, and the depth of pile embedment. In keeping with the simplified assumptions, linear vertical and horizontal soil springs were used to represent the soil resistance. Surprisingly, standard geotechnical and bridge engineering textbooks and even some advanced earthquake engineering ones offer little on methods to determine the stiffness properties of soil, choosing to focus rather exclusively on capacity estimation. Results presented in a FEMA guidance document [4] were used to estimate the spring constants considering the projected area of the pile and the elastic modulus of the soil.

Isolation of the intermediate bents for lateral load analysis is valid to the extent that the deck moves uniformly so that no bending or torsional resistance is provided by adjacent bents. The simple deck spans help to minimize this effect through the discontinuity of the bearings. In the case of continuous main spans, however, the deck is supported on pile supported concrete piers with either one or two columns of significantly different heights and size, so significant resistance from adjacent bents is anticipated. Figure 11 shows a 3D model developed using another FE software [2] oriented toward bridge design analysis used to explore the effect of the interaction between bents in these spans.

5. FE Evaluation process – System behavior analysis

The previous section indicates that the goals of the vulnerability evaluation influences the selection of FE modeling options including software (structural or general purpose), level of analysis (2D or 3D), element selection (structural or continuum), connectivity (rigid connections or flexible bearings), boundary conditions (fixed, flexible, or absorbing). These choices not only influence the behavior and response details that may be estimated and Visualized, they also determine what output measures are available for estimating physical damage, performance characteristics, and vulnerability.

In the MEMA UM campus study [17], a basic analysis approach was established that was followed throughout all the studies. Before proceeding to the complex nonlinear dynamic time history analysis, linear static and eigenvalue preliminary analyses were first performed. The

linear static gravity load analysis requires processing of all parameters and procedures involved in estimating the stiffness properties of the system. It is relatively fast computationally and enables visual and quantitative confirmation of element connectivity and effect of support fixity (fixed base models), support flexibility (soil springs), or absorbing boundary conditions (SSI models). The eigenvalue analysis requires processing of all parameters and procedures involved in estimating the mass properties of the system. The analysis is also relatively fast computationally and yields mode shapes and frequencies. These modal properties provide insight into the expected dynamic response characteristics under earthquake loading.

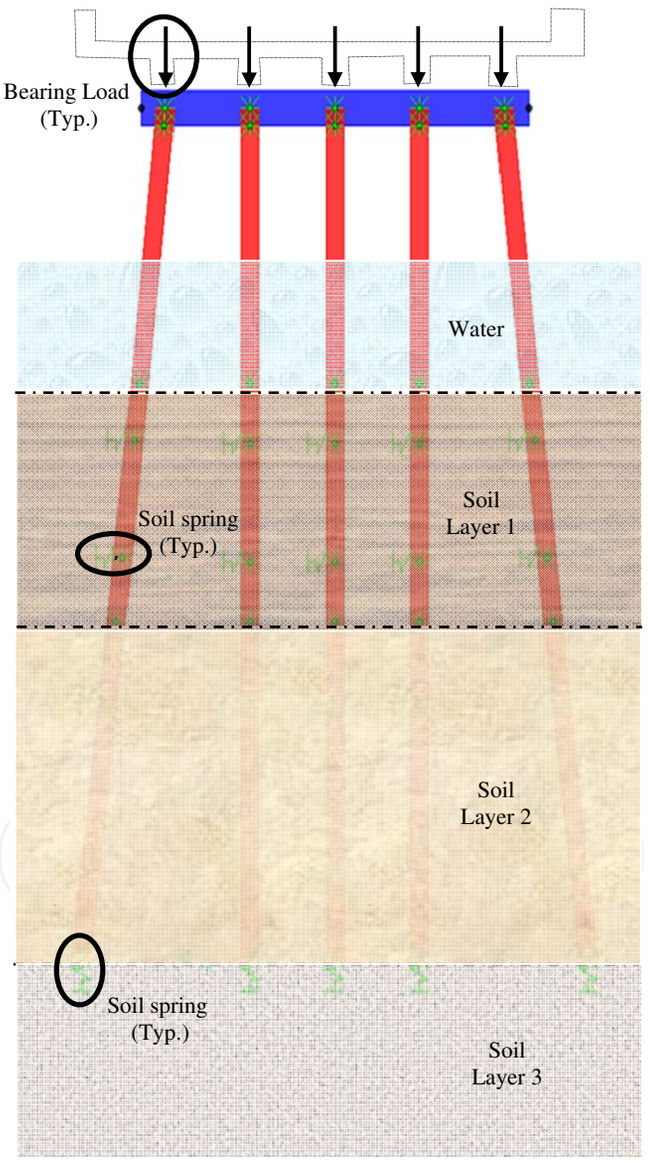


Figure 10. Model of typical intermediate bent for Coldwater River bridge [16] carrying two lanes of interstate highway traffic; concrete piles and cap modeled as frame elements (section behavior modeled with axial-bending interaction using fiber model); ground motion applied to soil springs

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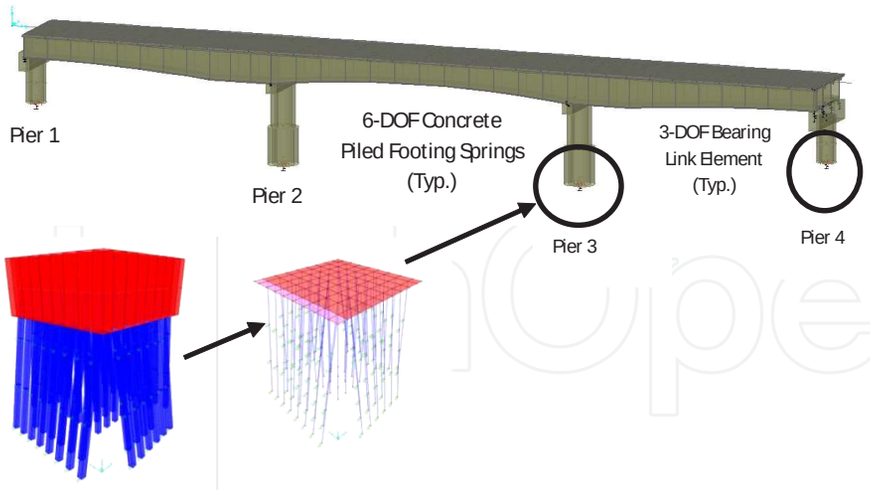


Figure 11. Model [16] of typical 3-span continuous concrete box girder bent for Coldwater River bridge carrying two lanes of interstate highway traffic; concrete pier columns and footing piles modeled with frame elements; box girder flanges and webs and footing pile cap modeled with shell elements; footings modeled with equivalent 6-DOF springs; ground motion applied to footing springs

Figure 12 illustrates some of the benefits of performing the preliminary analyses before proceeding to the nonlinear time history response analysis. The issues of stiffness and mass distribution become evident from the plotting and animation of the mode shapes associated with global movements of the system. These shapes may be broadly categorized as ones that involve significant net movement of the center of mass of the system and those that do not (sometimes called breathing modes). In the case of the campus bridge shown, it is seen that the mode involving transverse movement of the mass center becomes coupled with a rotational movement because of the skew of the deck necessitated by the angle between the centerlines of the street carried and the one crossed. Also visualized in the case shown in Figure 12 is the effect of the SSI, in this case the embankments and abutments interacting with the main span deck and intermediate bents.

Behavior similar to that observed for the MEMA UM campus study bridge is found in the case of the MDOT study bridge. Figure 13 shows the transverse mode shape for the fixed base model. The bridge proportions (both deck length to width and deck span to column height ratios) and skew angle are different in the two cases. The translational and rotational coupling is less pronounced, and the transverse column bending is more pronounced.

The eigenvalue analyses not only provide insight regarding the expected deformation patterns, they also provide the frequencies associated with these characteristic modes. These frequencies provide quantitative information which provide insight into the expected influence of the SSI effects as well as the dominance of deformation modes associated with specific earthquake events.

The influence of SSI was examined in detail in the MDOT study which included ambient vibration measurements using a portable array of accelerometers [11, 14]. Simultaneous readings were taken at each bent location under excitation of the bridge by truck traffic. Using

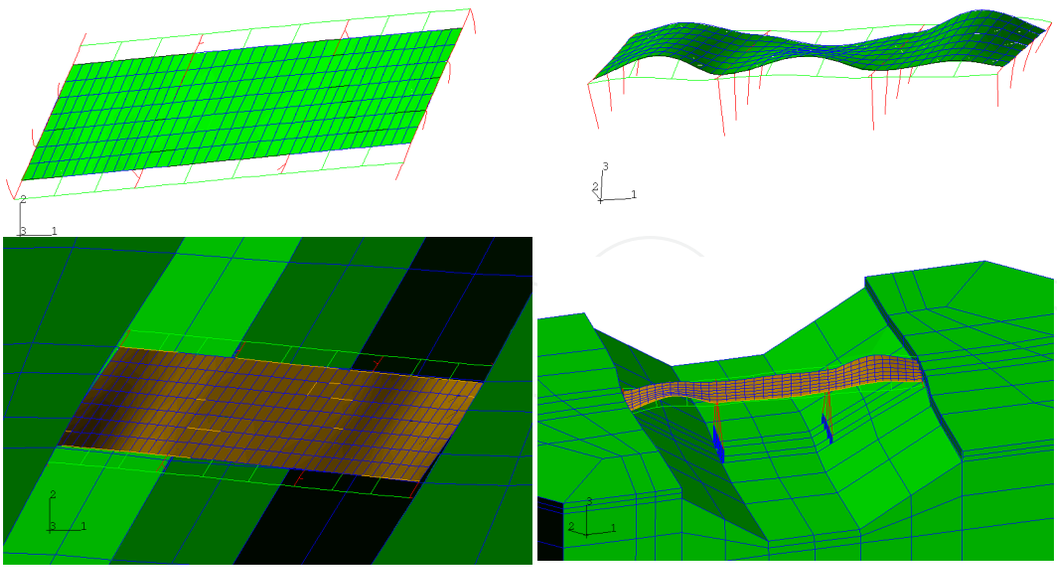


Figure 12. Eigenvalue analysis results for the MEMA UM campus study bridge models [17]; top figures show plan and isometric views of fixed based model transverse mode causing bent and abutment column deformation; bottom figures show comparable modes for SSI model; skew of roadway alignment introduces coupling of translation and rotation of the deck mass as well as bending and torsion of the deck; the resistance provided by the embankment is apparent from the contact developed during rotation

a point on the bridge deck as a reference point, frequency response functions were derived that eliminated the influence of the excitation, and system response frequencies were extracted corresponding with excellent correlation to the 3D model SSI case without any model parameter modification. Accelerometers were then moved to the abutments and frequency extraction performed [11] revealing evidence of the participation of the abutments in the transverse mode shape comparable to the one in Figure 13.

In the MEMA bridge study, the preliminary analyses were again performed prior to time history analysis. Figure 14 shows that the fundamental mode of vibration for a typical intermediate bent in the interstate highway river crossing is one involving net translation of the deck and corresponding bending of the piles which were designed as axially loaded members. Consideration of the eccentricity of the deck mass with respect to the center of resistance of the soil-pile system provides for expectation of an overturning moment. Such a moment would generate an increase of axial force in one of the batter piles which would combine with the bending action.

6. FE evaluation process — Seismic response analysis

The benefit of FE based evaluation is that a great bit of detail of the response of the system is made available through the analysis especially when the time history approach is taken. In essence all DOF selected in the modeling process are accessible over the full length of the simulated event. With further post-processing whether computational or graphical, additional response quantities and behavior can be accessed, plotted, and visualized.

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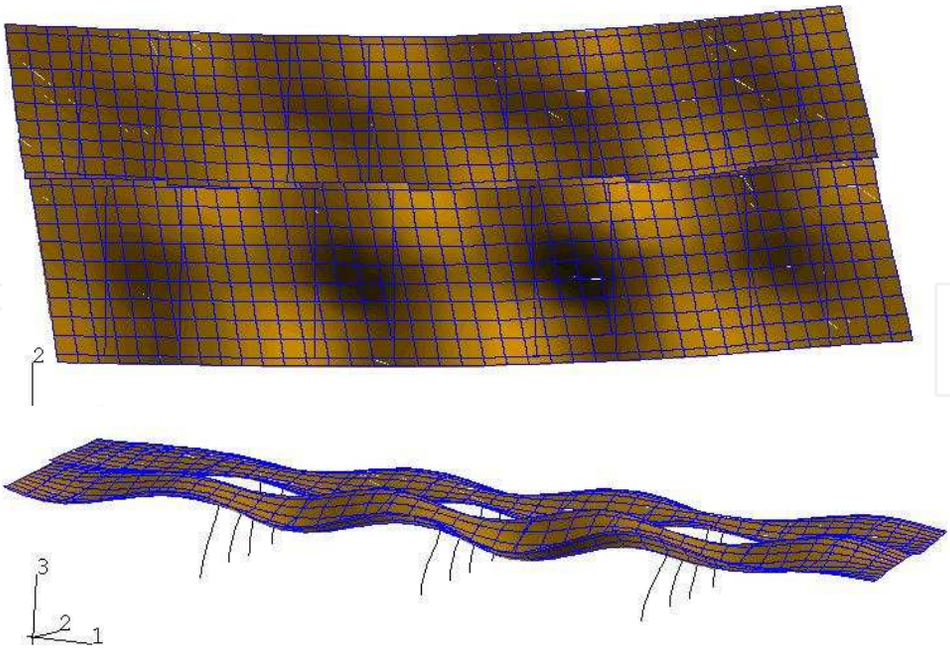


Figure 13. Eigenvalue analysis results for the MDOT bridge study; plan and isometric views of fixed base model transverse mode; lateral deck and column bending dominates response in this pair of adjacent bridge structures; some bending and torsional coupling in the deck is evident

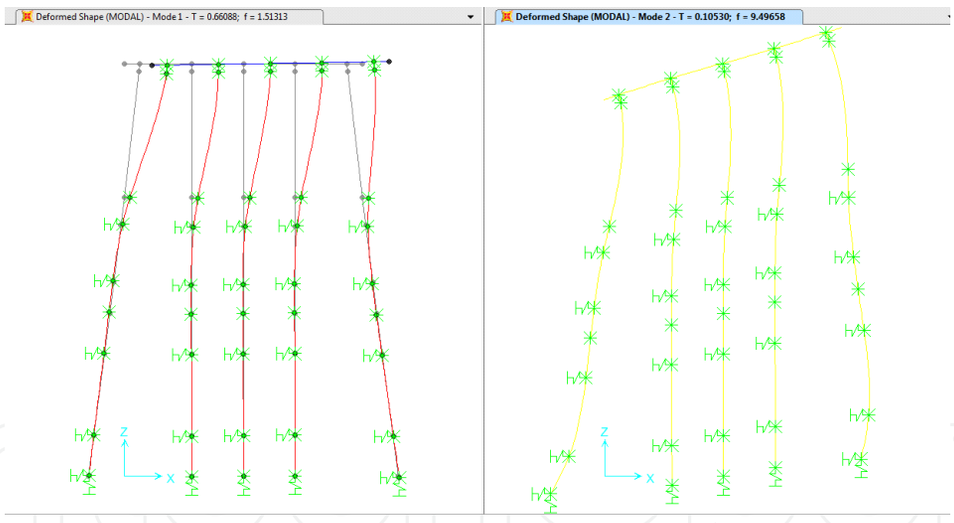


Figure 14. Eigenvalue analysis results for the MEMA bridge study [16]; elevation views of 2D intermediate bent model showing deck transverse displacement (left) and rotation (right) modes; pile bending dominates response although combined action of bending and axial force in the piles is implied

In the MEMA UM campus study [17], it became particularly useful to examine hysteresis of the column section in the plastic hinge region. Figure 15 shows a typical plot of simulated moment-curvature response during the severe (*M 8.3*) event case. The results demonstrate that the yield limit state is achieved in both directions for a corner column, and the ultimate limit state is achieved in one direction. The latter result provided clear evidence of vulnerability and the possibility of complete failure or collapse.

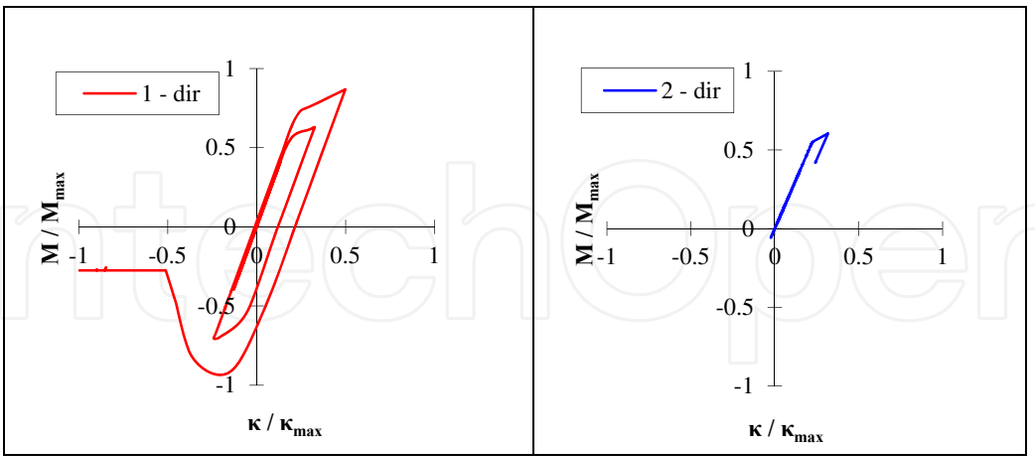


Figure 15. Normalized moment-curvature hysteresis plots for a corner column of the MEMA UM campus study bridge (see Figs. 3, 8, 12) subject to an extreme event (see Fig. 6); nonlinear user-input curves developed separately using a fiber section model [12, 17]

In the MDOT study [14], with the availability of the USGS simulation tool for developing random realizations of input ground acceleration time histories (Fig. 6) at different intensities, limit state determination was enabled for the columns and piles over the full range of damaging events. Comparison of the peak and characteristic responses enabled a performance evaluation of the system based on critical material, section, or member limit states such as first cracking, first yield, plastic hinge formation, and plastic collapse mechanism. In the case of the bridge studied, it was learned that the piles at the abutments and the columns of the central bent provided substantial energy absorption in the extreme event case through ductile hysteretic response in these members. It was also learned that the pile system at the abutments and central bent adequately distributed lateral forces so that the soil remained linear throughout the event. While nonlinear slip at the superstructure to abutment pile cap bearing connection was attempted, this proved too difficult for the software to resolve and convergence was never reached. Ultimately, rigid connections were assumed and the slip mechanism was interpreted as another potential energy absorption source.

In the MEMA Coldwater River bridges study [16], linear dynamic response was performed for most of the analysis runs. An example of the response motion time histories at the level of a typical intermediate bent pile cap is shown in Figure 16. Peak internal force (axial force, shear, and bending moment) responses in the piles were obtained and compared with design values and pile test data.

In the critical case, a nonlinear static pushover analysis was performed to estimate the capacity of the pile system. In the FE model, both geometric and material nonlinear options for the software were used. In the latter option, a fiber representation of the cross-section was used that accounted for 1D nonlinear normal stress-normal strain behavior in the concrete and the steel reinforcement, enabling computation of the force-displacement behavior shown in Figure 17. A nonlinear time history was also run for this critical case.

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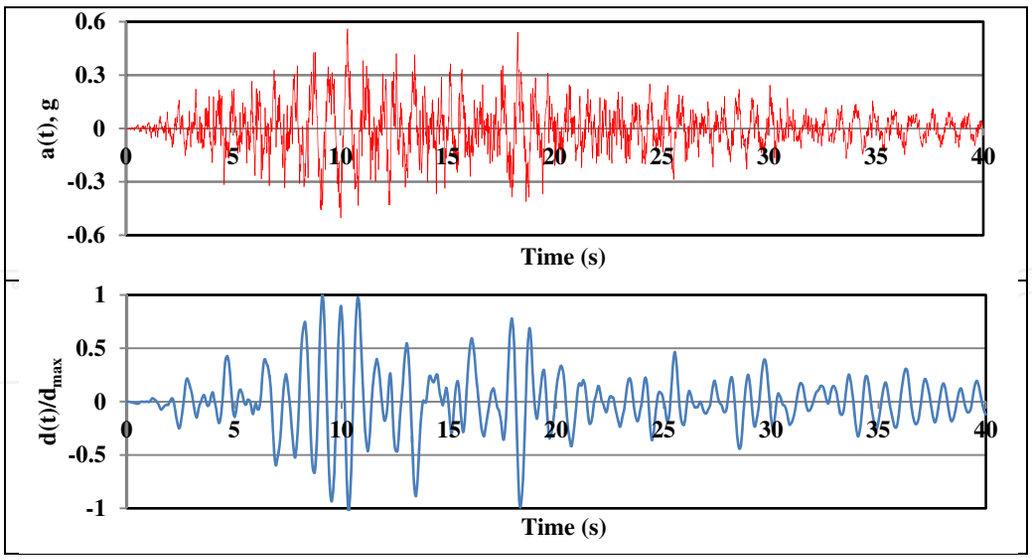


Figure 16. Normalized time history plots of response at center of intermediate bent pile cap for one of the Coldwater River bridges studied [16] (see Figs. 5 and 10) subject to an extreme event (see Fig. 6 scaled to PGA=0.25g); top plot shows acceleration; bottom plot shows displacement)

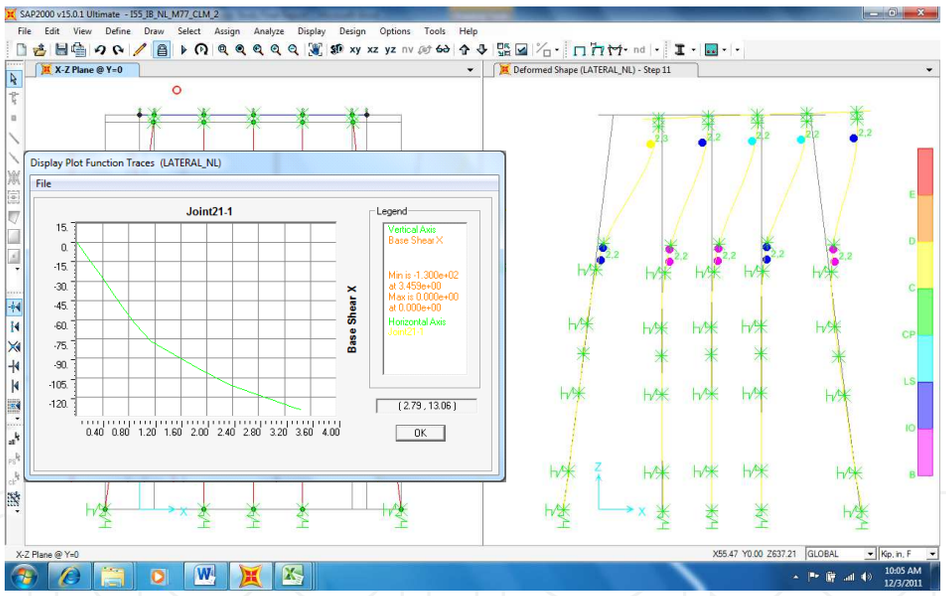


Figure 17. Plots of pushover response to lateral load at bearing positions of intermediate bent pile cap for one of the Coldwater River bridges studied [16] (see Figs. 5 and 10); left plot shows force-displacement response; right plot shows deformed shape and limit state condition for plastic hinge locations

In assessing the results of the time history analysis, a simplified analysis was performed using a single DOF equivalent model using a lumped stiffness based on a unit force lateral load analysis. When compared to the linear dynamic analysis of the full bent, this simplified analysis was able to demonstrate that the first mode of the system dominated the overall response and could have been used as a predictive tool.

A decision was made not to depend on nonlinear dynamic response analysis for all the bridges. This was in part due to the lack of confidence in the soil properties at the site from which reasonable assumptions could be made for simulation of nonlinear soil response and in part due to the scope of the work which was limited as has been mentioned previously. A limited attempt was made to verify at least the elastic properties of the soil adjacent to the sites using seismic refraction tests performed near the embankments which were accessible on dry land.

7. Conclusions

This chapter highlights objectives, modeling options, and analysis results for a range of FE based vulnerability assessments of highway bridges performed at the University of Mississippi by the author. To illustrate the range of conditions and considerations, three projects have been selected as case studies. Finite element software, and the operating systems and hardware, especially microprocessors which support the software, have advanced significantly over the time period since the first of these projects was conducted. The lessons learned, however, remain fundamental in a sense for vulnerability assessments that are premised on mechanics of highway bridge materials, elements, and structural systems that inevitably include soil and construction materials such as concrete and steel.

The objectives of the vulnerability analysis depend in part on the nature of the hazard, the inventory exposed to the hazard, and the agency concerned with the inventory. For the study cases the hazard for the region is characterized by a high consequence but low probability event. The inventory is not near enough to the hazard to be considered in a high seismic exposure but the potential ground shaking is significant enough to inflict severe damage especially to older bridges that pre-date seismic design provisions. Furthermore, and perhaps of most interest to the state emergency management and transportation officials that have sponsored the studies, the bridges selected for detailed evaluation are located on important lifelines between a major metropolitan area and the multiple surrounding communities that are growing rapidly. Many of these communities would become isolated in the event of the complete functional loss of the highway network. Both urban and rural stakeholders will depend on these bridges remaining serviceable not only for the densely populated area closer to the hazard needing to exit the concentrated region of potential seismic damage but also for incoming emergency responders and other personnel providing assistance. The understanding of both the hazard and the inventory in the study region is evolving even at the present time, and a research study is now underway. The study is exploring the short and long term impacts of potential damages on traffic flow in north Mississippi as well as the resulting economic losses.

The development of seismic ground motion records for the study cases is addressed only to the extent necessary to characterize the hazard and help interpret the results obtained from the FE simulation. In most situations the input motion is a major uncertainty in both the model analysis and the vulnerability assessment. A performance based approach has been adopted where consistent with the study objectives. A range of hazard and ground motion intensities

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has been considered in these studies and FE based time history response analysis has formed the basis of the performance evaluation. In one case, the objective was to validate results of a regional study that did not consider many of the key details of the structural system using FE based analysis. In this case, the hazard and ground motion intensity were selected to be consistent with that used in the regional study.

Examples of 2D and 3D structural models are presented that incorporate a wide variety of finite element and material types and consider the effects of soil-foundation-structure interaction which, in the view of the author, is an essential part of reliably establishing the performance of bridge structural systems. The incorporation of such interaction presents challenges to the analyst which are not well represented in standard textbooks on highway bridge design and even some of the FE literature. To complement such reference works, a portion of the chapter is devoted to discussion of preliminary analyses that are quite naturally performed while the more complex models for final evaluation are constructed. The discussion highlights the importance of first capturing behavioral aspects of the system revealed by static response analysis under gravity or idealized lateral loads and subsequent examination of vibration mode shapes and natural frequencies obtained by eigenvalue analysis. These preliminary analyses provide not only quality assurance but also insight that may guide expectations for the results of the more complex models. The information obtained from subsequent static, nonlinear, and dynamic response analysis is then maximized so that the most useful or telling information is extracted from the analysis under seismic excitation.

The FE based approach to vulnerability assessment ensures that quantitative data formulated on basic mechanics principles is generated for consideration during the assessment. Extracting the data and using it to establish measures of performance remains somewhat of an art. In the study cases, a range of measures has been adopted including peak dynamic response acceleration and displacement as well as maximum internal forces in critical members and damage distribution in major subsystems. It is hoped that an appreciation of the complexity of highway bridge systems has been provided through the description of the many details of the FE models and the results obtained from analysis of response to seismic excitation.

Application of the results of FE analysis to a specific vulnerability assessment requires consideration of the objectives and end-user needs. A range of complexity in successive models used in the evaluation may be appropriate depending on the sensitivity of the evaluation on the outcomes of the analysis. Furthermore, the availability of powerful analysis tools should not overshadow lack of confidence in data provided to the analysis. In particular, soil property and earthquake intensity and motion characteristics are often not known precisely.

In regions of moderate seismic hazard it may prove difficult to establish a sense of urgency for action on the basis of the results of a vulnerability analysis whether or not is based on FE modeling and considered highly accurate. In such a context it may be useful to incorporate the seismic vulnerability assessment in a broader one considering multiple hazards exhibiting comparable levels of risk.

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