Predicting Erosion Impact on Highway and Railway Bridge Substructures

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ABSTRACT

Detailed finite element analysis is performed to characterize the dynamic characteristics of two bridges identified in the study area. The two bridges lie in different geologic formations such that one was designed with a deep foundation system and the other with a shallow one. Fixed base models highlight the significant difference in fundamental frequencies for the two structural systems even when the different foundations are not considered. Soil-structure interaction models are developed to incorporate the soil and foundation elements and account for scour conditions. The deep foundation or flexible system is used to characterize the effect of soil-structure interaction and the influence of scour, first on the dynamic characteristics and then on the response to a simulated earthquake event. Changes in dynamic characteristics are evaluated for a symmetric scour scenario in which the stream bed depends to a depth justified by current conditions observed in the field projected to a depth likely in the operational life of the bridge. Vibration modes involving horizontal movement of the deck mass exhibit a noticable reduction in frequency which would make them more excitable under significant excitations. An earthquake scenario of the type used in emergency management plans for the study region is used to assess the effect of scour on vulnerability to ground motion. An asymmetric scour scenario is used in which the footings of one of the two piers closest to the stream is left completely exposed. Simulated time history response is computed for the flexible system with and without scour. Acceleration response time histories are presented that show a significant increase in the transverse acceleration which tends to increase the instability of the system. The supporting erosion/scour studies identified substantional erosion resulting from the negative consequences of channelization, easily erodable geologic materials, and inadequate erosion mitigation measures. Past practices have ignored the "under-bridge" stream which is the primary agent of erosion. Stream geometry should be recorded on design plans and monitored as part of standard bridge inspection practices.

ACKNOWLEDGMENTS

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Bridge design drawings, soils data, and inspection reports were provided by the Bridge Division of the Mississippi Department of Transportation.

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The Mississippi Department of Transportation has provided information from their files as well as background information on bridges and bridge maintenance in Mississippi. The U.S. Geological Survey also provided background information regarding scour beneath bridges in Mississippi. We acknowledge their time and assistance.

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INTRODUCTION

Nearly 204 million daily crossings occur on 58,495 U.S. structurally deficient bridges in need of repair. So says the Association of Road and Transportation Builders Association based on data in the January 2016 release of the National Bridge Inventory (NBI) (*1*). Of the 17,057 bridges in the database located in the state of Mississippi, 2184 bridges are defined as "structurally deficient". This places Mississippi as 8th nationally for total number with that designation and 12th nationally as a percentage of the state's inventory.

The large inventory of both highway and railroad bridges service corridors of importance to the economic competitiveness of the state linking neighboring major cities of Memphis, TN, with Birmingham, AL, and New Orleans, LA. Figure 1 shows the major highway routes and bridge locations in the northern part of the state. Figure 2 illustrates the railroad network within northern Mississippi.

A subset of these bridges spans surface water. These bridges have a unique set of stability concerns relating to the surface environment on which the bridge is founded. Understanding this surface water system (fluvial system) allows the engineer to not only understand on-going processes likely to impact the structure, but to also better plan and site bridges where future problems (and maintenance expenses) can be minimized. This investigation focused, in part, on the erosive capabilities of fluvial streams in North Mississippi and the potential controls that the geological units present at the surface would have on erosion rates. Both scour (erosion concentrated in a specific area) as well as overall fluvial erosion is considered.

The use of finite element modeling methodologies has the advantage of embracing both the natural conditions surrounding the bridge plus the bridge characteristics (condition, siting, construction materials, age). Combining both sets of factors into a digital model allows interaction of all the component factors into a single evaluation of the structure. Allowing soil and structure interaction allows evaluations that are not possible by evaluating individual component factors only. Characterizing the erosional vulnerability can be included by modeling future erosion and the erosion's consequences to the bridge structure. Modeling is also particularly useful to evaluate bridge performance during events such as earthquakes.

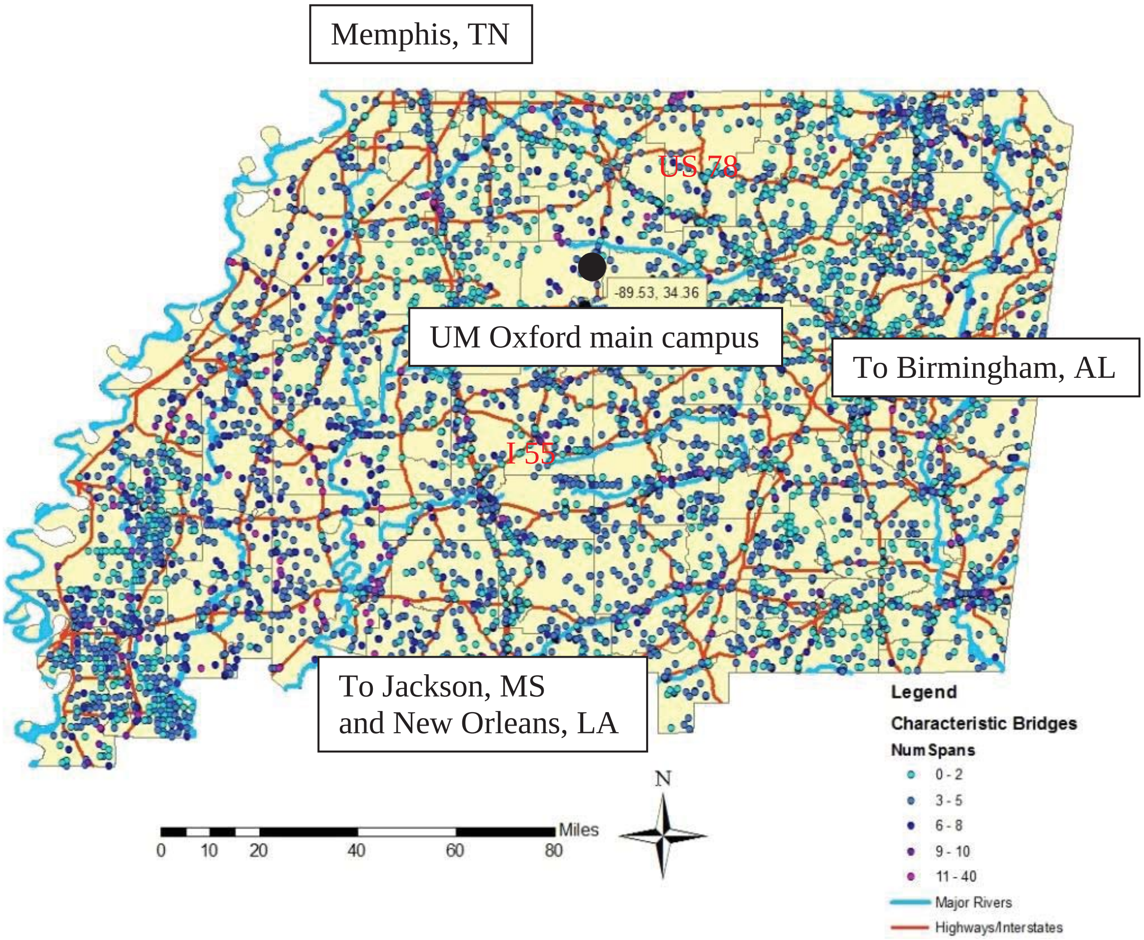


Figure 1. Locations of highway bridges in north Mississippi

* Note: County bridges are shown but the routes on which they are located are not

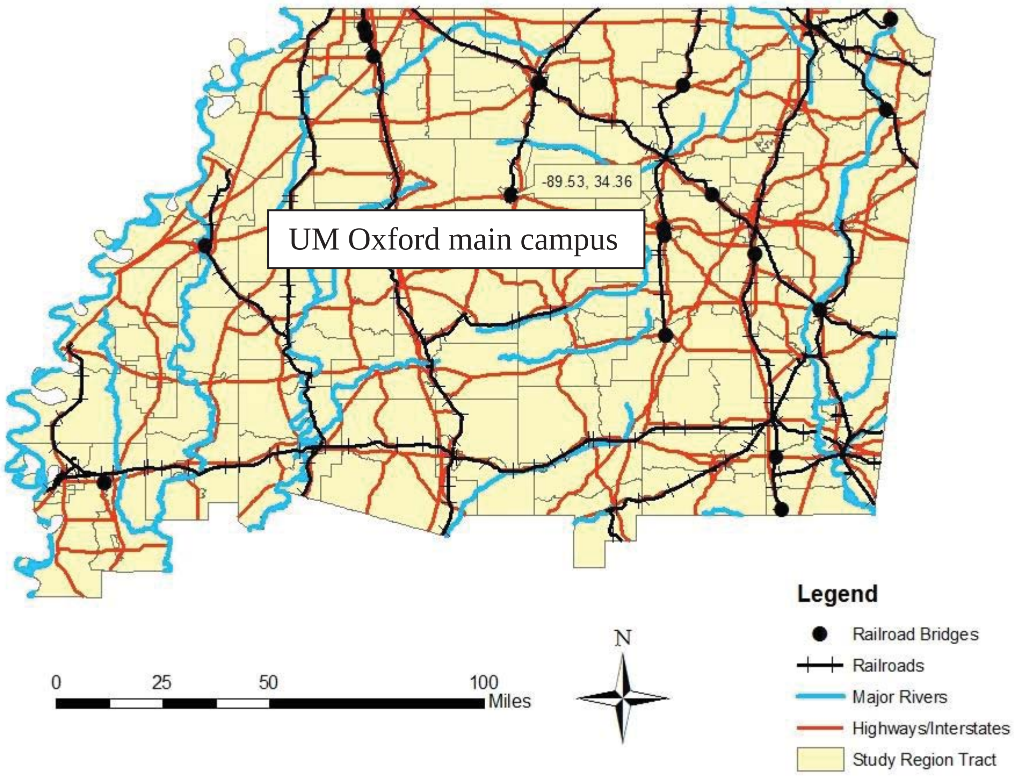


Figure 2. Locations of railroad bridges on private lines in north Mississippi

Located along these corridors are major manufacturing facilities that include two major automobile plants. It is thus of vital importance that the bridges servicing these corridors remain functional to ensure that the many communities and facilities that depend on them are not severely impacted.

The two bridges shown in Figures 3 and 4 have been selected as case studies for purposes of this study. The bridges were readily accessible to the project team and characterize a range of structure, foundation, and deterioration conditions that exist in the operational bridge inventory of the state. Both bridges are located on US 178 near one of the automobile plants located in the northeastern part of the state as shown in Figure 5. The route is part of the federal highway system, so the bridges are subject to federal inspection and reporting requirements which the state department of transportation oversees.

It was intended to also study a railroad bridge located on this corridor shown in Figure 6. The engineer from the railroad company declined to participate in this project, however.

Figure 3. US 178 bridge with deep foundation- embankment eroded by scour (B-002)

Figure 4. US 178 bridge with shallow foundation- footing exposed by scour (B-005)

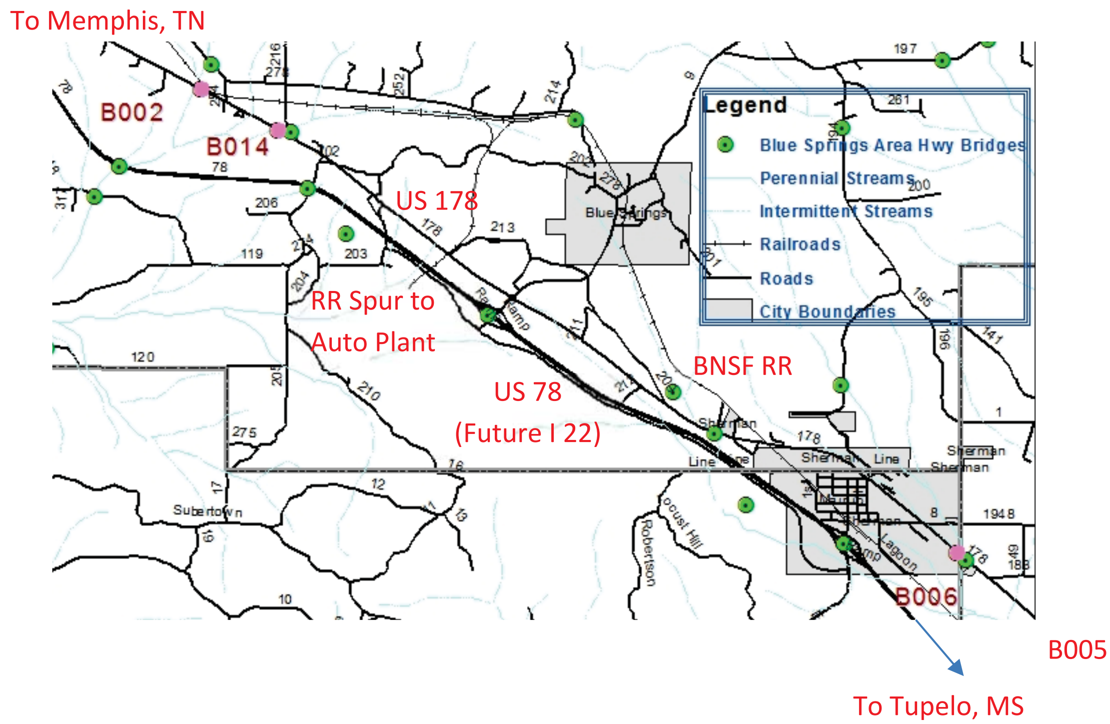


Figure 5. Highway bridges along major corridor in northeast MS

* Note: Bridge numbers (B-0XX) were assigned as part of a field condition survey

The substructure elements are difficult to access in visual inspections due to field conditions. Further, the internal nature of some damage such as material deterioration makes visual inspection misleading or inconclusive. In the case of scour around submerged pier footings, visual inspection requires special mobilization including divers and underwater equipment (*2*).

Detailed finite element (FE) models are constructed here for the complete full scale bridge systems representing the two case studies. Characteristic mode shapes and frequencies are identified by eigenvalue analysis of the FE system matrices. Such mode shapes provide a preliminary view of what is identifiable through modal extraction of field vibration measurement data. Damage here is limited to scour at the pier footing level. Damage conditions associated with a variety of material deterioration scenarios and their effects on the bridge system are studied in more detail in a companion 2013 NCITEC project (*3*).

Figure 6. Railway bridge on deep foundation with piles exposed by scour.

OBJECTIVE

The primary objectives of this project are 1) evaluate the scour present at these selected bridges and compare the scour conditions with the geological unit in which it is sited, 2) evaluate the selected bridge in regards to natural hazards such as earthquakes using digital modeling techniques. The overarching goal is to produce information that will be useful to the engineering community to improve bridge design with regard to natural hazards.

Detailed FE models are developed for the two case studies. Included are the full-scale superstructure (concrete deck and steel girders), substructure (concrete piers and abutments), foundations (concrete footing and wood piles), and supporting soil layers (sand/silt/clay or chalk). The presumption here is that, while the computational effort is significantly increase, it is the experience of the investigators that including all of the listed elements is essential to the successful prediction of modal characteristics and dynamic response of bridge structural systems in a variety of geologic settings.

Eigenvalue analysis is performed to obtain mode shapes and frequencies of the soil-structure interaction (SSI) models. An idealized reference model is first developed using information in design drawings and soils reports from the time of construction. The reference model is then modified to account for a severe scour scenario involving significant loss of soil around foundation elements in a part of the stream where high velocity flow has likely occurred.

Comparison of the modal characteristics of the scour and reference models provides an initial estimate of changes in dynamic response that might indicate loss of structural integrity or stability. An earthquake response scenario is then defined and response simulation performed to gain insight into the difference in dynamic response between the model with severe scour and the reference model.

SCOPE

The geographic study area consists of the New Albany East, Miss., Ellistown, Miss., Northeast Pontotoc, Miss., and Sherman, Miss., 7.5 minute topographic quadrangles. These four quadrangles total approximately xx square miles encompassing portions of Lee, Pontotoc, and Union Counties, of northern Mississippi (Figure 5). Only highway bridges within this area were included (inclusive of county / city, State and Federal bridges). The study was also limited to bridges that crossed a surface water body. The original intent was to include trestles on the Burlington Northern and Santa Fe Railroad (BNSF) line that is within the study area, BNSF, however, chose not to cooperate with the study and their trestles were not included. Since the digital modeling effort is a time-intensive process, only three representative highway bridges were included. All of these bridges are on highway 178 which parallels the present day U.S. 78 and the future I-22 interstate corridor.

The detailed FE modeling of full system behavior is performed for two case studies of three span highway bridges located in the study region. While no longer located on the primary highway route, the two case studies exemplify aging superstructures commonplace in the MS and US inventory. By virtue of their respective locations, they also permit the study of the effect on bridge system dynamic characteristics of two very different geologic formations, one relatively flexible and the other relatively stiff. Both bridges used as case studies are accessible to the investigators enabling field surveys of current site conditions.

The project team was also able to obtain design drawings, soil reports, and a limited set of inspection reports for these bridges from Bridge Division personnel at the Mississippi Department of Transportation (MDOT) located in Jackson, MS. The data enabled development of detailed reference models consistent with both design and construction practice as well as field observations.

The project team had hoped to use as a third case study an adjacent railroad bridge that shared the same geologic formation conditions as one of the highway bridges selected here. The railroad bridge exhibits severe scour that has exposed the piles of one of the piers. Unfortunately, attempts to gain the cooperation of the railroad owner’s structural engineers in were unsuccessful, and the project team was denied permission to access the site or any engineering data that might assist in detailed FE modeling.

One of the geologic formations consists of a relatively flexible layer of soil that caused the bridge designer to select a deep foundation system consisting of concrete footings/pile caps supported on wood piling. The other formation consists of a thick chalk layer that caused the bridge designer to select a shallow foundation system consisting of spread footings resting directly on the chalk layer. The bridge with the deep foundation system has experienced significant scour on one side due to channelization of the waterway beneath the bridge. The piled footings will likely become exposed during the service life of the bridge. The bridge with the shallow foundation has similarly experienced scour on one side that has already exposed the spread footings.

Detailed FE fixed base and SSI reference models are developed for the two bridge cases. Self-weight static analysis followed by eigenvalue extraction is performed to compare modal characteristics of the two bridge cases. Two soil profiles are considered for the SSI model of the flexible case to represent as constructed and severely scoured conditions. Mode shapes and frequencies are compared for the two profiles to observe the effect of the scour. Time history analysis of the flexible case models is performed to observe the effect of the scour on the dynamic response to the scenario earthquake event.

METHODOLOGY

Geologic Investigation

Field Evaluations

The field evaluations were designed to identify and locate bridges in the field area and to estimate the overall condition of bridges. The national bridge inventory was initially used as a guide to location, but later county maps proved a better source of information and were used extensively. The procedure upon visiting a bridge consisted of assigning a project number to the bridge, determining and recording accurate latitude, photograph the approaches to the bridge, photograph any significant characteristics of the bridge that may be indicative of vulnerability and then photograph the stream beneath. The "below deck" The bridge was then evaluated as to overall condition of the bridge. Features such as cracks in concrete were noted as well as any obvious damage to the deck. Spalling and effervescence of concrete were noted. If the features were thought to be significant they were photographed.

Next the "below deck" area was examined to determine if there was apparent erosion features present not only within the stream but also in the fill beside and beneath the bridge. Any significant features were photographed. The examination determined if piers were within the stream bed, partially within the stream, or outside of the stream bed. The presence or absence of rip-rap was noted and its location (in the stream bed or on the fill only). The condition of the rip-rap was noted *i.e*. if it was in place within the stream or if it had been moved down the stream due to water flow or if it had been concreted in place or was loose. Any apparent stream erosion features were also noted. The undercutting of rip-rap or other bridge structures, such as footings was also noted. The presence or absence of debris dams was also determined. The nature of the underlying geological subsurface materials were noted when it could be observed. Virtually all of the streams beneath the bridges were channelized.

Erosion Studies

The value of the field studies was to identify streams with significant erosion beneath the bridge, consult the "as built" plans to compare the ground level and stream elevations with the present conditions. A measure of the historical erosion rates could then be made based on actual measured data rather than predicted erosion rates. These rates were then to be compared to the study area's geological map to determine if the average erosion rates could be reliably correlated with the geological on which the bridge was founded. Soon after the field evaluations were completed, it was noted that the plans contained a ground surface beneath the bridge, but appeared not to contain information regarding the stream location relative to the bridge piers, width, or depth. This issue was discussed with the Mississippi Department of Transportation and it was confirmed that bridge plans seldom contain any information on the stream the bridge was designed to cross. The older bridge plans are almost always devoid of such information.

Lacking these data on the original stream characteristics, only broad observations could be made to correlate erosion rates with the geological units. The most severe erosion, for example, appears to correlate with a particular geological unit and the least erosion with another.

Although the erosion rates could not be determined as originally proposed, the study was not without value. When problems were noted in the field investigations, additional time was spent to determine why the problems existed. As described later, problems were identified and solutions are offered.

Finite Element Modeling

Reference Cases

The case studies selected for detailed FE modeling shown in Figures 3 and 4 each consist of three-span bridges having two reinforced concrete (RC) end abutments and two RC intermediate piers. Each bridge carries traffic across a stream whose alignment with respect to the highway and flow patterns have caused severe scour. Loss of soil is concentrated at the embankments and pier footings on the side where increased water velocity has been induced by the stream flow pattern.

The first case (Fig. 3) consists of two 30 ft. side spans and a 40 ft. center span. The superstructure is comprised of a RC deck slab poured compositely with four steel W-shape girders. Each girder rests on a steel bearing plate that is bolted into the top of a RC abutment or pier. There are no cross-bracing elements between girders.

The substructure abutments and piers are each comprised of two columns and a cap beam. The columns of the abutments are tapered, fully embedded in embankment soil, and supported on RC footings poured over a square pattern of four tapered wood piles. The columns of the piers are straight, partially embedded in soil, and supported by a similar piled footing configuration.

The soil consists of well-graded fill material placed above the natural deposits which consist of mainly stiff sand and silty sand layers.

The ABAQUS CAE modeling and analysis environment (*4*) has been selected for the study. The CAE software provides a powerful graphical user interface (GUI) that enables generation of virtually any geometry as well as automated mesh, load, boundary condition, and constraint generation. The GUI within CAE also enables interactive activation of the FE formulation and solution algorithms available in ABAQUS (*5*) as well as data checking, monitoring and post-processing of all results generated by the solution.

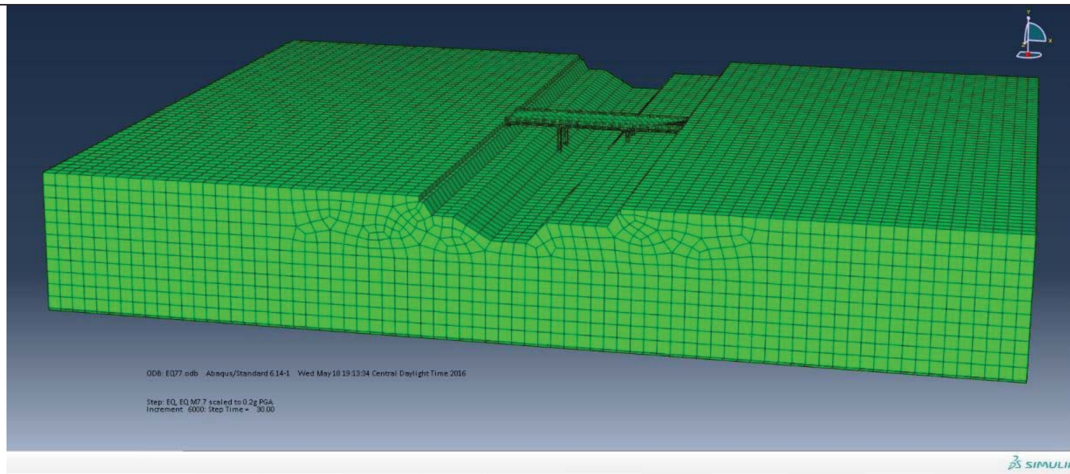
Three-dimensional (3D), 8-noded, continuum (solid, homogeneous), reduced-integration elements (C3D8R) have been selected to perform all modeling of components of the superstruction, substructure, and soil systems. These elements require only the nodal coordinate, the Youngs modulus of elasticity, and the mass density to fully construct the element mass and stiffness matrices.

Figure 7 shows the fully meshed model geometry at subsystem and system levels for the first case study (Fig. 3). SSI has been enabled through an Embedded Region Interaction in which the soil elements serve as the Host region. Piles are likewise embedded in the host footing regions. Reinforcing steel could in principle be embedded in the host concrete regions, but the contribution of the steel has been neglected in this study which is more concerned with relative effects on system dynamic characteristics induced by damage. In an FE model comparison with actual field investigation, the steel may neet to be included to obtain reliable results.

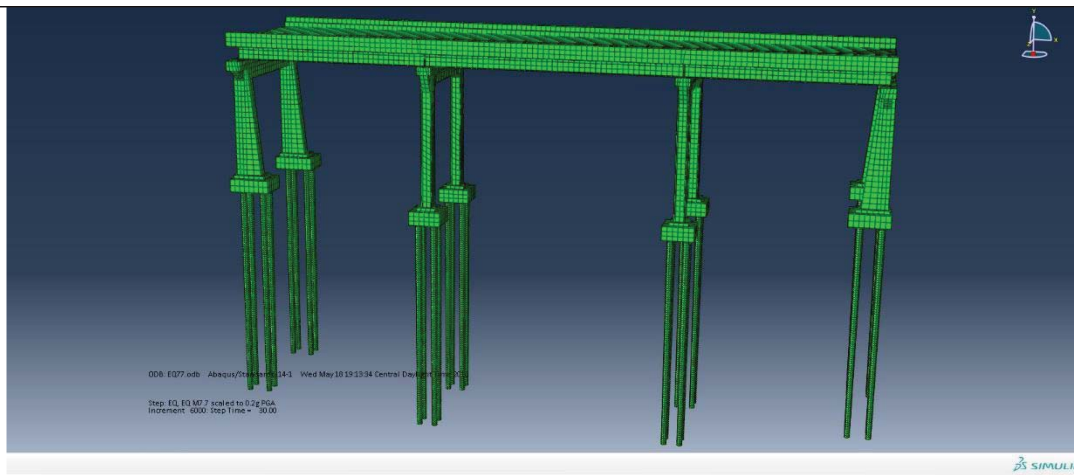
All locations of contact have been treated as a Tie Constraint between the surfaces in contact. Such a constraint assumes full transfer of load. Slip is not allowed in this approach. Instances of contact surfaces arise in the bridge models at, for example, the interface between concrete deck slab and top flange of steel girders, the bottom flange of steel girders and top of bearing plate, and top of bearing plate and top of concrete abutment/pier cap beam.

Figure 8 shows a partial side view of the model geometry or Part definition used in developing the mesh (Fig. 7). The soil is seen to have been subdivided into two layers for purposes of analysis. The top layer consists of embankment fill and roadway subgrade material added or disturbed during construction of the bridge foundation elements. The bottom layer is the naturally deposited geologic material that existed prior to bridge construction.

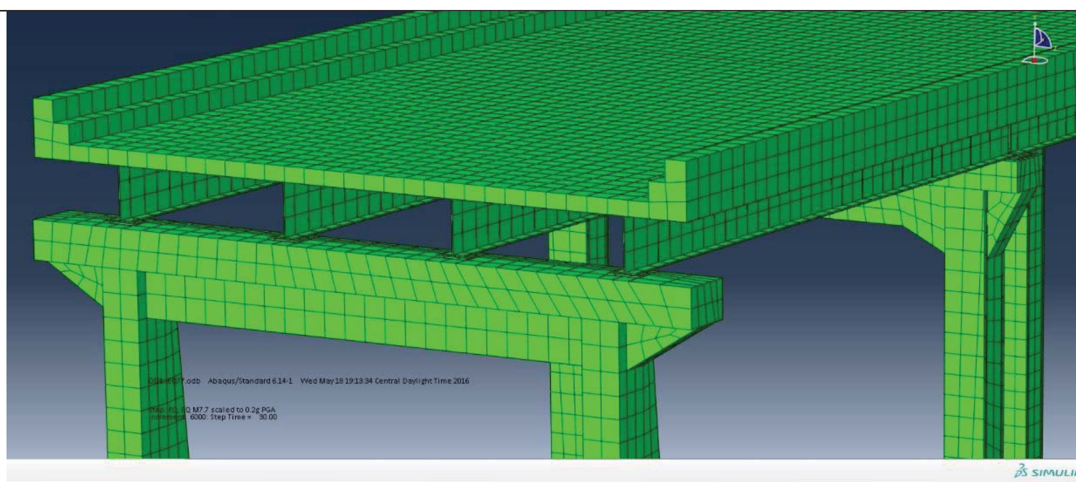
Boundary conditions have been applied to all side and bottom surfaces of the soil Parts preventing translation across the surface. The soil has been extended a span length in each horizontal direction to minimize the influence of the BC on the soil stiffness and frequency.



Soil-Foundation-Structure System

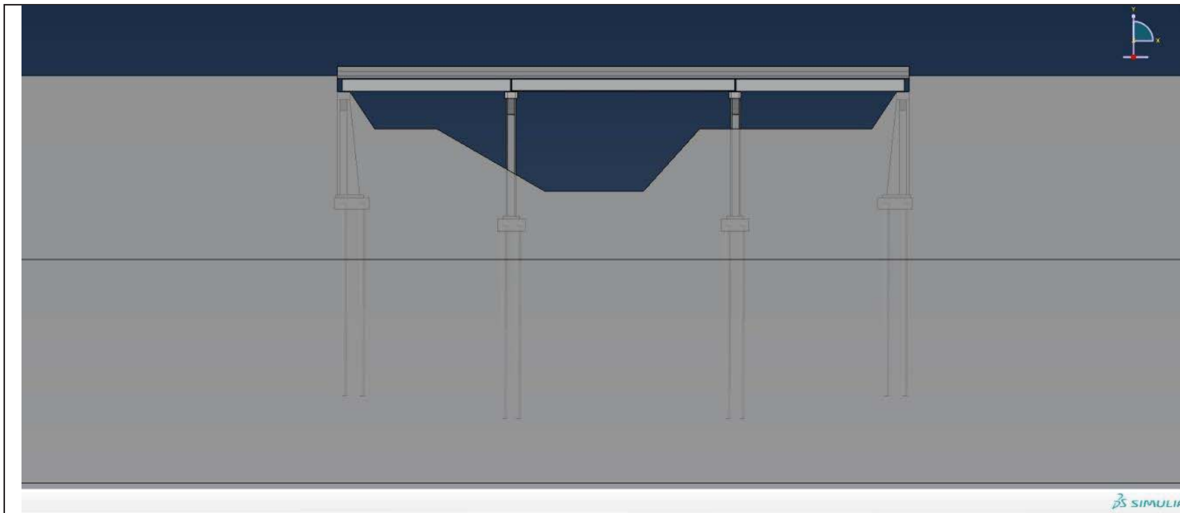


Structural System

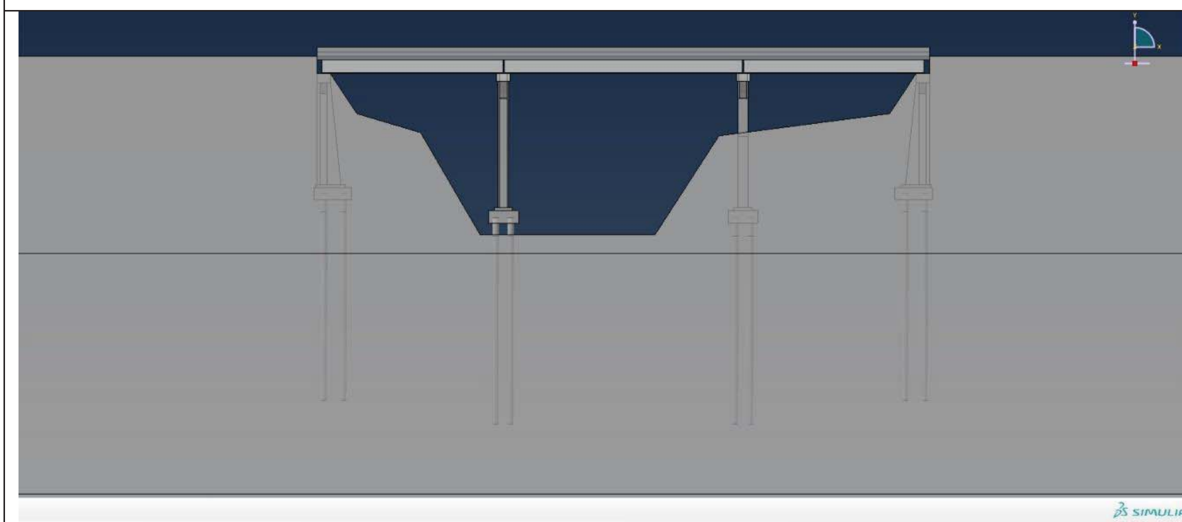


Superstructure

Figure 7. Flexible System Reference Model Mesh



Reference Model



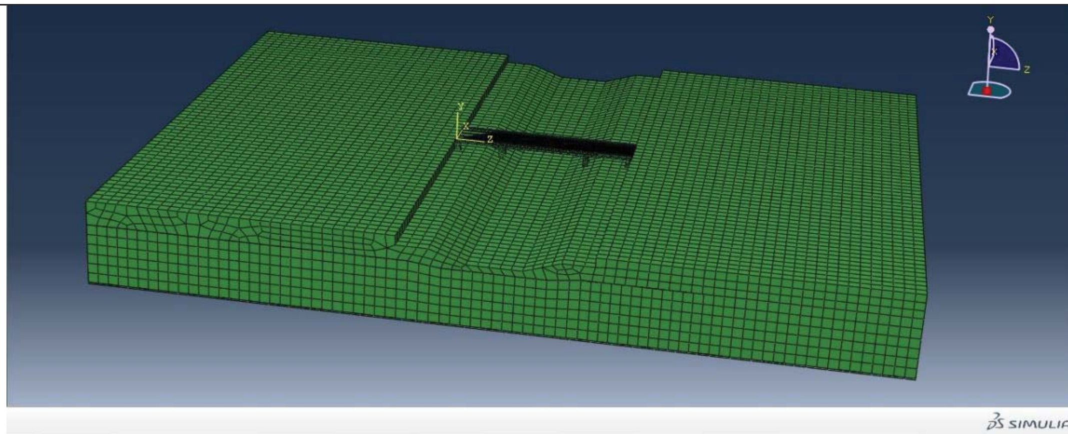
Asymmetric Scour Scenario Model

Figure 8. Flexible System Part Definition

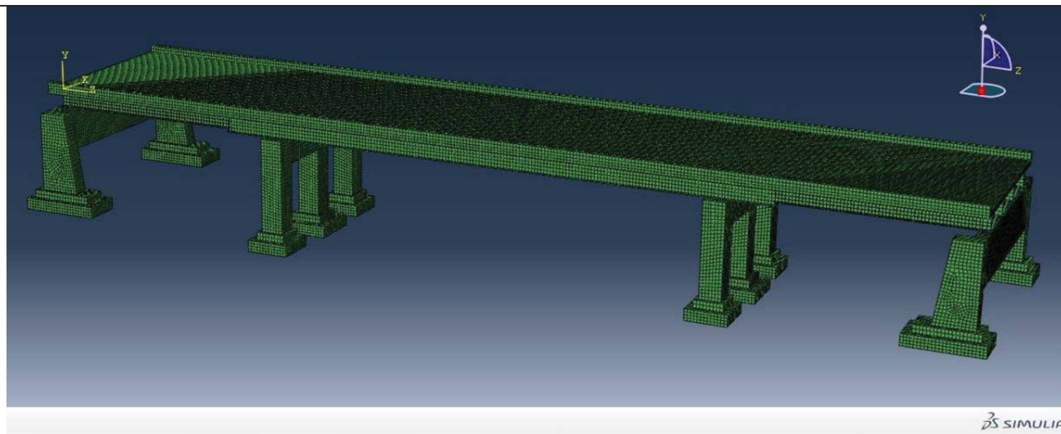
The second case (Fig. 4) consists of two 30 ft. spans and a 60 ft. center span. The superstructure is similar to the first case except that steel hot-rolled, L-shaped elements used to provide cross-bracing between girder webs. The substructure abutments are each comprised of two columns and a cap beam, whereas the piers are each comprised of three columns and a cap beam. The columns of the abutments are tapered, fully embedded in embankment soil supported on RC footings and are assumed here to sit on a thick chalk layer underlays the entire bridge foundation system. The columns of the piers are straight, partially embedded in soil, with RC footings supported on the chalk layer.

Figure 9 shows the fully meshed model geometry at subsystem and system levels. A graduate research assistant, Amir Irhayyim, documented his initial modeling of this case as the base of a masters project (*8*). In his project report, he provides a step-by-step description of the key features of the CAE software used to develop the component Parts and global system Assembly.

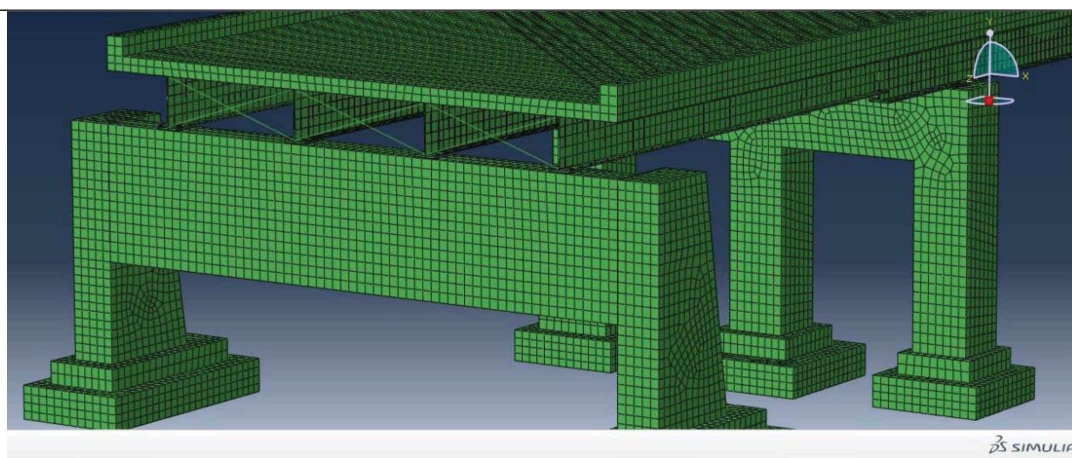
Solid elements have again been used throughout with the exception of the cross-bracing elements, where 3D beam (wire, BEAM) structural elements were considered sufficiently accurate for representing the dynamic characteristics. The point-wise cross-brace ends were connected to the girder web surfaces using a CONNECTOR interaction.



Soil-Foundation-Structure System



Structural System



Superstructure

Figure 9. Stiff System Reference Model Mesh

Table 1 summarizes the material property data used in the concrete, steel, soil, and chalk regions of the models. These represent the project team's best interpretation of the information in data provided on drawings, soil reports, and in the literature.

Table 1. Material Properties

Material	Youngs Modulus ksi	Poisson's Ratio	Weight Density lbf/ft^3
Concrete	3600	.20	150
Steel	29000	.30	487
Wood (Pile)	1500	.15	40
Soil-Case 1, Top	1450	.3	115
Soil-Case 1, Bot	24656	.25	125
Soil-Case 2, Top	30	.30	125
Chalk-Case 2, Bot	300	.30	125

Scour Scenarios

For purposes of establishing impact on modal characteristics on the flexible system, a symmetric scour scenario has been defined as shown in Figure 10 that projects the current observed scour pattern found in the center of the stream to a depth likely within the operational life of the bridge. Each of these cases would in principle impact the stiffness and mass distribution. Localized damage scenarios are investigated to observe to what degree the damage induces frequency changes that are in principle measurable and to observe the degree to which the 3D nature of the modal response causes observable changes at the deck level for at least some of the characteristic lower frequency structural modes such as deck translation, longitudinal and transverse, rotation, and torsion.

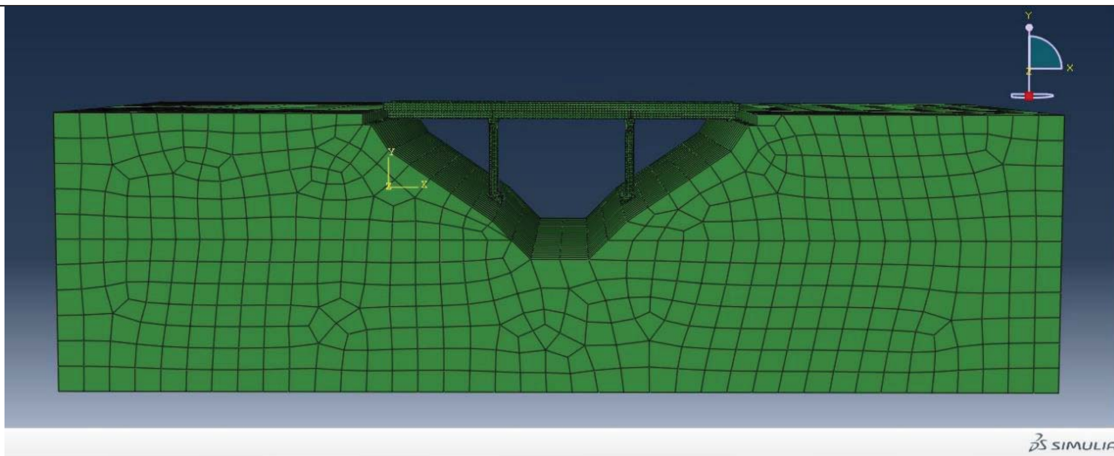


Figure 10. Flexible System Symmetric Scour Model Mesh

For the purposes of the earthquake response analysis, an asymmetric scour scenario is considered that exposes the footings beneath one of the piers. This scenario is considered to have the potential for making the structural system more vulnerable to the effects of the ground motion from the earthquake. The profile for this scenario is shown in the bottom of Figure 8.

Earthquake Scenario

An M7.7 earthquake scenario has been defined for use in state emergency management plans (*6*) which provides peak ground acceleration (PGA) contour maps for the multi-state region surrounding the New Madrid Seismic Zone. The anticipated PGA values for the two bridge cases studied here have been interpolated from these maps. Representative time history of ground acceleration for a similar catastrophic event were developed using simulation software made available by the United States Geological Survey to the co-PI in a prior study conducted for the Bridge Division of MDOT (*7*). The simulated records were generated for a different bridge location outside the study area, however. The records have been scaled to for two bridge cases studied here such that they reproduce the interpolated PGA values for the M7.7 scenario event for the resultant horizontal motion. The horizontal ground motion components resolved in terms of the bridge model coordinates are shown in Figure 11.

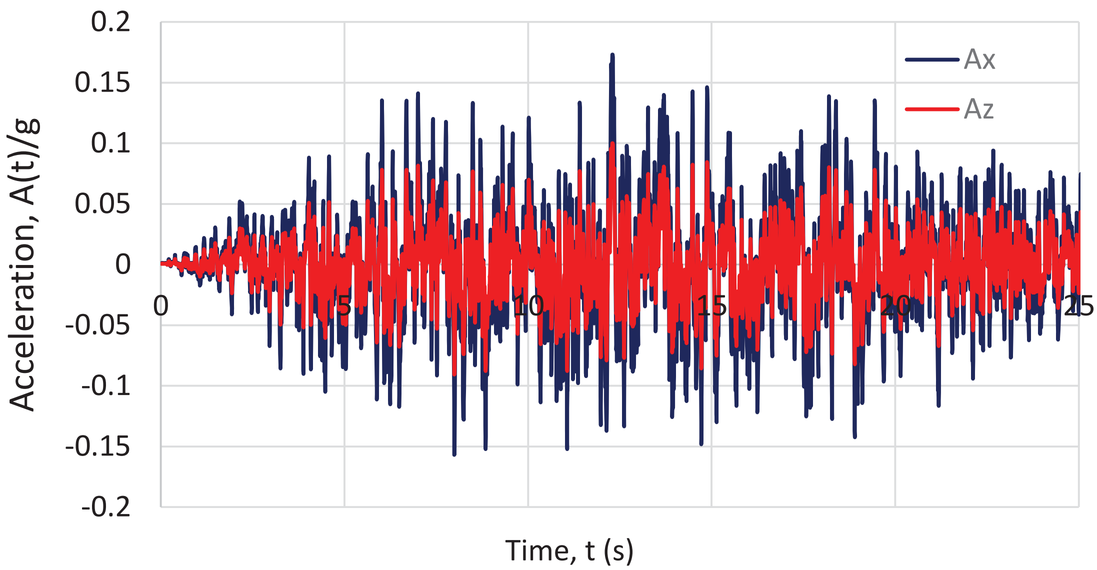


Figure 11. Input ground motion for simulated M7.7 earthquake event

DISCUSSION OF RESULTS

Geologic Investigation

Field Evaluation Results

The Mississippi Department of Transportation (MDOT) has often cited northern Mississippi bridges as an example of an area where bridge conditions were poor and in need of extensive bridge repair and / or replacement. The field investigataions sought to better understand the concerns of MDOT and to characterize the type of bridges and their condition within the field area. A total of 65 bridges were inspected within the study area. All of these data would be important to evaluate earthquake vulnerability and also supported the FE modeling effort discussed elsewhere in this report. The investigation identified a variety of bridge types (see Figure 12 and 13 below) and a variety of conditions. Date of construction varied from the 1930s to bridges along the recently completed Mississippi Highway 9. The original intent was to use the National Bridge Inventory (NBI) as a guide to bridge location. The actual field investigations demonstrated that NBI bridges were often poorly located geographically. There were also a number of bridges on the NBI that were no longer present having been replaced by box culverts. Discussions with local engineering firms verified that the trend has been to replace bridges as often as possible with box culverts. The major reason cited for replacing bridges with box culverts is that the culverts have much less maintaince required for their upkeep and it is felt that the box culverts will save funds through reduced maintaince. A combination of maps published by the Mississippi Department of Transportation and U.S. Geological Survey (USGS) maps (7.5 minute topographic quadrangles) proved the most useful for locating the bridges in the study area. The NBI, as any other database requires periodic updating and an update would be useful in the field area. A lack of accurate data is a vulnerability to the responders in the case of natural

Figure 12. Bridge B-038 located on Union County road, CR 194, approximately 1.25 miles north of Sherman, Miss. (lat. 34.37675, long. -88.84149). Bridges of this type are not uncommon, but are being systematically replaced with box culverts.

disaster, such as a major earthquake. Future studies that evaluate regional transportation issues involving bridges should accomidate the vulnerabilites associated with the NBI as it presently exists.

In order to illustrate the scope of brigde types, Figure 12 and 13 represents the end-members of bridges present in the study area.   The type of bridge in Figure 12 is not uncommon and were noted in all counties within the study area. Bridges of this type are the type of bridge that would be targeted for replacement by a box culvert. The Figure 12 bridge is of steel and wood construction. Corrosion and damage to the wood deck is obvious during inspection. This is clearly a bridge vulnerable to natural hazards. Figure 13 is an example of the bridge construction on a new segment of Mississippi Highway 9S. This new construction is concrete with adequate rip-rap beneath the bridge and in the stream channel. These new bridges pose few concerns and are considered to have low vulnerabilites to natural hazards.

Figure 13. Bridge B-019 is a recent bridge on Mississippi Highway 9S in Pontotoc County. These new bridges are the least vulnerable within the study area. This bridge is approximately 0.8 mile from Endville, Miss. (lat. 34.311967, long.-88.888418). Neither this bridge nor any of the other bridges on the new portion of Highway 9 appear on the NBD.

The review of the bridges also includded an inspection of the bridge beneath the deck. The goal was to identify any features that may relate to bridge vulnerability and to estimate the general condition of the bridge. These data are useful to the FE modeling.

Spalling of concrete exposing rebar to oxidation was not uncommon to varying degrees. The spalling is not restricted to any part of the bridge structure, but is most common in “below the deck” components. General degradation of the concrete in piers and beams was also noted in several of the older bridges. The most pronounced damage of this type was noted in bridge B-007 on Miss. Highway 178 in the western edge of Sherman, Mississippi. Figure 14 (below) is a photograph of the general degredation of the concrete on B-007. Note the extensive spalling, cracking and effervescence. Although not evident in the photograph, rebar was exposed and corrosion was evident. Also note that an I-beam frame has been added to assist in supporting the bridge deck. Pieces of concrete from the spalling was noted at the base of the pier. Damage this extensive certainly has implications in evaluating natural hazards, particularly the earthquake hazard. It is not difficult to anticipate the damage likely to occur to this bridge from a high magnitude earthquake originating from the New Madrid Fault Zone, approximately 150 miles northwest. Fortunately, damage this extensive was unusual and present in only three bridges.

Figure 14. Bridge B-007 is located on the western edge of Sherman, Mississippi (lat. 34.451122, long. -88.760082) on Highway 178. Extensive damage to this bridge has required the insertion of an I-beam frame beneath the deck to assist in supporting the bridge. This bridge is considered a vulnerable to natural hazards such as earthquakes.

Bridge footings were also examined to determine if the footing itself or the piles beneath were exposed and/or there was obvious damage to the footing. Exposed footings and pilings were noted in bridges to varying extent. The erosion associated with piers within the stream itself or other bridge-centered erosion is the cause of the exposed footings in most cases. The most marked case of exposed footings and the piles are in the railroad bridge illustrated in Figure 6. Erosion-prone geological matierials, channelization, and debris dams is the most likely factors leading to this erosion problem (erosion factors are discussed more fully in the next section).

A broad conclusion is that many of the bridges in the study area have sustained damage to varying degrees. As logic would suggest, the older bridges have acquired the most severe damage (see Figure 14). In the most severe cases the MDOT has installed I-beam frames to add additional support for the bridge. Spalling of concrete often exposes rebar to an oxidizing environment resulting in corrosion. Metal piles exposed below the footing are also subject to oxidizing condititions resulting in corrosion, both cases have been noted in the field area bridges. The damage noted in the field studies suggest that some bridges would be vulnerable to natural hazards, particularly the earthquake hazard.

Erosion Studies Results

There are a number of factors that contribute to the erosion documented beneath bridges in the study area. A majority of the factors relate to the stream beneath the bridge itself, which is the most importat agent of on-going erosion. An assumption often made is that the stream flowing beneath a bridge is rather static. Calculations are made regarding gradient, flow and drainage area and the bridge is designed acordingly. Few seem to appreciate that stream systems (fluvial systems) are dynamic rather than static and the system is constatly changing to accommodate it's immediate physical and environmental setting, as well as changes in its drainage basin. Although behavior of the fluvial system can be predicted in a broad sense, the immediate reaction of a system may be related to less obvious and difficult to measure changes in drainage systems. The point to be made, is that the stream beneath a bridge is an agent of active change that is likely to influence the well-being of the bridge above.

A second idea that is poorly apprecaited is that remote drainage basin changes can initiate stream adjustment. These changes may be remote from the bridge site and not easily recognized. A fluvial system is is ideally in balance (referred to as in grade) with deposition and erosion taking place in equal amounts. A change in the drainage basin, such as land use change, can modify stream dynamics and result in the fluvial system becoming out of grade. This change may initiate a system-wide geomorphic change to return to balance. Time is also a factor to consider. Change may be immediately obvious, or may take years to develop, so monitoring the stream channel location and depth is important.

Initially, the goal was to use existing bridge plans to estimate actual erosion rates from the year the bridge was constructed through the present. This idea was suplimented by the bridge inspection reports which also measured bridge erosion that would provide "snapshots" through time and so specific erosion episodes might be identified that could be related to specific drainage basin events, such as channelization. The hope was to produce a documented erosion rate based on historical events. This rate was then to be applied to the geological map to see if there were obvious correlations between the erosion rate and geological unit. Unfortunately, it was discovered that the plans and bridge inspections do record the top of the soil on the piers, but they do not record any information regarding the stream beneath the bridge. Neither the stream location laterally beneath the bridge nor the vertical depth of the stream nor location of the channel is noted. This situation precluded development of an erosional history for the bridge as planned.

Although the erosional history could not be constructed, the bridge survey did allow qualitative analysis to be conducted regarding erosion verses outcropping geological unit. The field area was geologically mapped on a 1:24,000 scale topographic map. The geological maps constructed on these individual sheets were used as a guide to correlate erosional features (8).

Perhaps the most widespread source of increased erosion in northern Mississippi is channelization. Schumm (1977, p.327) (9) states, "… forcing of a channel into an unnatural straight alignment almost always produces serious consequences." Among the many consequences of channelization, downward (vertical) erosion, resulting from an imposed steep stream gradient is the most obvious. The increased gradient results in greater velocities and thereby increases the stream's ability to erode its bed. Channelization has been imposed on nearly all northern Mississippi streams and rivers.

A remarkable example of channelization induced erosion is the railroad tressel (Figure 6) and the adjacent B-002 highway bridge (Figure 3). Erosion at both of these structures are a result of a combination of factors. These factors include 1) an erodeable geological foundation material, 2) misaligned channelization, 3) debris piles that enhance the erosion of the misaligned channelization, and 4) a lack of mitigation measures at the railroad tressel. The channelized stream below the railroad tressel is not aligned with the area between piers, but rather centered on a pier. This alignment results in the piers diverting stream flow and depositing debis on the upstream side. The debris pile acts to further divert stream flow into the adjacent pier causing erosion at a second peir and the fill material below the tressel. There appears to be little, if any, effort to mitigate the erosion.

A somewhat better situation exists at the B-002 bridge, although the substrate is the same as the railroad tressel. Here the stream flows between the piers, but downward erosion has been significant. The MDOT has taken measures to mitigate the erosion by placing rip rap beneath the bridge and then at some point concreting the rip rap so, presumably, the rock fragments will not be as easily moved downstream. As can be seen in Figure 3, the downward and laterial erosion on the east side of the stream has undercut the concreted rip rap blanket resulting in it breaking apart and fragments moved down stream. It was also noted during the field examination that individual pieces of rip rap (not part of the blanket) were being moved down stream, suggesting the rip rap was too small to accomodate stream flow, particularly during storm events. Bridge B-007 (Figure 15) is another example of induced scour. The piers on this bridge are within the stream and have collected a pile of debris on the upstream side. The debris is redirecting the stream flow toward the bank resulting in lateral erosion, and scour around the footings. Note also there is no erosion mitigation (such as rip rap) beneath the bridge. The slightly darker colored areas of water around the piers indicate areas of scour. High water levels during flood events probably enhance the erosion rates.

Figure 15. View beneath bridge B-007 (lat. 34.451122, long. -88.760082) showing a debris pile that is redirecting stream flow against the west bank causing additional lateral erosion not directly associated with the stream channel. The lateral erosion (and perhaps the in stream scour) here may be accelerated by flood conditions. Note there is no erosion mitigation such as rip rap.

Erosion associated with the stream channel is the most active source of scour and of primary concern. During the investigations it was discovered that the stream beneath the bridge is typically discounted in both the bridge plans and susequent bridge inspections. Neither set of data contains the location of the stream relative to bridge components, width of stream, depth of the channel or record of channel instability. These data set are essential to evaluate the erosion concerns over the lifetime of the structure. With consistent monitoring, erosion trends should become evident and mitigation measures can be designed prior to them causing problems requiring immediate attention. Figure 16 is an example of a bridge B-002 where the soil levels are measured at the piers, but the stream itself is ignored. Presently, the

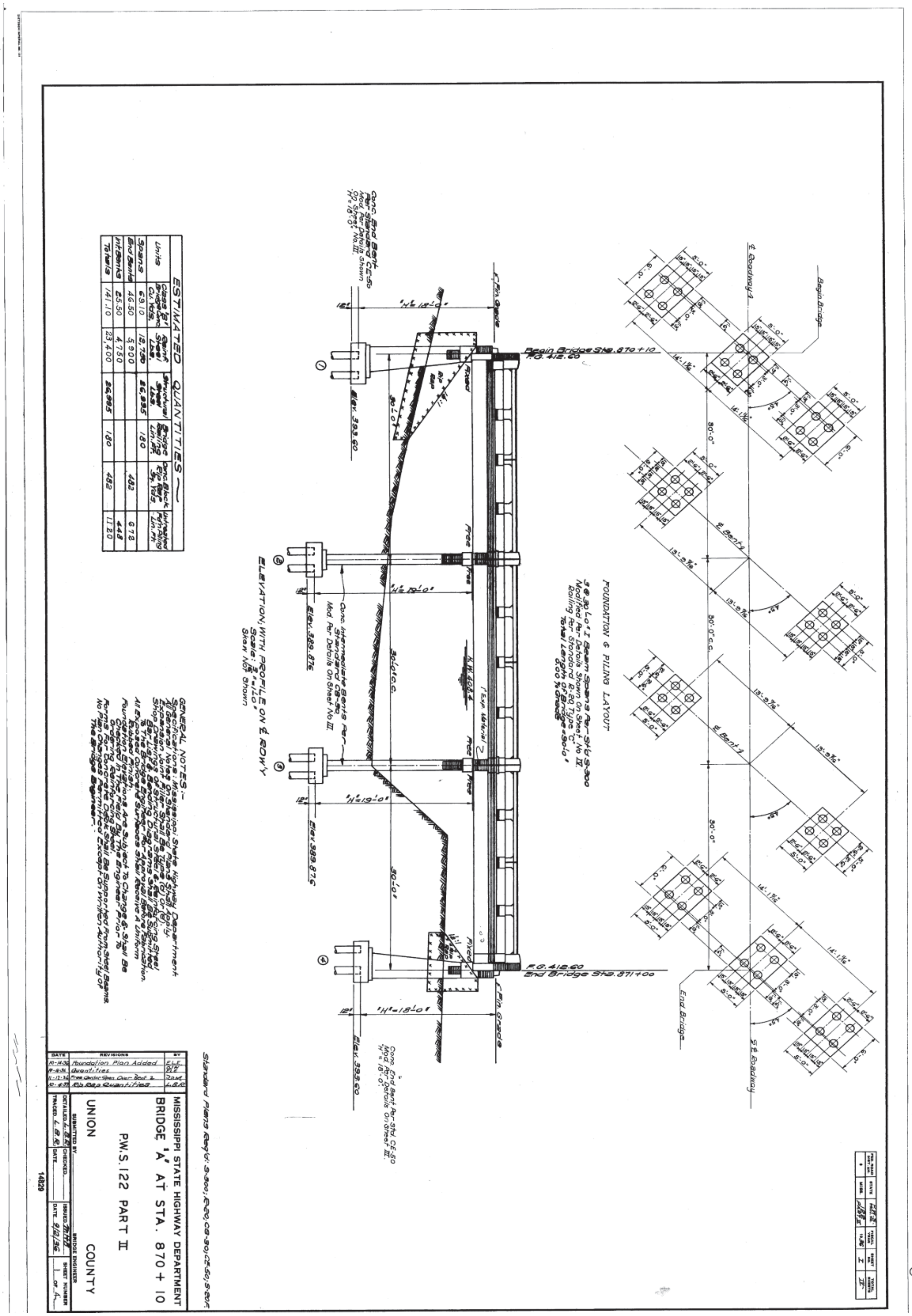


Figure 16. Cross section of bridge B-002 as it was in designed in 1936. Note that the location of the stream or stream characteristics below the structure is not indicated.

stream is located between the piers and approximatelly midway the structure. Erosion has removed the foundation materials to a level at or below the footings.

Although the stream is of primary concern, it was noted that addidional sources of erosion are present. Expansion joints and drainage downspouts from the deck are the most important. Erosion from rain water drainage through expansion joints was of concern in only a few of the bridges. The soils below these bridges were usually unconsolidated, fine-grained sand. The drainage through expansion joints and the downspouts had eroded the loose sand from below the geosynthetic fabric and rip rap at bridge B-005 (illustrated in Figure 4 also note downspouts). The result is gully erosion which continues to remove soil from around the piers. Erosion from downspouts is more common and was noted in several bridges, in varying degrees of severity. The erosion from these downspouts typically start in as a linear gully below the downspouts and expands laterally to include the adjacent piers. An example of this type of erosion is illustrated below at bridge B-013 (see Figure 17). Note that the downspout erosion has undercut the rip rap which is collapsing into the gully. This bridge is founded on chalk, but the fill beneath the bridge is a loose sand that is easily eroded. Perhaps a more erosion-resistant soil with increased clay content would be an improved fill material. Early indications of downspout erosion were noted on several of the newer bridges along U.S. Highway 78.

Figure 17. Above is an example of erosion originating from sources other than the stream channel. Downspouts direct the deck water downward forming linear gullying which expands to include the piers. Here (B-0013, lat. 34.44944, long. -88.83196) the gullying has exposed the piling to surface oxidation and erosion.

General conclusions can be made regading stream erosion associated with a particular geological unit. The Ripley Formation and more particularly the lower Ripley section seemed the most prone to erosion. The railroad tressel and the B-002 bridge (Figure 3) are both founded on the lower Ripley Formation. The formation which seems to have the least vulnerable to erosion is the Demopolis Chalk.

The significance of correlating erosion with geological units is that predictions can be made as to where erosion is likely to be a long-term issue while in the bridge or road is in the design phase. An examination of the geologcial maps, for example, would suggest that the Demopolis Chalk would be an area of low potential erosion requiring little extra design considerations. A future bridge in the Ripley Formation outcrop, may warrant additional consideration to accommodate likely erosion issues. The design engineer should also note that bridges may well exceed the "design life" usually assumed. Some bridges in the study area are 80 years old. Low rates of erosion on a yearly basis may appear minor, but the soil removed will accumulate through time and become problematic decades later.

Meanders are common in unchannelized streams and will become re-established even within channelized streams given sufficient time. Meanders are also a concern to bridge siting as they are not static features and will "migrate" down stream. If a bridge is sited immediately downstream of a meander, migration of the meander will initiate scour not only from the stream below the bridge, but also where the meander intersects the road and bridge approach. This situation appears to be case as illustrated in Figure 18 below. Meander erosion is

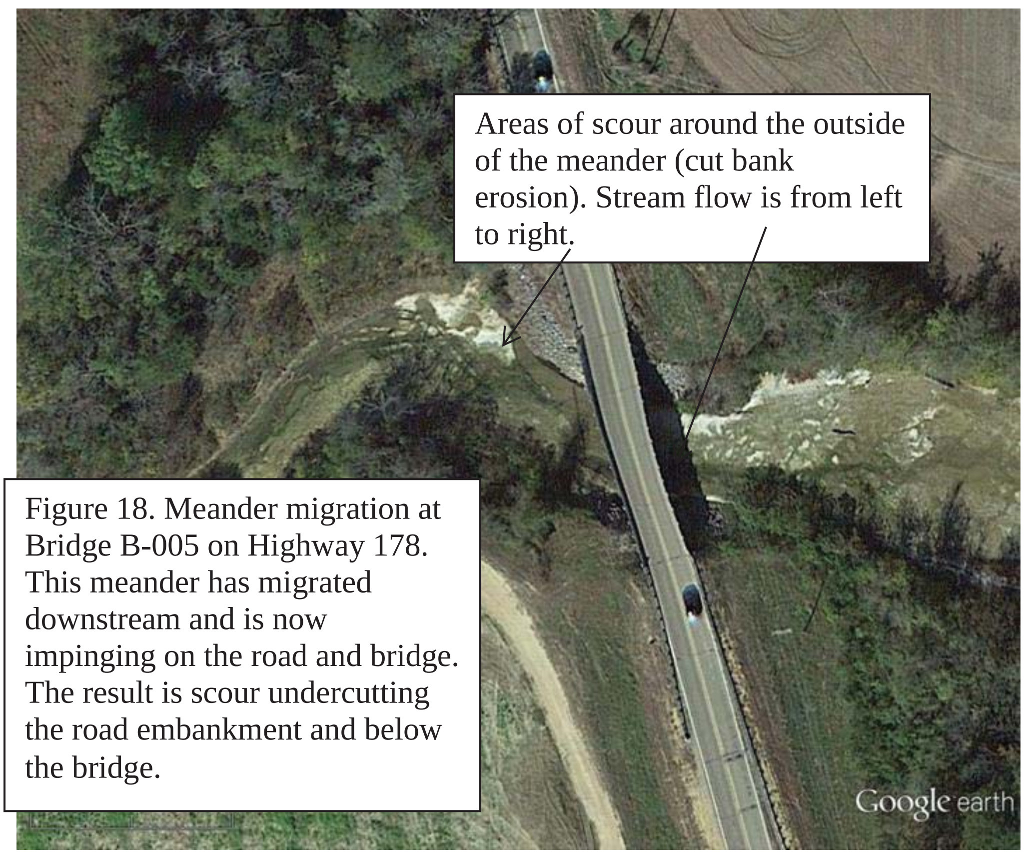


Figure 18. Meander migration at Bridge B-005 on Highway 178. This meander has migrated downstream and is now impinging on the road and bridge. The result is scour undercutting the road embankment and below the bridge.

concentrated on the outside of the meander in what is referred to as the cut bank. In the case of B-005, the cut bank has intesected the embankment and scour has required MDOT to place rip rap for protection and then to bind the rip rap with concrete to form a cohesive "blanket" of rip rap. When the field inspections were conducted, scour in the cut bank of the meander was undercutting the rip rap blanket. It was breaking apart and was being moved downstream. Without changing the channel orientation, this area will continue to need repair and will be a continuing cost to MDOT. Had the bridge been sited only a few hundered feet to the west,on the upsteam side of the meander, this problem could be avoided.

Finite Element Simulation

Reference Case Modal Characteristics

Static self-weight analysis was first performed to develop initial stress and deformation conditions and to evaluate overall integrity of the assembled reference models shown in Figures 7 and 9 respectively. Eigenvalue analysis was then performed to obtain the mode shapes and frequencies of the assembly.

Preliminary analysis was performed in stages as a check on the model performance. First, the superstructure was fixed at the bearing level to obtain the characteristic behavior of the composite deck system. Next, the substructure was added and the base of the footings restrained to define a fixed base model to obtain the characteristic behavior of the structural system. Last, the soil and piles were added to obtain the characteristic SSI system.

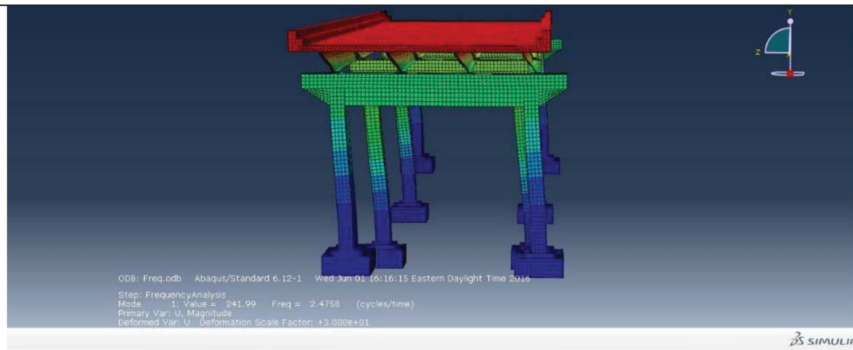
Addition of the soil and piles in the SSI system introduces numerous additional modes. This makes it difficult to identify characteristic modes associated with the resistance to the structural system provided by the soil system and structure. Here the fixed base frequencies and mode shapes are used to define the characteristic structural system modes, and a search of a limited number of modes in the neighborhood of the fixed base modal frequencies is then performed. Sequential display of the mode shapes for this subset of modes is then used to confirm the SSI mode corresponding to the comparable fixed base one.

Figures 19 and 20 show characteristic modes for the fixed base models of the flexible and stiff systems, respectively. Modal characteristics of the first three modes for each system are summarized in Table 2.

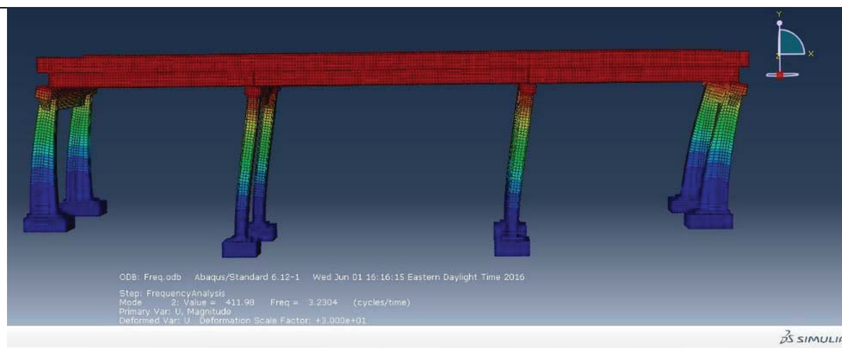
Table 2. Modal Characteristics of Fixed Base Models

Mode Number	Flexible System		Flexible System	
	Frequency, Hz	Deck Movement	Frequency, Hz	Deck Movement

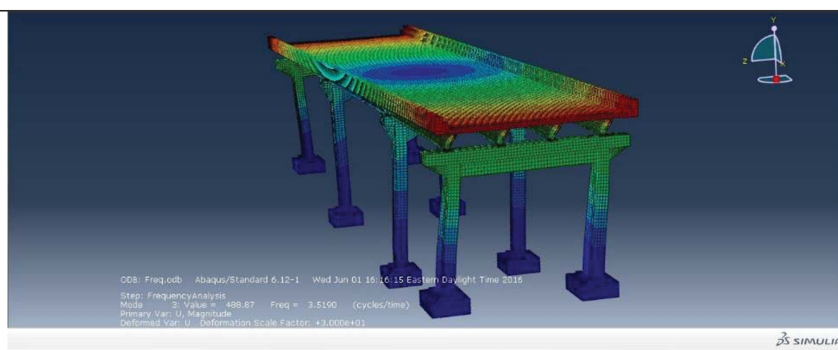
1	2.48	Transverse	7.06	Vertical
2	3.23	Longitudinal	7.25	Out-of-Plane Rotation
3	3.52	In-Plane Rotation	8.78	Longitudinal



Transverse Mode 2.48 Hz



Longitudinal Mode 3.23 Hz



Rotation Mode 3.52 Hz

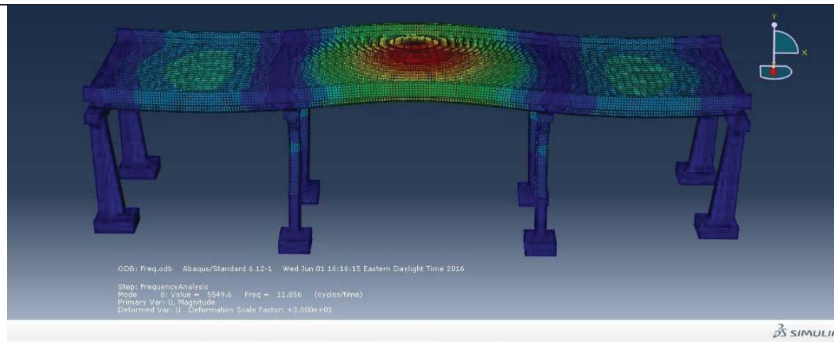
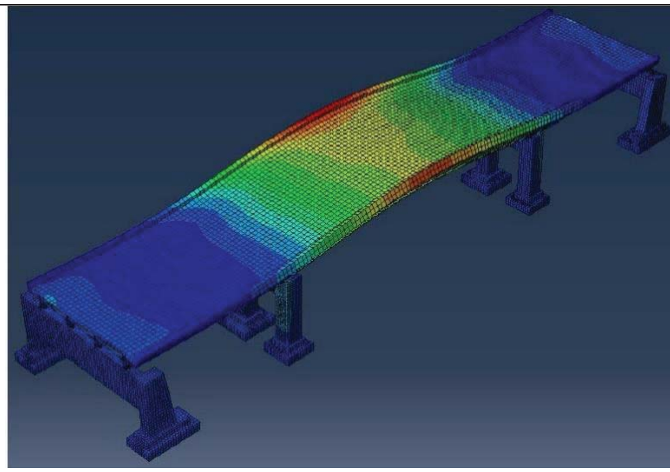
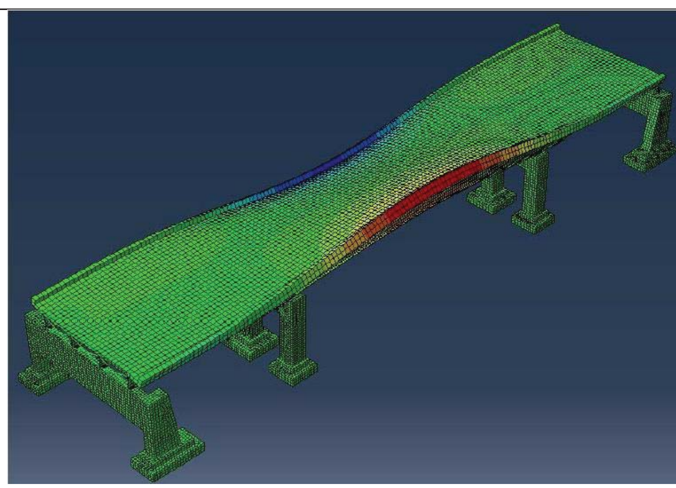
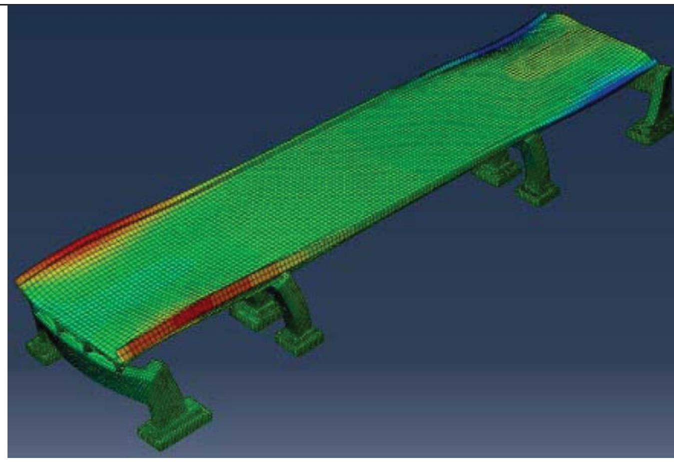
 Vertical Mode 11.9 Hz

Figure 19. Fixed base modes for the flexible system

 Vertical Mode 7.06 Hz
 Center Span Deck Torsion Mode 7.25 Hz



Longitudinal Mode 8.78 Hz

Figure 20. Fixed base modes for the stiff system

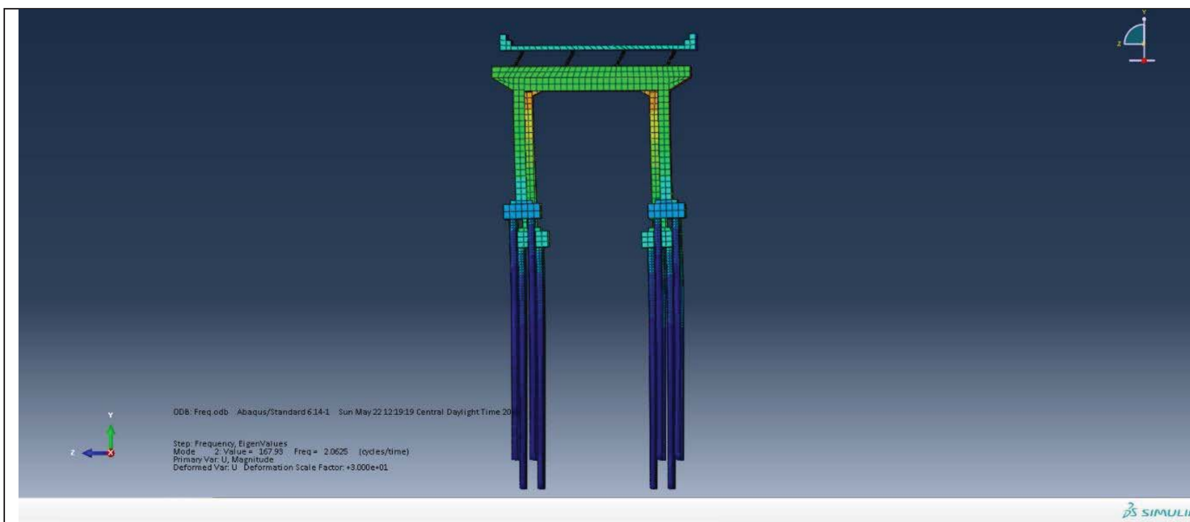
The top three modes shown in Figure 19 are the lowest three modes for the fixed base model of the flexible system. The fundamental mode is lateral translation at a relatively low frequency of about 2.5 Hz. This mode involves movement of the deck and substructure mass laterally. Without the cross-bracing this movement causes severe bending in double-curvature of both the girder webs and the columns below. The deck slab remains flat as it translates essentially as a rigid body. In the second mode, at about 3.2 Hz, the deck slab and girders translate longitudinally as a rigid body inducing out-of-plane bending of the piers and abutments. In the third mode, at about 3.5 Hz, the deck slab rotates as a rigid body inducing anti-symmetric in-plane bending of the columns . Vertical translation of the center span deck slab is exhibited in the eighth mode at about 11.9 Hz. The fourth through seventh modes involve counterbalancing translation of pier and abutment pairings.

The top three modes shown in Figure 20 are the lowest three modes for the fixed base model of the stiff system. The fundamental frequency of about 7.1 Hz, and the fundamental mode is now vertical translation of the center span deck. The second mode, at about 7.2 Hz, is rotation of the center span deck about the centerline or the roadway which induces torsional deformation in the deck slab. The third mode, at about 8.7 Hz, is longitudinal translation of the deck inducing out-of-plane bending of the columns. Without any soil to resist the translation, the abutment cap beam bends significantly.

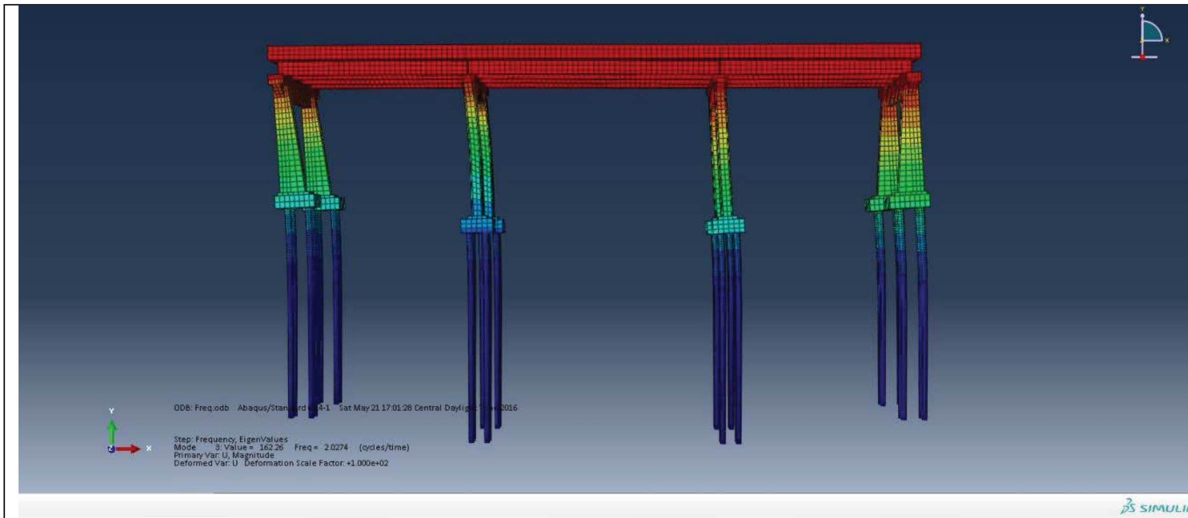
Comparing the flexible and stiff systems, it is first noted that the fundamental fixed base frequency of the stiff system is nearly three times higher than than of the flexible system. This is mostly due to the difference in column size and number. The relative order of the characteristic modes in terms of frequency is also quite different. This is primarily due to differences in center and side span lengths. The aspect ratio of center/side span length for the flexible system is roughly 4:3 whereas that for the stiff system is closer to 2:1.

The SSI models include the foundations supporting of the fixed base systems which introduce changes to these modal characteristics. The nature of the changes are often complex and subject to many issues including choice of material properties, boundary conditions, and interactions at contact surfaces. Here these effects are demonstrated through the SSI model of the flexible system which will than be the focus of the study of the additional effects of damage.

Figure 21 shows how each of the four characteristic modes identified in Figure 19 is altered by SSI. In the first three modes shown, the soil has been removed for clarity. In the fourth mode, it is included and illustrates the faceted appearance of the relatively coarse soil mesh when amplified 30 times to highlight the bending action in the stiffer structural elements.

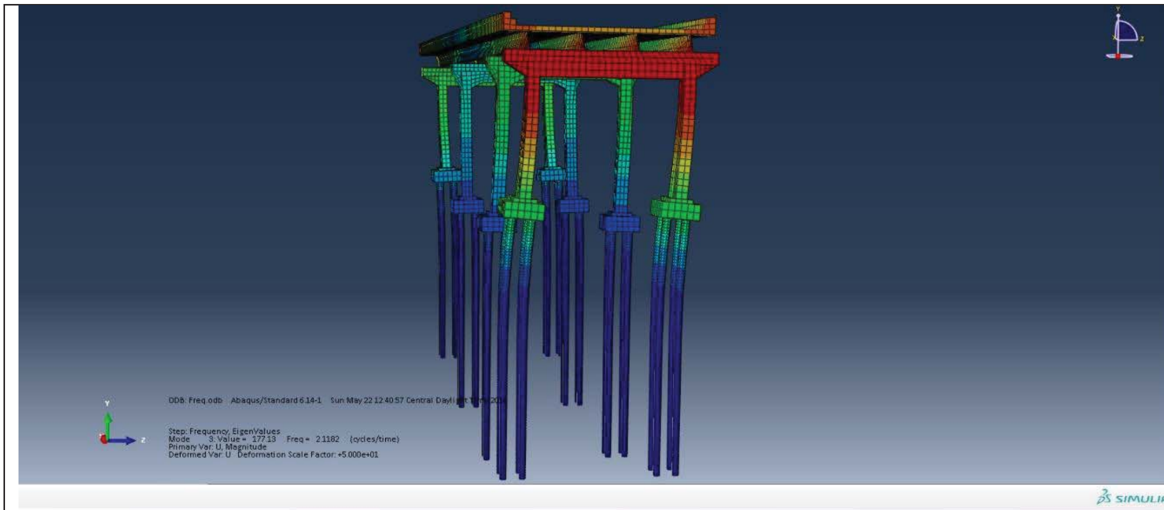


Transverse Mode 2.06 Hz

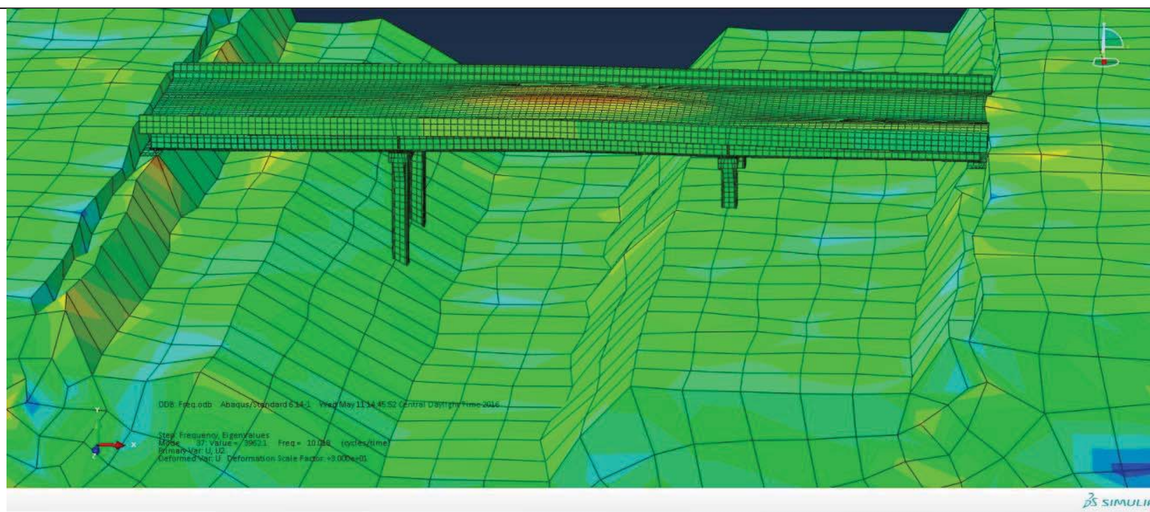


Longitudinal Mode 2.03 Hz

Figure 21. SSI modes for the flexible system



Rotation Mode 2.12 Hz



Vertical Mode 10.0 Hz

Figure 21 (Cont'd). SSI modes for the flexible system

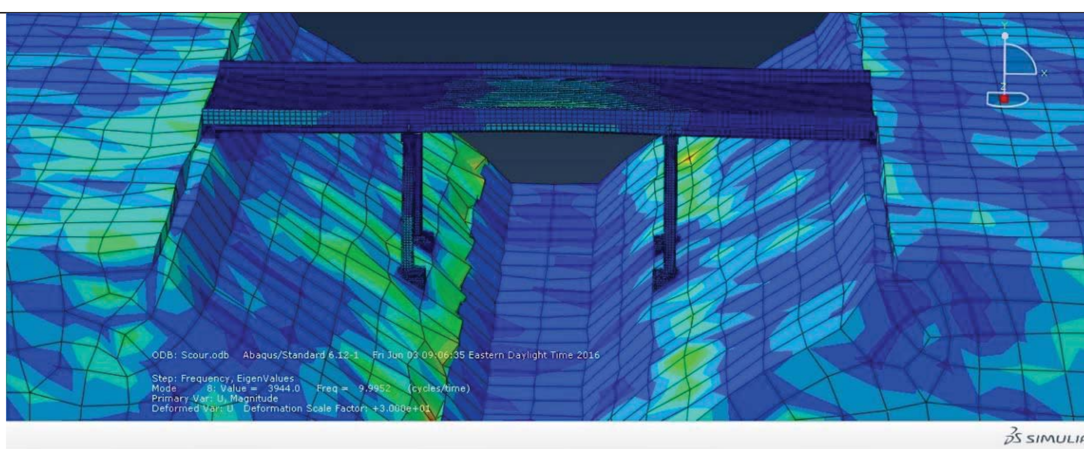
Scour Scenario Modal Characteristics

In the case of the symmetric scour scenario shown in Figure 10, eigenvalue analysis indicates that the effect varies significantly with mode type. Table 3 compares the frequencies computed for the reference and symmetric scour scenario models of the SSI flexible system for characteristic modes identified in the fixed base model analysis.

Table 3. Modal Characteristics of SSI Model of Flexible System

Deck Movement	As Constructed	Symmetric Scour
	Frequency, Hz	Frequency, Hz
Longitudinal	2.03	1.54
Transverse	2.06	1.69
In-Plane Rotation	2.12	1.66
Vertical	10.0	10.0

It is seen that the symmetric scour scenario significantly alters all the modes listed except the vertical mode frequency which is virtually unchanged. Comparison of Figure 22 with the reference model case (Fig. 21) confirms that little change is observed in the vertical mode shape as well.



Vertical Mode 10.0 Hz

Figure 22. SSI mode for flexible system with symmetric scour scenario

Earthquake Response Comparison

A point on the bottom flange of an interior girder at the middle of the center span has been selected for characterizing the response to the scenario earthquake event. The computed time histories for the horizontal acceleration components at this location are plotted in Figure 23 for the reference no scour case. The results have been normalized with respect to the acceleration of gravity, g. The comparable results for the scour case are plotted in Figure 24.

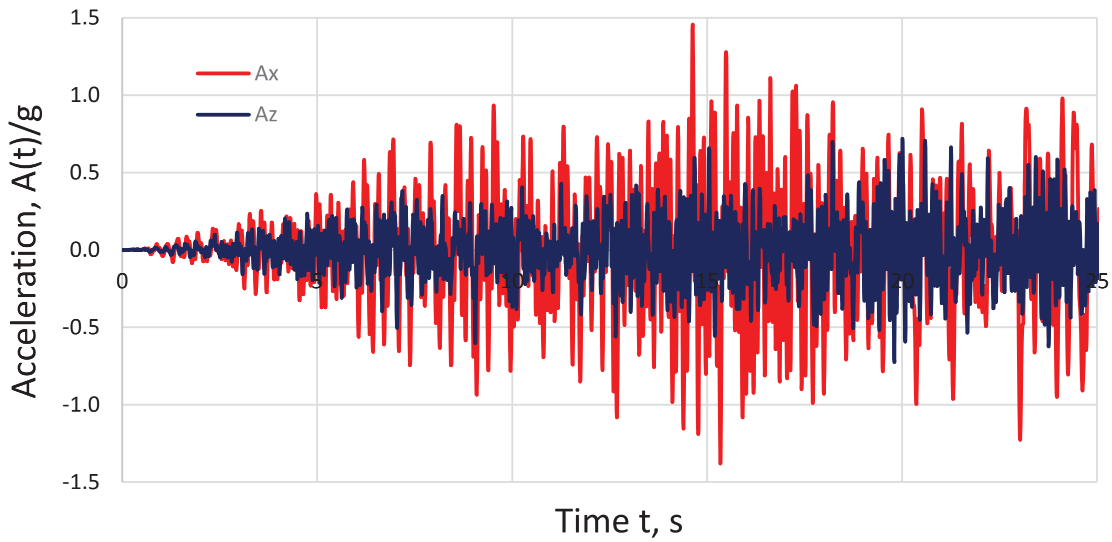


Figure 23. Reference model response time history for simulated earthquake event

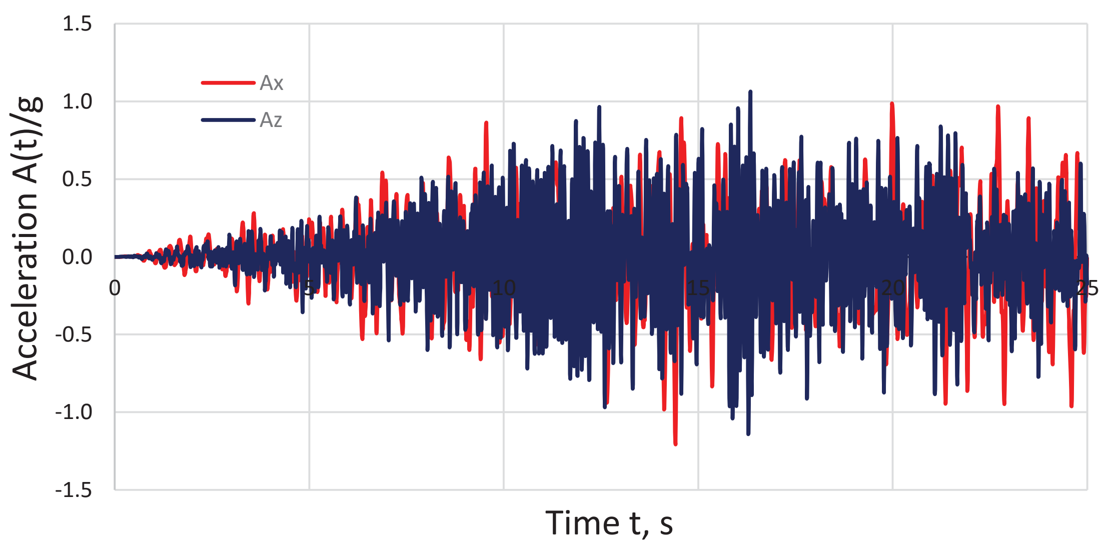


Figure 24. Asymmetric scour model response time history for simulated earthquake event

Comparison of the response records in Figures 22 and 23 with the input motion (Fig. 11) indicates a significant amplification occurs. The amount of this amplification will depend on the amount of damping present in the soil, foundation, structure, and interface conditions.

Comparing Figure 23 to Figure 22 indicates that the significant loss of soil around the footing associated with the asymmetric scour profile (Fig. 8) causes a significant increase in the amplitude of the transverse (Z) acceleration and a higher frequency response overall.

The computed time histories for the vertical acceleration components at this girder location by a significant amount due to the selection of the middle of the central span. Such motions are of less concern typically for the stability of the structural system and become important only if stresses approach damaging levels. The computed stresses due not appear significant enough here to be cause for concern unless significant deterioration of the material occurs. The effect of localized deterioration on dynamic response is considered in the companion study (*3*).

CONCLUSIONS

A bridge inventory and inspection was conducted to support the modeling effort and to ascertain the general conditioin of bridges in the study area. General bridge consition varies remarkably from poor to excellent. Condition appears to be somewhat a function of age, as the older bridges are in poorer condition that the new ones. Erosion was noted in a large number of bridges to varying extent. The most severe case was the B-002 bridge where vertical erosion had removed a significant amount of material. The reasons for the erosion is accounted to channelization, erodable geological material on which the bridge is founded and erosion mitigation that is useful, but not completely successful. It was noted that erosion mitigation was not universally present amoung the bridges. Erosion was also noted from bridge downspouts draining the deck area and from water seeping through expansion joints.

The geological map of an area can be a guide to erosion vulnerabilities as some geological formations are easier to erode than others. The Demopolis Chalk appears to be the least vulnerable and the lower section of the Ripley Formation is the most vulnerable units in the study area.

Stream meanders can become problematic if bridges are sited down stream of the meander. The meander will migrate downstream so proper bridge siting would be upstream of the meander. The migration of a meander is presently causing scour and undercutting the rip rap blanket at bridge B-005 on 178 north of Belen, Mississippi.

Detailed finite element analysis is performed to characterize the dynamic characteristics of two bridges identified in the study area lying in different geologic formations, one of which led to incorporation of a deep foundation or flexible system and the other a shallow or stiff one.

Fixed base models indicate that the first three frequencies for the two structural systems are significantly different such that the bridge with the deep foundation system has a structural system that is also significantly more flexible than the one with the shallow foundation.

Soil-structure interaction models are developed to incorporate the soil and foundation elements and account for scour conditions. The deep foundation or flexible system is used to characterize the effect of soil-structure interaction and the influence of scour, first on the dynamic characteristics and then on the response to a simulated earthquake event.

Changes in dynamic characteristics are evaluated for a symmetric scour scenario in which the stream bed depends to a depth justified by current conditions observed in the field projected to a depth likely in the operational life of the bridge. Vibration modes involving horizontal movement of the deck mass exhibit a noticable reduction in frequency which would make them more excitable under significant excitations.

An earthquake scenario of the type used in emergency management plans for the study region is used to assess the effect of scour on vulnerability to ground motion. An asymmetric scour scenario is used in which the footings of one of the two piers closest to the stream is left completely exposed. Simulated time history response is computed for the flexible system with and without scour. Acceleration response time histories for the two cases show a significant increase in the transverse acceleration of the scour case over the reference one thus indicating an increase of the vulnerability of the system with scour toward instability in the presence of severe ground shaking.

RECOMMENDATIONS

Many factors contribute to the structural integrity and stability of aging bridges. The focus of the FE analysis performed in this study is on dynamic response characteristics of the soil-foundation-structure system whose properties are often difficult to assess or observe through visual inspection.

A detailed solid modeling approach has been adopted to account for many of the complex 3D aspects of geometry and component interactions affected by scour. Even though many simplifications have been made in order to make the problem tractable, generation of the analysis models required significant learning curves even for the graduate research assistants involved in the project. Sustaining this modeling knowledge base throughout the study proved formidable. For successful expansion of the understanding of the complex effects of scour, it is recommended that continued training and project funding opportunities be made available by the transportation industry to technical personnel in academia, research, and practice.

The findings of the study demonstrate tendencies of scour to soften dynamic characteristics of bridge soil-foundation-structure systems and to increase the vulnerability of these systems to destabilizing responses induced by significant ground motion events such as earthquakes. It is recommended that further attention, through both computational and experimential studies, be given to the better understand the nature and extent of these softening and destabilizing tendencies for a variety of aging bridge cases that exist throughout the national inventory.

The effect of scour on railway bridges was not investigated due to lack of cooperation of private owners in providing access to bridge design and inspection data and to sites. Incentives should be developed to encourage these owners to participate in studies of scour on this important component of the national transportation infrastructure.

In support of the modeling studies the scour / erosion studies identified several specific recommendations that would prove useful to better maintain the overall integrety and well-beining of bridges. These recommendations are listed below:

1) Include the stream geometry over which bridges are constructed on design plans and the same data should be monitored during bridge inspections.

2) Erosion mitigation should be placed beneath all bridges and the rip rap should be of appropriate size, being mindful that stream dynamic may change remarkably during storm events -- rip rap that has been moved downstream of the bridge serves little purpose.

3) Examination of geological maps during the design phase is insightful to evaluate potential erosional concerns. These maps will also provide useful information regarding the geotechnical aspects of the materials on which the bridge is founded.

4) Appreciation of the dynamic nature of streams (meander migration, for example) will prevent costly long-term maintaince.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

DOF	degree-of-freedom
FE	finite element
FHWA	Federal Highway Administration
ft.	foot (feet)
g	acceleration due to gravity
lb.	pound(s)
MDOT	Mississippi Department of Transportation
NBI	National Bridge Inventory
NCITEC	National Center for Intermodal Transportation and Economic Development
RC	reinforced concrete
UM	University of Mississippi
USGS	U.S. Geological Survey

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(Below not used in narrative currently but may need to be included in the supplemental information on impact which Waheed requested)

11. Ervin, E. and Mullen, C. “Bridge Damage Detection using Deck Level Vibrations-Preliminary Findings from FE Analysis and Shake Table Tests,” 2015 UTC

12. Swann, C. and Mullen, C. “Predicting Erosion Impact on Highway and Railway Bridge Substructures,” 2015 UTC Conference for the Southeast Region, Birmingham, AL, March 26, 2015.

13. Mullen, C., and Ervin, E. “Bridge Damage Detection using Deck Level Vibrations-Preliminary Findings from FE Analysis and Shake Table Tests,” 2015 UTC Conference for the Southeast Region, Birmingham, AL, March 26, 2015.

14. Mullen, C., Tanner, K. and Irhayyim, I., “3D FE simulation of aging bridges on soil and rock foundations,” Simulia South Regional Users Meeting, Houston, TX, October 15, 2015

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