Research Report
KTC-06-20/SPR-206-00-1F

KENTUCKY TRANSPORTATION CENTER

SEISMIC EVALUATION OF I24 BRIDGES AND EMBANKMENTS IN WESTERN KENTUCKY

SUMMARY REPORT

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Research Report
KTC-06-20/SPR206-99-1F

SEISMIC EVALUATION OF I-24 BRIDGES AND EMBANKMENTS IN WESTERN KENTUCKY - SUMMARY REPORT

by

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College of Engineering, University of Kentucky

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16. Abstract

I-24 is considered as one of the high priority and emergency routes in the region. Hence, it is essential that I-24 remains functional and operational after an earthquake event. The objective of this study is to perform seismic evaluation and risk assessment of bridges and embankments along I-24 in western Kentucky. The assessment assists identifying and prioritizing bridges that are susceptible to failure.

The study aims at evaluating the seismic risk for 127 bridges, of which 82 bridges lies on I-24 and 45 bridges cross over I-24. This report is the first (1^{st}) in a series of seven reports for Project SRP 206: “Seismic Evaluation of I-24 Bridges”. The seven reports represent a comprehensive study evaluating the seismic vulnerability of bridges and embankments along I-24 in western Kentucky. This report is intended to provide a summary of the results of the comprehensive study. Basic ranking results and/or deficiencies of the seismic performance of the 127 bridges are documented, and retrofit recommendations, if any, are presented in this report. However, all details and records for Project SRP 206, “Seismic Evaluation of I-24 Bridges”, are presented in the accompanied six reports.

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EXECUTIVE SUMMARY

Interstate-24 (I-24) in western Kentucky lies just east of the New Madrid Seismic Zone (NMSZ). The last *major* earthquake near this region was the Great New Madrid Earthquake of 1811-1812 with a magnitude of 7.5 or greater on the Richter scale. The NMSZ remains active, recording about 200 earthquakes per year, though most of them are too small to be felt by humans. Seismologists, however, believe that there is a high probability of a major earthquake event in the near future. I-24 is considered as one of the high priority and emergency routes in the region. Hence, it is essential that I-24 remains functional and operational during a major earthquake event. The objective of this study is to perform seismic evaluation and risk assessment of bridges and embankments along I-24 in western Kentucky.

The study aims at evaluating the seismic risk for 127 bridges, of which 82 bridges lie on I-24 and 45 bridges cross over I-24. This report is the first (1st) in a series of seven reports for Project SPR 206: "Seismic Evaluation of I-24 Bridges". The seven reports represent a comprehensive study to evaluate the seismic vulnerability of bridges and embankments along I-24 in western Kentucky. This report is numbered as KTC-06-20/SPR206-99-1F, and is entitled: "Seismic Evaluation of I-24 Bridges and Embankments in western Kentucky – Summary Report". The report is intended to provide a summary of the results of the comprehensive study. Basic ranking results and/or deficiencies of the seismic performance of the 127 bridges are documented, and retrofit recommendations, if any, are presented in this report. However, all details and records for Project SRP 206, "Seismic Evaluation of I-24 Bridges", are shown in the accompanied six reports. A Table that provides a list of the reports for Project SRP 206 is shown at the end of this executive summary.

Determination of the seismic risk of the bridges along I-24 in western Kentucky requires evaluating the current condition of all individual elements of the bridges. Therefore, each bridge site along I-24 in western Kentucky was visually inspected. One objective of the site inspection was to obtain an informative source of bridge records, which are required to identify, rank, and prioritize vulnerable bridges and their embankments along I-24 in western Kentucky. Another objective of the site inspection was to provide state engineers and other transportation officials with information delineating the current conditions of I-24 bridges in western Kentucky. The information shall facilitate future comparisons with post-earthquake conditions immediately after the occurrence of an earthquake. Through these comparisons, significant changes can be reported, and further insight studies can be carried out. All bridges along I-24 were visually inspected, pictured, and the records were stored in a database for future references. Data of the visual inspection and the pictures were combined to form the completed site inspection forms of the I-24 bridges. Over 1500 pictures were taken for the main components of the bridges from multiple angles. The completed site inspection forms represent a significant supplement to the "as-built" bridge plans and may assist in pre-earthquake evaluation studies as well as post-earthquake inspection. A comprehensive inventory of the bridges was compiled by review of the "as-built" bridge plans, construction and maintenance records, and site inspection forms. For compilation of the bridge inventory, necessary data pertinent to characteristics, year of construction, and attributes of the bridges was collected to form a seismic evaluation information system. All details and records of the site inspection of the bridges along I-24 in western Kentucky are shown in the accompanied report, KTC-06-21/SPR206-99-2F that is entitled: “Site Investigation of Bridges along I-24 in Western Kentucky”.

A seismic rating system and a detailed evaluation procedure for the bridges along I-24 in western Kentucky were presented. The seismic rating system, which is based on structural vulnerability, seismic and geotechnical hazards, and socioeconomics factors, was used to rank the 127 bridges along I-24 in western Kentucky. All but four bridges were evaluated for the 50-year and the 250-year seismic events. The 50-year and the 250-year events are events that have a 90 % probability of not being exceeded in 50 years and 250 years, respectively. The resulting preliminary seismic evaluation and ranking of the 127 bridges along I-24 in western Kentucky for the 50-years and the 250-years are illustrated in this report. All supplementary details and records of the preliminary seismic ranking/rating of the bridges along I-24 in western Kentucky are provided in the accompanied report, KTC-06-22/SPR206-99-3F that is entitled: “Preliminary Seismic Evaluation and Ranking of Bridges along I-24 in Western Kentucky”.

The preliminary seismic evaluation of the 127 bridges along I-24 showed that 14 bridges were deemed susceptible to severe damage during a future major earthquake event. Therefore, the 14 bridges were selected for subsequent detailed seismic evaluation. The detailed seismic evaluation was based on the capacity/demand ratio method. The detailed evaluation focused on four distinct bridge components: (*a*) expansion joints; (*b*) bearings; (*c*) columns; and (*d*) footings. Deficiencies of the seismic performance of those 14 bridges were documented, and retrofit recommendations were presented. The results indicate that the rating system is an effective means to identify and prioritize highway bridges for seismic evaluation and retrofit. Details, results, and the required course of action, if any, of the detailed seismic evaluation of those 14 bridges can be found in the accompanied report, KTC-06-23/SPR206-99-4F that is entitled: “Detailed Seismic Evaluation of Bridges along I-24 in Western Kentucky”.

Included in this study are two parallel bridges, which cross the Tennessee River and connect Marshall and Livingston counties in western Kentucky. Two other parallel bridges cross the Cumberland River at the borders of Lyons and Livingston counties in western Kentucky, and are included in the study. Due to the importance of the two parallel bridges along the Tennessee River and the two parallel bridges along the Cumberland River along I-24 in western Kentucky, it was decided that a complete seismic evaluation be carried out on these bridges. The four bridges were evaluated for the 250-year and the 500-year seismic events. The 250-year and the 500-year events are events that have a 90 % probability of not being exceeded in 250 years and 500 years, respectively. During the 250-year event, the bridges shall remain in the elastic range without any disruption to traffic. During the 500-year event, partial damage shall be permitted to the bridges, but they are to remain accessible to emergency and official vehicles. The following tasks were completed to judge the structural integrity and the seismic vulnerability of those four bridges: (1) field testing of the main bridges; (2) finite element modeling and calibration; (3) time-history seismic response analysis; and (4) seismic evaluation/retrofit for both the main and the approach spans of the bridges.

Deficiencies of the seismic performance of the four bridges at the Tennessee River and the Cumberland River crossings were documented, and retrofit recommendations were presented in this report. All details of the seismic evaluation of the two parallel Tennessee River Bridges on the I-24 are shown in the accompanied report, KTC-06-24/SPR206-99-5F that is entitled: "Seismic Evaluation of the Tennessee River Bridges on I-24 in Western Kentucky". Details of the seismic evaluation of the two parallel Cumberland River Bridges on the I-24 are shown in the accompanied report, KTC-06-25/SPR206-99-6F that is entitled: "Seismic Evaluation of the Cumberland River Bridges on I-24 in Western Kentucky".

The seismic assessment of the embankments at the sites of the bridges along I-24 in western Kentucky was performed and reported in this summary report. A ranking model that provides a priority list of embankments with the highest seismic risk of failure is generated. A step-by-step methodology is presented in a flowchart to estimate the seismic slope stability capacity/demand ratio, displacement, and liquefaction potential of bridge embankments. Three categories are presented to identify the failure risk of the embankments. The ranking model is useful for a quick sensitivity assessment of the effect of various site conditions, earthquake magnitudes, and site geometry on possible movement of designated embankments. The priority list will enable decision makers to decide on either carrying out further detailed evaluation or considering other appropriate actions for the bridge embankments with the highest seismic failure risk. Full details of the methodology that was used to identify the seismic risk of the embankments and all associated results are provided in the accompanied report, KTC-06-26/SPR206-99-7F that is entitled: "Seismic Evaluation and Ranking of Bridge Embankments along I-24 in Western Kentucky".

NOTE: This report is the first (1st) in a series of seven reports for Project SRP 206: "Seismic Evaluation of I-24 Bridges". The seven reports are:

Report Number:	Report Title:
(1) KTC-06-20/SPR206-99-1F*	Seismic Evaluation of I-24 Bridges and Embankments in Western Kentucky – Summary Report
(2) KTC-06-21/SPR206-99-2F	Site Investigation of Bridges along I-24 in Western Kentucky
(3) KTC-06-22/SPR206-99-3F	Preliminary Seismic Evaluation and Ranking of Bridges along I-24 in Western Kentucky
(4) KTC-06-23/SPR206-99-4F	Detailed Seismic Evaluation of Bridges along I-24 in Western Kentucky
(5) KTC-06-24/SPR206-99-5F	Seismic Evaluation of the Tennessee River Bridges on I-24 in Western Kentucky
(6) KTC-06-25/SPR206-99-6F	Seismic Evaluation of the Cumberland River Bridges on I-24 in Western Kentucky
(7) KTC-06-26/SPR206-99-7F	Seismic Evaluation and Ranking of Bridge Embankments along I-24 in Western Kentucky

* Denotes current report

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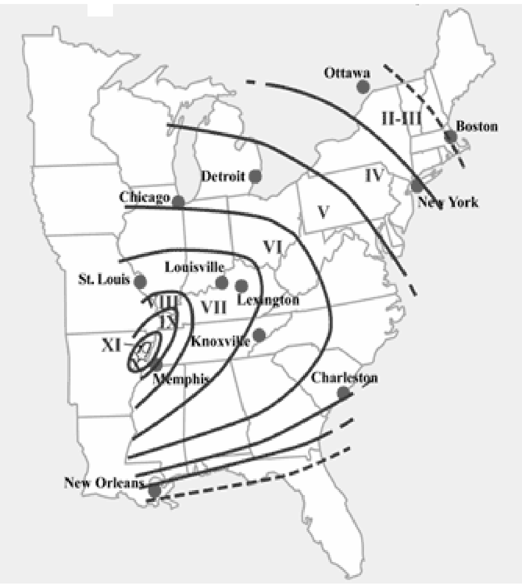
1. THE NEW MADRID SEISMIC ZONE

The New Madrid Seismic Zone (NMSZ) extends more than 120 miles southward from Cairo, Illinois, at the junction of the Mississippi and Ohio rivers, into Arkansas and parts of Kentucky and Tennessee.

The greatest earthquake risk east of the Rocky Mountains is along the NMSZ. Damaging earthquakes are not as frequent as in California. However, the expected destruction covers more than 15 times the area because of the underlying geology and soil conditions prevalent in the region (National Earthquake Information Center, 2003). The zone is active, averaging about 200 earthquakes per year, though most of them are too small to be felt by humans.

A *damaging* earthquake in this area (6.0 or greater on a Richter scale) occurs, on average, once every 80 years. An earthquake with an estimated magnitude 6.4 occurred near Marked Tree, Arkansas, 1843, and another earthquake with a magnitude of 6.8 occurred near Charleston, Missouri, 1895. A *major* earthquake (7.5 or greater) occurs every 200-300 years. It was believed that there is a 10 percent chance of such a disaster by the year 2000 and a 25 percent chance by 2040. The last major earthquake was the Great New Madrid Earthquake, 1811-1812. This earthquake occurred over a series of over 2000 tremors in five months, five of which were 8.0 or more in magnitude (National Earthquake Information Center, 2003). Fig. 1 shows the Modified Mercalli intensity for the first event of the 1811-1812 New Madrid earthquakes (Bolt, 1993).



Modified Mercalli Intensity Scale

INTENSITY	EFFECTS	AVE. PEAK ACCEL.
VI Strong	Felt by all. Damage slight	0.06-0.07g
VII Very Strong	Everybody runs outdoors. Considerable damage to poorly designed buildings	0.10-0.15g
VIII Destructive	Considerable damage to ordinary buildings	0.25-0.30g
IX Ruinous	Great damage to ordinary buildings	0.50-0.55g
X Disastrous	Many buildings destroyed	> 0.60g
XI Disastrous	Few, if any, structures remain standing	

Fig. 1 Isoseismal Map for the Arkansas Earthquake of December 16, 1811 (Bolt, 1993)

2. INTERSTATE 24 IN WESTERN KENTUCKY

Due to their close proximity to the New Madrid Seismic Zone, counties in the western part of Kentucky are vulnerable to a major earthquake. Many bridges along I-24 were designed prior to the implementation of stringent seismic design specifications, and were not constructed to withstand severe seismic events. Fig. 2 shows the I-24 in western Kentucky.

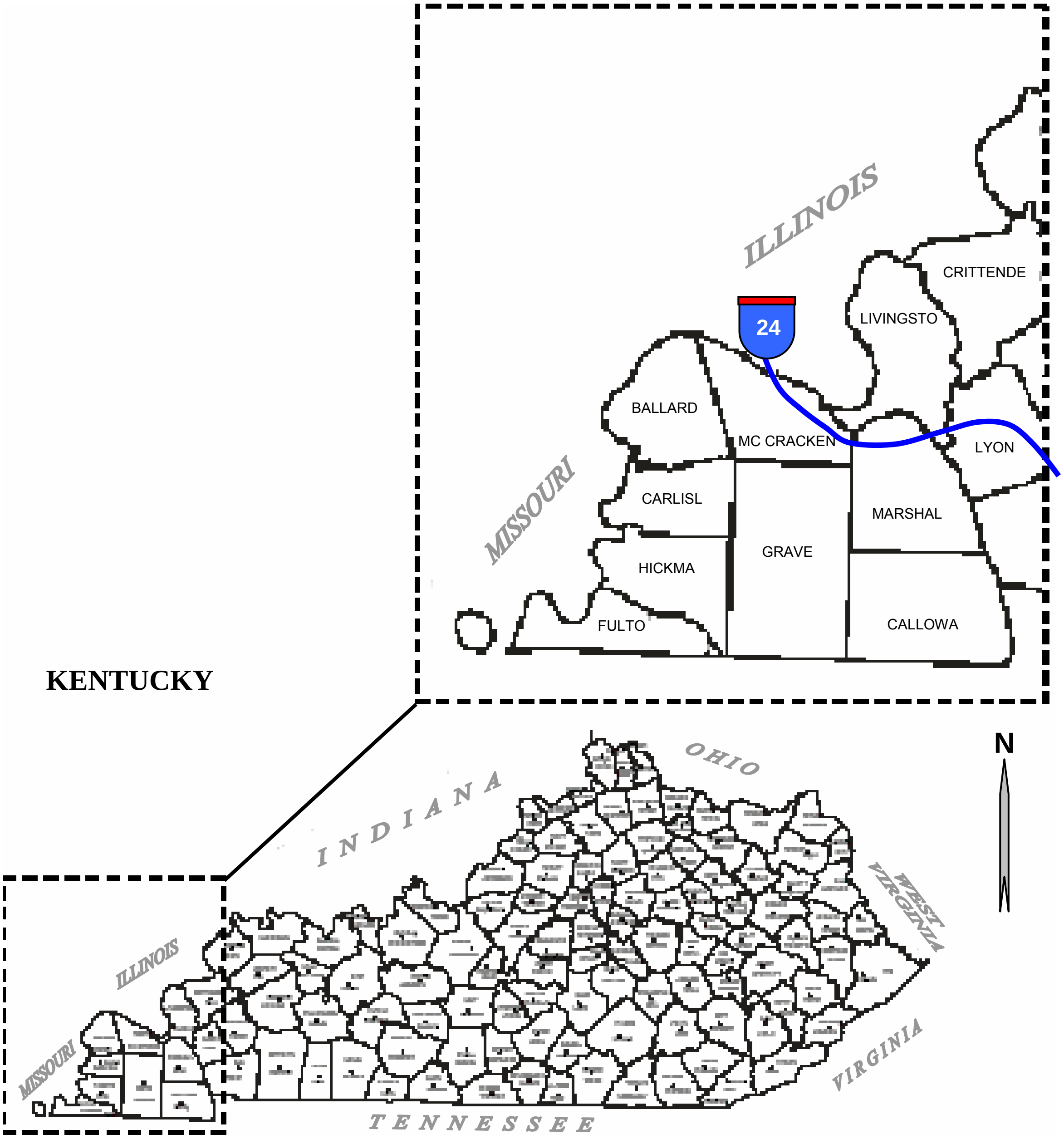


Fig. 2 I-24 Corridor in Western Kentucky

In 1998, the Federal Highway Administration sponsored a research project to identify critical links along highways in western Kentucky. I-24 is one of the most vital transportation links that was identified as a high priority route and as an emergency route for the city of Memphis, Tennessee. I-24 crosses seven counties in western Kentucky. Because of their close proximity to the New Madrid Zone, considerable damage to I-24 bridges in western Kentucky may result if a major earthquake occurs. Due to its importance, I-24 has to remain open in the event of a major earthquake. The Commonwealth of Kentucky sponsored a research project to evaluate the seismic vulnerability of I-24 bridges and their embankments in western Kentucky. The study includes identifying the seismic risk associated with 82 bridges on I-24 and 45 bridges over I-24, and resulting in a total of 127 bridges.

3. SITE INSPECTION OF I-24 BRIDGES

Determination of the seismic risk of I-24 bridges requires evaluating the current condition of all individual elements of the bridges. Therefore, each bridge site along I-24 was visually inspected. One objective of the site inspection was to obtain an informative source of bridge records, which are required in the current study to identify, rank, and prioritize vulnerable bridges and their embankments along I-24 in western Kentucky. Another objective of the site inspection is to provide state engineers and other transportation officials with information delineating the current conditions of I-24 bridges in western Kentucky. The information shall facilitate future comparisons with post-earthquake conditions immediately after the occurrence of an earthquake. Through these comparisons, significant changes can be reported, and further insight studies can be carried out. All bridges along I-24 were visually inspected, pictured, and the records were stored in a database for future references. Data of the visual inspection and the pictures were combined to form the completed site inspection forms of the I-24 bridges. Over 1500 pictures were taken for the main components of the bridges from multiple angles. The completed site inspection forms represent a significant supplement to the "as-built" bridge plans and may assist in pre-earthquake evaluation studies as well as post-earthquake inspection.

A comprehensive inventory of the bridges was compiled by review of the "as-built" bridge plans, construction and maintenance records, and site inspection forms. For compilation of the bridge inventory, necessary data pertinent to characteristics, year of construction, and attributes of the bridges was collected to form a seismic evaluation information system. Data was organized and processed through a database utilizing Microsoft Access. The I-24 bridge inventory provides an essential data record, which was utilized for the seismic risk assessment of I-24 bridges and their associated embankments.

Observations and comments that were gathered during the visual inspection are reported for each designated bridge in a separate site inspection form. Each site inspection form includes five sections to report the screening observations regarding the bridge's general attributes or features, superstructure, bearings, substructure, and other relevant observations and/or comments. Each bridge is identified by a bridge bin number. The bridge bin number represents information regarding the county through which the bridge passes, the route, and the bridge number.

The general characteristics included information regarding the crossing at the bridge site, year of completion of the construction, location of the bridge along I-24, detour length in miles, latitude, and longitude of each bridge. Notes have been made for each bridge to report: (a) any modifications in the bridge; (b) if the bridge crosses a body of water; (c) if the bridge was seismically retrofitted; and (d) if the bridge is of the culvert type.

The site inspection of the superstructure of each bridge focused on gathering information regarding the existence of box girders, visibility of lateral movement under traffic loading, skewing of the bridge, unusual gap or offset at an expansion joint. Judgment made regarding: (a) the possibility of the bridge to collapse during an earthquake after toppling failure of the bearings; (b) the integrity of the superstructure with the abutments; and (c) any instability that might occur due to the gross movement of the bridge, are reported. The judgment was based the visual assessment of the current condition of the various elements of the bridge.

The bearing types and conditions for each bridge are reported. The bearings of the I-24 bridges were of five possible types: (a) rocker; (b) roller; (c) elastometric; (d) sliding; or (e) multi-rotation bearings. The possibility of overturning during a seismic event, existence of pedestals, whether or not girders are supported on individual pedestals or columns, and the existence of continuous bearing seats under the abutment end-diaphragms were investigated. Furthermore, the existence of exterior girders supported on the seat edge at the top of the columns was investigated for bridges with less than three girders. Longitudinal support length was reported.

Visual inspection of the characteristics of the substructure for each bridge included observations regarding any horizontal or vertical movement at the abutments, columns or piers. Also, observations were reported regarding any unusual or extensive erosion of soil at or nearby any of the substructure elements of the bridge. The type of connection between the concrete columns and the superstructure was observed. The abutment type and the possibility of slope failure during a seismic event were reported.

The last section of the site inspection form is used to either report any unusual visual observation or to detail a point that was provided in any previous section of the form. Pictures to point out the current condition of the different elements of the bridge, the global view of the bridge, or a certain visual observation are provided in the last section of the site inspection form of each bridge. A sample inspection form for bridge #73-0024-B00100 and bridge #73-0024-B00100P is shown in Fig. 3. All details and records of the site inspection of the bridges along I-24 in western Kentucky are shown in the accompanied report, KTC-06-21/SPR206-99-2F that is entitled: “Site Investigation of Bridges along I-24 in Western Kentucky”.

GENERAL	Crossing	Ohio River		Bridge Number- 73-0024-B00100 and Parallel	
	Year Built	*1968*	County	McCRACKEN	Detour Length (Miles)	
	Latitude	037D 07.957M	Longitude	088D 41.232M	If *yes*. Please list them (Structure or load).
	Have modifications been made since the bridge was constructed? → *No.* ☒				
	Does the bridge cross a body of water?			*Yes* ☒ *No* ☐	
	Has the bridge been seismically retrofitted?			*Yes* ☐ *No* ☒	
	Is it a rigid box culvert?			*Yes* ☐ *No* ☒	

SUPERSTRUCTURE	Is the superstructure integral with the abutments?	*Yes* ☐ *No* ☒	**Comments:**
	Does the superstructure contain box girders?	*Yes* ☐ *No* ☒	
	Is there lateral movement under traffic loading?	*Yes* ☐ *No* ☒	
	Is the bridge likely to collapse in an earthquake after toppling failure of the bearings?	*Yes* ☐ *No* ☒	
	Would gross movement of superstructure cause instability?	*Yes* ☐ *No* ☒	
	Is the bridge skewed?	*Yes* ☒ *No* ☐	
	Is there any unusual gap or offset at an expansion joint?	*Yes* ☐ *No* ☒	

BEARINGS	Type	*Rocker* ☐ *Roller* ☐ *Elastometric Pad* ☐ *Sliding* ☒ *Multi-rotation* ☐	Condition	*FAIR* [1]
	If there are pedestals, are the bearings likely to overturn in an earthquake?			*Yes* ☐ *No* ☒
	Does the bridge with less than 3 girders have exterior girder supported on the seat edge?			*Yes* ☐ *No* ☒
	Are the bearing seats, under the abutment end-diaphragm, continuous?			*Yes* ☒ *No* ☐
	Are there any girders supported on individual pedestals or columns?			*Yes* ☒ *No* ☐
	What is the longitudinal support length measured in a direction perpendicular to the support?			

SUBSTRUCTURE	Is the abutment a cantilever earth-retaining abutment?	*Yes* ☒ *No* ☐
	Are the reinforced concrete columns monolithic with the superstructure?	*Yes* ☐ *No* ☒
	Is there horizontal or vertical movement or tilting of the abutments, columns or piers?	*Yes* ☐ *No* ☒
	Is there unusual or extensive erosion of soil at or near any of the substructure units?	*Yes* ☐ *No* ☒
	Do you think abutment-slope failures are possible in an earthquake?	*Yes* ☐ *No* ☒

OTHER	[1] Corrosion of the steel plates connected to the abutments is noticeable.	

Fig. 3 Inspection of Bridge # 73-0024-B00100 and Bridge # 73-0024-B00100P on I-24

4. CHARACTERISTICS OF BRIDGES ALONG I-24 IN WESTERN KENTUCKY

The observations of the bridges along I-24 in western Kentucky, which were reported in the site inspection forms, were used together with the bridge inventory to obtain adequate statistical figures.

I-24 passes through McCracken, Marshall, Livingston, Lyon, Trigg, Caldwell, and Christian counties in western Kentucky. Lyon and Marshall Counties are located approximately 72 miles and 60 miles northeast of the center of the New Madrid seismic zone, respectively. McCracken County, located approximately 45 miles northeast of the center of the New Madrid seismic zone has the largest number of bridges among all other counties with an average of two bridges per mile. Because of their proximity to the New Madrid seismic zone, the seismic adequacy of the bridges in McCracken, Marshall, Livingston, and Lyon counties is questionable. The geographic locations of the counties through which I-24 passes in western Kentucky enabled a preliminary rough estimation of two categories of seismic risk. The first category may be associated with high seismic risk and includes McCracken, Marshall, Livingston, and Lyon counties. The second category, which includes Trigg, Caldwell, and Christian counties, is expected to have a comparatively lower seismic risk than that the first category. Sixty five percent of the total bridges along the I-24 are located in the counties of the first category, excluding those bridges which were constructed after 1974 in Livingston County.

The 127 bridges are categorized based on their characteristics. These characteristics included: (a) structural type; (b) structural length; (c) number of spans; (d) maximum span length; (e) skew angle; (f) construction materials; and (g) and bearing types. The types that were encountered for the bridges along I-24 included: (a) two-span continuous composite steel girder; (b) two-span reinforced concrete box girder; (c) one-span steel; (d) four-span continuous composite steel girder; (e) multi-span steel plate girder; and (f) reinforced concrete culverts.

Being built within the same period, most bridges over I-24 are quite similar in their structural types and material. Of the bridges over I-24, there are 40 two-span continuous composite steel girder bridges. Three bridges are two-span reinforced concrete box girder bridges. There are two one-span steel bridges and one four-span continuous composite steel girder bridge. Excluding the Cumberland River Bridges, the Tennessee River Bridges, and a few other bridges, the structural length of all bridges is less than 152.4 m (500 ft).

A wider range of structural systems were used for the bridges on I-24 as compared to the bridges over I-24. Of the 82 bridges on I-24, 38 pairs of parallel bridges were constructed in the west and eastbound lanes, in addition to five reinforced concrete culverts. Excluding the long bridges that cross waterways, the maximum span length of the majority of the bridges on I-24 varies, with many being in the range of 45 feet to 200 feet.

Eighty three percent of the bridges along I-24 are skewed, 13 percent have a skew angle exceeding 40 degrees, and the remaining 17 percent of the bridges are not skewed. The highest Number of bridges is found in McCracken County (38 bridges), followed by Lyon County (27 bridges), Marshall County (21 bridges), Christian County (20 bridges), Trigg County (11 bridges), Livingston County (7 bridges), and Caldwell County (3 bridges).

Fifty percent of the bearings of the bridges along I-24 are of the rocker type, 40 percent are of the roller type, and 10 percent are of the elastometric type.

The main girders of the superstructure of the Cumberland River parallel bridges are of a steel plate-girder type. The total length of each bridge is 509 m (1671 ft). Each of the two parallel bridges consists of six spans, including three approach spans. The three main spans are supported on three concrete piers and one abutment.

The superstructure of the Tennessee River parallel bridges is of a steel plate-girder arch type. Each of the two parallel bridges consists of nine spans. The bridges are symmetric with an arch span at the middle. The total length of each bridge is 643 m (2110 ft), and the maximum span length is 163 m (535 ft). Twenty-six main suspended steel wires, 13 on one side, are vertically attached to the arches and the floor system.

The site inspection of the bridges along I-24 revealed several issues. Minor to extensive corrosion at the abutment locations was commonly observed in several bridges. The problems or possible deficiencies, which were observed during the site inspections, are provided in the site inspection forms. Examples of these deficiencies include: (a) rotation of the superstructure of bridge#73-0024-B00114 on I-24; (b) holes in front of abutment within the perm of bridge#73-0024-B00120 on I-24; (c) partial failure of the abutment of bridge#73-0024-B00114 and bridge#24-0024-B00130 on I-24; (d) absence of lateral shear keys at abutments of bridge#79-0024-B00114 on I-24; (e) large distance to the back wall from the girder end , which may result in excessive rotation of the bearings of bridge#70-0024-B00063 on I-24; and (f) cracking of pavement on bridge#24-0024-B00090 on I-24.

5. SEISMIC RANKING METHEDOLOGY OF BRIDGES ALONG I-24 IN WESTERN KENTUCKY

The process of seismic ranking, or rating, of bridges involves three major stages. These are: (a) preliminary screening that includes site inspections; (b) detailed evaluation; and (c) design of retrofit measures. Preliminary screening of the inventory of the bridges is used to identify those bridges that are seismically deficient and those in the greatest need of retrofitting. Factors considered in the seismic rating process include structural vulnerabilities, seismic and geotechnical hazards, and bridge importance.

The Retrofitting Manual (Buckle and Friedland, 1995), which was published by the Federal Highway Administration (Report No. FHWA-RD-94-052), describes a method of preliminary screening to determine those bridges that are in need of a detailed seismic analysis and those bridges that are considered to be of the highest priority during analysis.

Although the performance of a bridge is based on the interaction of all of its components, it has been observed during past earthquakes that certain bridge components of four general types are more vulnerable to damage than others. These are (a) the connections, bearings, and seats; (b) columns and foundations; (c) abutments; and (d) foundations. Of these four types, bearings are generally the least expensive to retrofit. Therefore, the Retrofitting Manual (Buckle and Friedland, 1995) proposed a vulnerability-rating factor (V_1) for the connections, bearings, and seat details. The other three components are combined under another rating factor (V_2). The overall rating for the bridge is then given by the larger of these two factors.

A brief summary of the Seismic Rating System is described in this section. The Seismic Rating System is used as a basis for selecting bridges for detailed seismic evaluation. The Seismic Rating System involves the following five steps (Fig. 4).

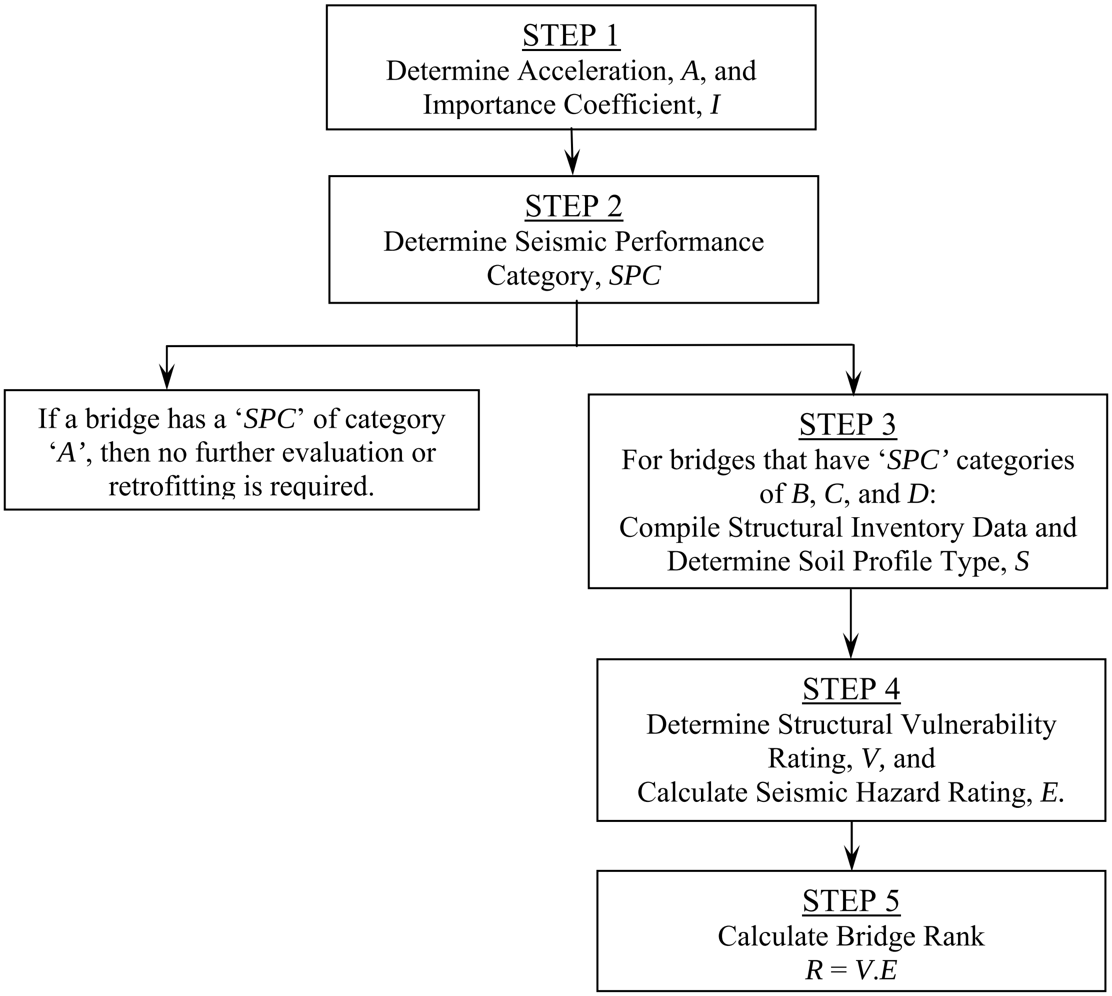
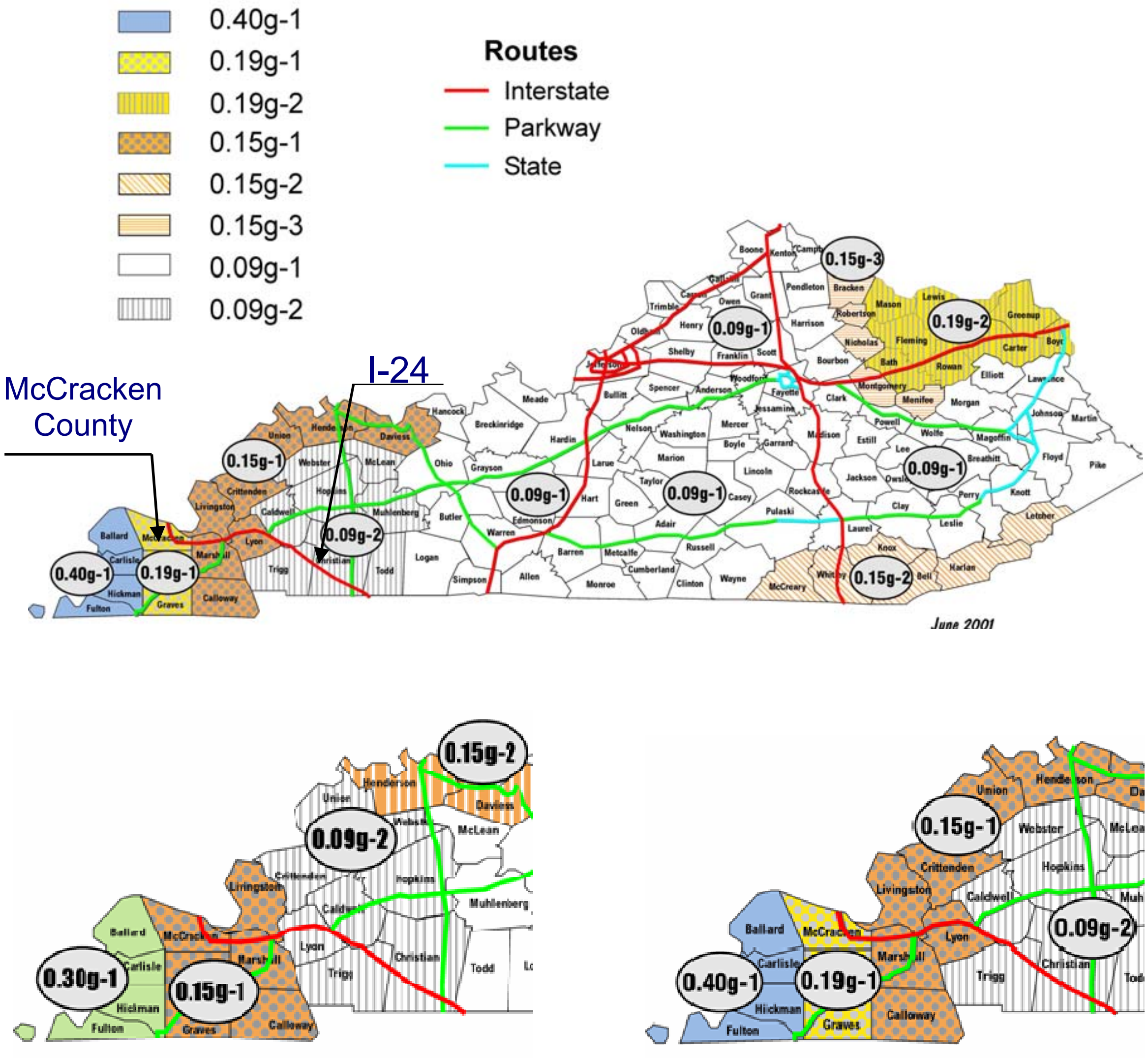


Fig. 4 Seismic Rating System

STEP 1: Determination of Acceleration (A) and Importance coefficient (I)

Since bridge structures are attached to the earth, they will typically move back and forth rather irregularly during a major earthquake. This movement can be described by a time history for: (a) displacement; (b) velocity; and (c) acceleration. Most building codes prescribe how much horizontal force a building should withstand due to a design earthquake. The horizontal force is typically related to the ground acceleration. The peak ground acceleration (PGA) is the maximum acceleration experienced by the building structure during the course of the earthquake motion.



b) *Predicted PGA for the counties through which I-24 passes in Western Kentucky during a 50-year seismic event*

c) *Predicted PGA for the counties through which I-24 passes in Western Kentucky during a 250-year seismic event*

Fig. 5 Predicted "*Peak Ground Acceleration*" (*PGA*) of All Counties in the Commonwealth of Kentucky during a 50-year and a 250-year Seismic Events

Peak ground acceleration contour maps, which are used to define the seismic zones and response spectra, are provided for all counties in Kentucky (Street et al. 1996). The peak ground acceleration is a function of the acceleration (*A*) coefficient and the gravitational acceleration constant (*g*), where g = 9.81 m/sec^2 or 386 in/sec^2. The peak ground acceleration contour maps are essential for the seismic design of new bridges and the seismic evaluation of existing bridges. The peak ground accelerations (PGA) for the 50-year and the 250-year events, which were used for the bridges along I-24 in western Kentucky are based on the identification maps for the 50-year and the 250-year events derived by Street et al. (1996). The peak ground accelerations for the 50-year and the 250-year events range from 0.09 to 0.015 (Fig. 5 and Table 1). The peak ground accelerations for the 500-year event range from 0.09 to 0.019 (Fig. 5).

Two categories, known as '*essential'* and '*standard'*, are used to describe the Importance coefficient (*I*) (Buckle and Friedland, 1995). Bridges classified as '*essential'* are bridges that must remain functional and operational after an earthquake event. All the other bridges are categorized as '*standard'*. Since I-24 has been designated as a priority and an emergency route, all bridges along I-24 are therefore considered as '*essential'* bridges.

Table 1 Peak Ground Acceleration (*PGA*) and Seismic Performance Category, *SPC*

County	Seismic Events			
	50-Years[1]		250-Years[1]	
	PGA	***SPC***	***PGA***	***SPC***
Christian	0.09g	*B*	0.09g	*B*
Trigg	0.09g	*B*	0.09g	*B*
Caldwell	0.09g	*B*	0.09g	*B*
Lyon	0.09g	*B*	0.15g	*C*
Marshall	0.15g	*C*	0.15g	*C*
McCracken	0.15g	*C*	0.15g	*C*
Livingston	0.15g	*C*	0.15g	*C*

[1] 90% probability of not being exceeded in the specified years

STEP 2: Determination of Seismic Performance Category

Table 2 is used to determine the Seismic Performance Category, *SPC,* based primarily on the Acceleration (*A*) and Importance (*I*) coefficients. Table 2 shows that all the I-24 bridges have a C classification.

Table 2 Classification of Seismic Performance Category, *SPC*
(Seismic Retrofitting Manual, Table 1)

Acceleration Coefficient (A)	Importance Classification (I)	
	Essential	Standard
$A \leq 0.09$	B	A
$0.09 < A \leq 0.19$	C	B
$0.19 < A \leq 0.29$	C	C
$0.29 < A$	D	C

STEP 3: Soil Profile Type or Site (S) coefficients and Structural Inventory Data

Table 3 shows the soil profile types or site coefficient, *S* that may be applicable for the I-24 bridges in western Kentucky.

Table 3 Soil Profile Type and Site Coefficient, *S*
(Seismic Retrofitting Manual, Table 3)

Soil Type	Soil Profile	Site Coefficient (S)
I	Rock or stiff soils. Soil depth less than 60 m (200 ft)	1.0
II	Stiff cohesive or deep cohesionless soil. Soil depth exceeds 60 m (200 ft)	1.2
III	Soft to medium stiff clays and sands. Soil depth exceeds 9 m (30 ft)	1.5
IV	Soft clays or silts. Soil depth exceeds 12 m (40 ft)	2.0

STEP 4: Structural Vulnerability Rating (V) and Seismic Hazard Rating (E)

Structural vulnerability rating, V, is determined based on four bridge components: (a) the connections, bearings, and seats; (b) columns and foundations; (c) abutments; and (d) soil type and characteristics. Fig. 6 illustrates a flow chart to show how to determine structural vulnerability rating (V). The structural vulnerability rating for the other components in the bridges that are susceptible to failure, V_2, is calculated from the individual component ratings as follows:

$$V_2 = CVR + AVR + LVR \leq 10$$

Where, CVR = column vulnerability rating
AVR = abutment vulnerability rating
LVR = liquefaction vulnerability rating

Further details on how to determine the structural vulnerability rating can be found in Section 2.3.1.1 of the Seismic Retrofitting Manual (Buckle and Friedland, 1995). The seismic hazard rating (E) is calculated using the following equation:

$$E = 12.5 \cdot A \cdot S \leq 10 \quad \text{(Seismic Retrofitting Manual, Eq. 2-4)}$$

STEP 5: Calculation of Bridge Rank

The bridge rank (R) is calculated based on the structural vulnerability rating (V) and the seismic hazard rating (E). Each rating (V and/or E) ranges from 0 to 10 and the rank (R) is found by multiplication of these two ratings:

$$R = V \cdot E \qquad \text{(Seismic Retrofitting Manual, Eq. 2-2)}$$

Since both of V and E range from 0 to 10, the minimum and maximum values for the rank, R, shall then be 0 and 100, respectively, where zero stands for the lowest risk and 100 stands for the highest risk. In general, the higher the rank, R, the greater the need for detailed seismic evaluation and potential for retrofitting needs.

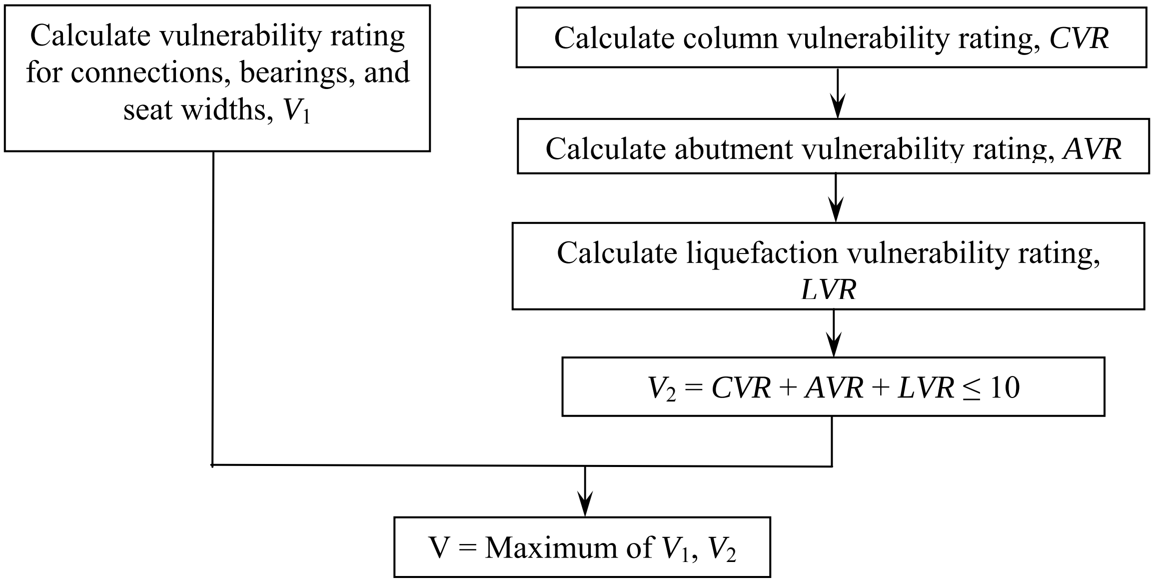


Fig. 6. Structural Vulnerability Rating, *V*
(Seismic Retrofitting Manual, Figure 8)

6. SEISMIC RANKING OF BRIDGES ALONG I-24 IN WESTERN KENTUCKY

Table 4 presents the resulting preliminary seismic evaluation and ranking of the 127 bridges along I-24 in western Kentucky for the 50-years and the 250-years. All details and records of the preliminary seismic ranking/rating of bridges along I-24 in western Kentucky are shown in the accompanied report, KTC-06-22/SPR206-99-3F that is entitled: “Preliminary Seismic Evaluation and Ranking of Bridges along I-24 in Western Kentucky”.

Table 4 Preliminary Seismic Ranking of Bridges along I-24 in Western Kentucky

County	BIN[1,2]	Year Built	Seismic Events			
			50-Year		250-Year	
			PGA[3]	Ranking[4]	PGA[3]	Ranking[4]
Livingston	70-0024-B00061	1974	0.15g	0	0.15g	0
	70-0024-B00062 & 70-0024-B00062 P	1977	0.15g	0	0.15g	0
	70-0024-B00063 & 70-0024-B00063 P	1977	0.15g	38	0.15g	38
	70-0453-B00064 & 70-0453-B00064 P	1976	0.15g	14	0.15g	14
Lyon	72-0024-B00035 & 72-0024-B00035 P	1697	0.09g	0	0.15g	0
	72-0024-B00036 & 72-0024-B00036 P	1969	0.09g	7	0.15g	11
	72-0024-B00037 & 72-0024-B00037 P	1976	0.09g	7	0.15g	11
	72-0024-B00039 & 72-0024-B00039 P	1976	0.09g	0	0.15g	0
	72-0024-B00041 & 72-0024-B00041 P	1971	0.09g	14	0.15g	23
	72-0024-B00044 & 72-0024-B00044 P	1967	0.09g	11	0.15g	19
	72-0024-B00048 & 72-0024-B00048 P	1967	0.09g	7	0.15g	11
	72-5123-B00046 & 72-5123-B00046 P	1967	0.09g	0	0.15g	0
	72-9001-B00049 & 72-9001-B00049 P	1976	0.09g	0	0.15g	0
	72-0093-B00042	1976	0.09g	0	0.15g	0

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[1] As defined in the Kentucky Transportation Cabinet (KyTC) Bridge Inventory

[2] The letter ‘P’ stands for parallel bridge

[3] The peak ground acceleration (PGA) is as defined in Street et al. (1996)

[4] The ranking methodology and procedure system is described in Chapter 2. A scale from zero (lowest risk) to 100 (highest risk) is employed.

Table 4 (Cont'd) Preliminary Seismic Ranking of Bridges along I-24 in Western Kentucky

County	BIN[1,2]	Year Built	Seismic Events			
			50-Year		250-Year	
			PGA[3]	Ranking[4]	PGA[3]	Ranking[4]
Lyon	72-0293-B00043	1976	0.09g	11	0.15g	19
	72-0295-B00038	1976	0.09g	7	0.15g	11
	72-0810-B00033	1976	0.09g	11	0.15g	19
	72-0903-B00047	1967	0.09g	11	0.15g	19
	72-5039-B00040	1976	0.09g	8	0.15g	14
	72-5118-B00045	1967	0.09g	0	0.15g	0
	72-5225-B00032	1977	0.09g	8	0.15g	14
	72-5229-B00034	1976	0.09g	11	0.15g	19
Caldwell	17-0139-B00065	1970	0.09g	11	0.09g	11
	17-0276-B00066 & 17-0276-B00066 P	1971	0.09g	0	0.09g	0
Marshall	79-0024-B00111	1967	0.15g	11	0.15g	11
	79-0024-B00109	1970	0.15g	19	0.15g	19
	79-0095-B00112	1967	0.15g	19	0.15g	19
	79-1042-B00081 & 79-1042-B00081 P	1966	0.15g	19	0.15g	19
	79-1610-B00092	1967	0.15g	19	0.15g	19
	79-0024-B00116 & 79-0024-B00116 P	1970	0.15g	11	0.15g	11
	79-0024-B00117 & 79-0024-B00117 P	1972	0.15g	19	0.15g	19
	79-0024-B00118 & 79-0024-B00118 P	1969	0.15g	38	0.15g	38
	79-0024-B00136	1973	0.15g	0	0.15g	0
	79-0024-B00082 & 79-0024-B00082 P	1964	0.15g	0	0.15g	0

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[1] As defined in the Kentucky Transportation Cabinet (KyTC) Bridge Inventory

[2] The letter 'P' stands for parallel bridge

[3] The peak ground acceleration (PGA) is as defined in Street et al. (1996)

[4] The ranking methodology and procedure system is described in Chapter 2. A scale from zero (lowest risk) to 100 (highest risk) is employed.

Table 4 (Cont'd) Preliminary Seismic Ranking of Bridges along I-24 in Western Kentucky

County	BIN[1,2]	Year Built	Seismic Events			
			50-Year		250-Year	
			PGA[3]	Ranking[4]	PGA[3]	Ranking[4]
Marshall	79-0024-B00113 & 79-0024-B00113 P	1967	0.15g	11	0.15g	11
	79-0024-B00114 & 79-0024-B00114 P	1974	0.15g	11	0.15g	11
	79-0024-B00115 & 79-0024-B00115 P	1969	0.15g	0	0.15g	0
Trigg	111-0024-B00027 & 111-0024-B00027 P	1969	0.09g	0	0.09g	0
	111-0024-B00044 & 111-0024-B00044 P	1969	0.09g	0	0.09g	0
	111-0024-B00048 & 111-0024-B00048 P	1970	0.09g	0	0.09g	0
	111-0024-B00043	1968	0.09g	11	0.09g	11
	111-0024-B00045	1979	0.09g	11	0.09g	11
	111-0024-B00050	1967	0.09g	0	0.09g	0
	111-6049-B00047	1969	0.09g	11	0.09g	11
	111-6051-B00049	1969	0.09g	0	0.09g	0
McCracken	73-0024-B00115 & 73-0024-B00115 P	1971	0.15g	29	0.19g	36
	73-0024-B00116 & 73-0024-B00116 P	1975	0.15g	14	0.19g	18
	73-0024-B00118 & 73-0024-B00118 P	1975	0.15g	14	0.19g	18
	73-0024-B00119 & 73-0024-B00119 P	1971	0.15g	14	0.19g	18
	73-0024-B00120 & 73-0024-B00120 P	1975	0.15g	14	0.19g	18
	73-0068-B00060 & 73-0068-B00060 P	1968	0.15g	14	0.19g	29
	73-0024-B00117	1972	0.15g	0	0.19g	0
	73-0062-B00121	1971	0.15g	14	0.19g	18
	73-0024-B00113	1974	0.15g	14	0.19g	48
	73-0131-B00009	1968	0.15g	14	0.19g	19

[1] As defined in the Kentucky Transportation Cabinet (KyTC) Bridge Inventory

[2] The letter 'P' stands for parallel bridge

[3] The peak ground acceleration (PGA) is as defined in Street et al. (1996)

[4] The ranking methodology and procedure system is described in Chapter 2. A scale from zero (lowest risk) to 100 (highest risk) is employed.

Table 4 (Cont') Preliminary Seismic Ranking of Bridges along I-24 in Western Kentucky

County	BIN[1,2]	Year Built	Seismic Events			
			50-Year		250-Year	
			PGA[3]	Ranking[4]	PGA[3]	Ranking[4]
McCracken	73-0787-B00064	1966	0.15g	14	0.19g	18
	73-0994-B00122	1971	0.15g	19	0.19g	24
	73-3075-B00065	1966	0.15g	38	0.19g	48
	73-0024-B00101 & 73-0024-B00101 P	1968	0.15g	14	0.19g	18
	73-0024-B00102 & 73-0024-B00102 P	1969	0.15g	23	0.19g	29
	73-0024-B00103 & 73-0024-B00103 P	1969	0.15g	11	0.19g	14
	73-0024-B00104 & 73-0024-B00104 P	1968	0.15g	14	0.19g	18
	73-0024-B00105 & 73-0024-B00105 P	1969	0.15g	11	0.19g	14
	73-0024-B00107 & 73-0024-B00107 P	1967	0.15g	29	0.19g	36
	73-0024-B00111 & 73-0024-B00111 P	1971	0.15g	0	0.19g	0
	73-0024-B00112 & 73-0024-B00112 P	1971	0.15g	11	0.19g	14
	73-0024-B00114 & 73-0024-B00114 P	1963	0.15g	28	0.19g	36
Christian	24-0024-B00090 & 24-0024-B00090 P	1976	0.09g	8	0.09g	8
	24-0024-B00122 & 24-0024-B00122 P	1968	0.09g	0	0.09g	0
	24-0024-B00125 & 24-0024-B00125 P	1972	0.09g	11	0.09g	11
	24-0024-B00129 & 24-0024-B00129 P	1969	0.09g	8	0.09g	8
	24-0695-B00124	1969	0.09g	0	0.09g	0
	24-0024-B00130 & 24-0024-B00130 P	1968	0.09g	0	0.09g	0
	24-0024-B00132 & 24-0024-B00132 P	1971	0.09g	8	0.09g	8
	24-0024-B00128	1969	0.09g	8	0.09g	8
	24-0024-B00133	1971	0.09g	8	0.09g	8

[1] As defined in the Kentucky Transportation Cabinet (KyTC) Bridge Inventory

[2] The letter 'P' stands for parallel bridge

[3] The peak ground acceleration (PGA) is as defined in Street et al. (1996)

[4] The ranking methodology and procedure system is described in Chapter 2. A scale from zero (lowest risk) to 100 (highest risk) is employed.

Table 4 (Cont') Preliminary Seismic Ranking of Bridges along I-24 in Western Kentucky

County	BIN[1,2]	Year Built	Seismic Events			
			50-Year		250-Year	
			PGA[3]	Ranking[4]	PGA[3]	Ranking[4]
Christian	24-0024-B00134	1971	0.09g	8	0.09g	8
	24-0107-B00127	1967	0.09g	8	0.09g	8
	24-0115-B00131	1970	0.09g	8	0.09g	8
	24-0164-B00123	1968	0.09g	11	0.09g	11
	24-0272-B00121	1968	0.09g	11	0.09g	11

[1] As defined in the Kentucky Transportation Cabinet (KyTC) Bridge Inventory
[2] The letter 'P' stands for parallel bridge
[3] The peak ground acceleration (PGA) is as defined in Street et al. (1996)
[4] The ranking methodology and procedure system is described in Chapter 2. A scale from zero (lowest risk) to 100 (highest risk) is employed.

7. I-24 HIGHWAY BRIDGES SELECTED FOR DETAILED SEISMIC EVALUATION PROCESS

The seismic rating or ranking, *R,* of the I-24 bridges in Western Kentucky falls between 0 and 48 on a scale of 100. The average rating, *R*, of all bridges is approximately 13. Based on the ranking system, the bridges, with a ranking of 14 or higher, are selected for further detailed seismic evaluation as indicated in Table 5.

Table 5 Selected I-24 bridges for Detailed Seismic Evaluation for the 250-Year Event

Bridge Identification Number (BIN)	Bridge	Year Built	Ranking
73-0024-00112 73-0024-00112 P*	I-24 over US45	1971	14
73-0068-00060 73-0068-00060 P*	US68-US62 Connector	1968	24
73-0024-00102 73-0024-00102 P*	Relocated Cairo Road	1969	29
73-0024-00120 73-0024-00120 P*	I-24 over Clarks River	1975	29
73-0024-00107 73-0024-00107 P*	Perkin Creek Channel Change	1967	36
73-0024-00115 73-0024-00115 P*	I-24 over Island Creek Road	1971	36
73-3075-00065	I-24 over Sheehan Road	1966	48
73-0024-00113	I-24 over Elmdale Road	1974	48

*: Bridges designated with the letter P are parallel bridges.

8. DETAILED SEISMIC EVALUATION OF I -24 BRIDGES

The Seismic Retrofitting Manual (Buckle and Friedland, 1995) was used as a guide for seismic evaluation of the selected I-24 bridges for detailed evaluation. The Manual proposes two methods known as the Capacity/Demand (*C/D*) ratio method and the Lateral Strength method for the seismic evaluation of those bridges requiring a detailed analysis based on the their Seismic Performance Category (*SPC*).

In general, the Lateral Strength method considers the entire bridge system, whether individual segments or frames of the bridge between expansion joints, as a single structural system. The structural system is then evaluated using an incremental collapse mechanism approach (Buckle and Friedland, 1995, Section 3.3.3).

The Capacity/Demand (*C/D*) ratio method, on the other hand, evaluates the ability of the individual bridge components (expansion joints, bearings, columns, footings, etc.) to resist the design earthquake. In general, the seismic '*Demands*', *D,* of the individual components are determined from an elastic spectral analysis. The seismic '*Capacities*', *C*, of the individual components are computed at their nominal ultimate values without considering the capacity reduction factors, ϕ, (Buckle and Friedland, 1995, Section 3.4). The two terms, '*capacities' (C)* and the '*demands*' (*D),* can be used to represent forces, displacements, and other quantities that may define the performance of the bridge. In this method, a calculated *C/D* ratio of less than 1.0 indicates that a component failure may occur during the design earthquake, and consequently, retrofitting of such components may be required.

The *C/D* method typically results in conservative retrofitting measures, which lead to higher costs. The lateral strength method, on the other hand, yields generally more accurate results, hence lower retrofitting costs (Harik et al., 1997). However, due to the complex nature of the lateral strength method, the Capacity/Demand, *C/D,* method is often preferred, and therefore was adopted for the detailed analyses of those selected bridges in Table 5.

8.1 CAPACITY/DEMAND (*C/D*) RATIO METHOD

Bridge components that may possess potential for seismic deficiency during a major earthquake require quantitative evaluation. The quantitative evaluation is satisfied by computing the seismic *C/D* ratios for the following bridge components:

(1) Expansion joints and/or bearings;
(2) Columns, piers, and/or footings;
(3) Abutments; and
(4) Foundation.

Only items (1) and (2) were evaluated and reported in this section of the study. However, the stability analysis of the bridge embankments is handled in a later section of this report.

The *demands* (forces and/or displacements) of the individual bridge components were first calculated. Three-dimensional bridge models were created for the finite element analysis. This process was performed with the aid of the commercially available structural analysis computer program, SAP2000 (Wilson E.L., 1998). The demands of the components are derived from SAP2000. A schematic drawing showing the three-orthogonal directions of each bridge is presented in Fig. 7.

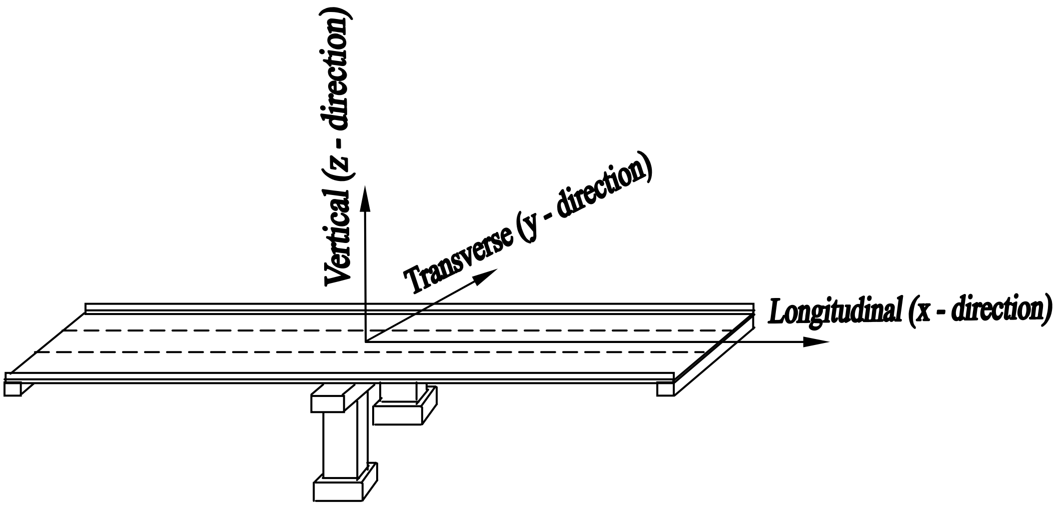


Fig. 7 Longitudinal, Transverse, and Vertical Directions of a Bridge along I-24 in Western Kentucky

In general, the longitudinal direction lies along the centerline of the bridge, and the transverse direction is then the perpendicular direction to the longitudinal axis, as shown in Fig. 7. Once the seismic demands were calculated in each direction for the specified individual bridge component, the demands were then combined to produce an overall demand (*D*) on the individual component. The combination of the orthogonal seismic force and/or displacement demands was required to account for the directional uncertainty of the earthquake motions and the simultaneous occurrence of earthquakes in two perpendicular directions (Buckle and Friedland, 1995, Section 3.3.2.4). The larger of the following two combinations of seismic demands were used for further analysis:

- Combination (1): 100% of longitudinal demands plus 30% of transverse demands
- Combination (2): 100% of transverse demands plus 30% of longitudinal demands

Guidelines that govern the capacity of the individual bridge components were given in 'Section 3.6' and 'Appendix A' of the Seismic Retrofitting Manual (Buckle and

Friedland, 1995). A list of the capacity/demand ratios for the detailed seismic evaluation is presented in Table 6.

Table 6 Capacity/Demand Ratios for Detailed Seismic Evaluation

No.	Symbol	Definition	Seismic Retrofitting Manual
1	r_{bd}	Displacement ratio for bearing/joint	Sections 3.6.2 & A.4.2
2	r_{bf}	Force ratio for bearing/joint	Sections 3.6.2 & A.4.3
3	r_{ec}	Force ratio for column	Sections 3.6.3 & A.5
4	r_{ef}	Force ratio for footing	Sections 3.6.3 & A.5
5	r_{ca} (for bent caps)	Anchorage length ratio for bent cap	Sections 3.6.3 & A.5.1
6	r_{ca} (footing)	Anchorage length ratio for footing	Sections 3.6.3 & A.5.1
7	r_{sc}	Splice length ratio for column	Sections 3.6.3 & A.5.2
8	r_{cv}	Shear ratio for column	Sections 3.6.3 & A.5.3
9	r_{cc}	Confinement ratio for transverse reinforcement	Sections 3.6.3 & A.5.4
10	r_{fr}	Footing rotation and/or yielding ratio	Sections 3.6.3 & A.5.5

8.2 FINITE ELEMENT MODELING WITH SAP 2000

Creating Models with SAP 2000

The dynamic responses (i.e. displacements and forces) of the 14 selected bridges were calculated using ‘SAP 2000’. Using the available wide variety of analytical options in the 3-D object-based graphical modeling environment of ‘SAP 2000’ made it easier to perform the analyses as a result of the relatively quick generation of the finite element structural models. The following procedures were followed:

1) Set up the 3-D Bridge Model
2) Define the Material Properties
3) Define the Sections
4) Define and Assign the Static Loads
5) Define the Time History Response Spectra
6) Perform the Analysis and study the Output

8.3 SUMMARY OF THE DETAILED SEISMIC EVALUATION OF THE US68-US62 CONNECTOR BRIDGE OVER I-24 IN McCRACKEN COUNTY, KY

Based on the ranking system, the bridges, with a ranking of 14 or higher, were selected for the detailed seismic evaluation. This section of the study is devoted to provide the complete evaluation process for the US68-US62 Connector Bridge over I-24 in McCracken County, KY. The US68-US62 Connector Bridge is a sample for the detailed evaluation process that was performed on all the 14 bridges. The remaining bridges are handled in a similar way.

Fig. 8 shows a three-dimensional view of the US68-US62 Connector Bridge over I-24 in McCracken County, KY. The bridge is a continuous bridge with two equal spans of 91.5 ft. The bridge was constructed in 1968. The superstructure consists of five steel plate I-girders supporting an eight-inch concrete bridge deck. The interior pier is made up of three columns supported on a pile footing (Fig. 9). The footing pedestal has a thickness equal to that of the column, 36 in. Soft to medium-stiff clays and sands were found at the bridge site.

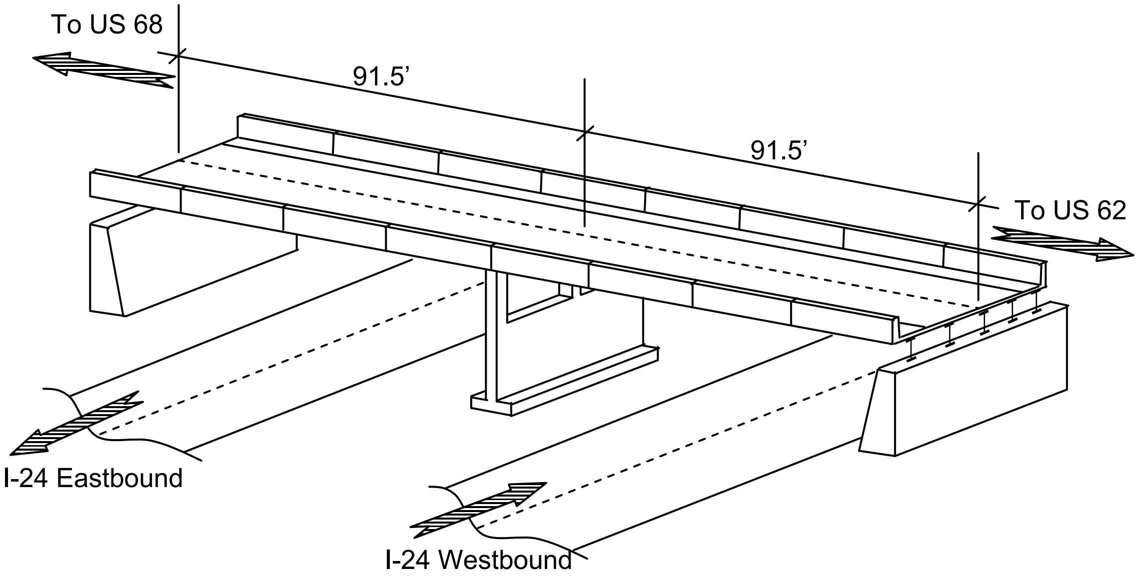


Fig. 8 U.S. 68- U.S. 62 Connector Bridge over I-24 in McCracken County in Western Kentucky

Based on the 250–year seismic event, which is shown in Fig. 5, the acceleration coefficient, *A*, for McCracken County is 0.19*g*. Since the bridge is located along a priority route, this bridge is viewed as “*essential*” based on AASHTO specifications. This combination of acceleration coefficient and importance classification results in a seismic performance category (*SPC*) of *C* (Buckle and Friedland, 1995, Section 1.5).

Section 3.3.2.1 of the Manual (Buckle and Friedland, 1995) specifies the minimum dynamic analysis required for a bridge. The US68-US62 Connector is a "*regular*" bridge by the Manual definition. Based on the criterion set forth in the Manual, a '*regular*' bridge has less than seven spans, no abrupt or unusual changes in weight, stiffness, or geometry, and no large changes in these parameters from span-to-span or support-to-support. Therefore, a uniform-load or single-mode spectral method was specified as the minimum required analysis.

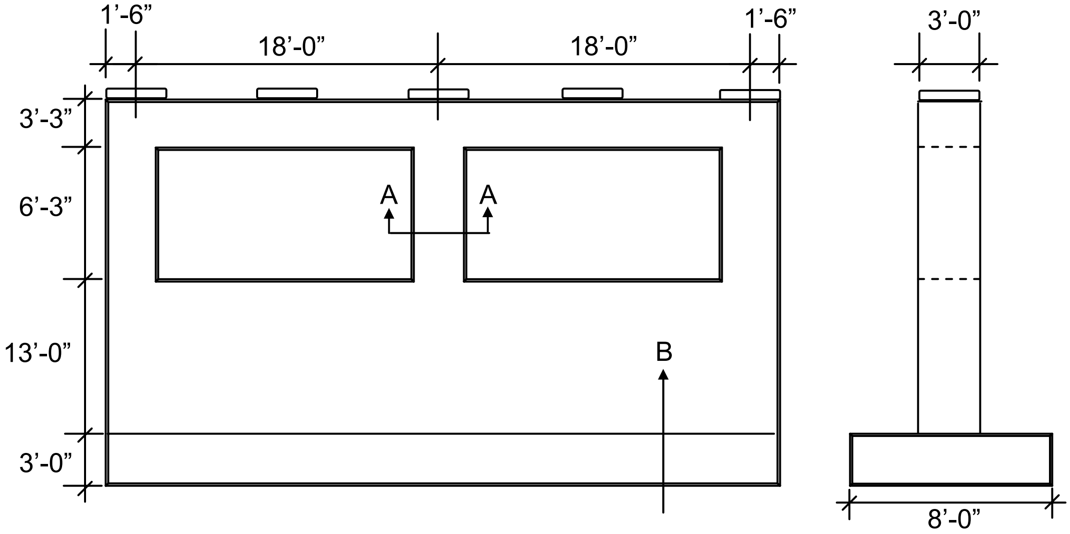


Fig. 9 Dimension of the Substructure of the US68-US62 Connector Bridge in Western Kentucky

Table 6 lists the Capacity/Demand Ratios that are required for the Detailed Seismic Evaluation, wherever applicable. For US68-US62 Connector Bridge over I-24 in McCracken County, KY, almost all the *C/D* ratios listed in Table 6 were investigated.

The seismic *demands* of the individual bridge components are determined using 'SAP 2000'. A three-dimensional bridge model was generated for this purpose. The mode shapes and the natural frequencies of the bridge were determined. The first periods corresponding to the three orthogonal directions were determined. The seismic demands were obtained from the results generated by the computer analysis. A summary of the analysis results for the bridge is shown in Table 7. The suggested location and type of retrofit are shown in Fig. 10.

Table 7 C/D ratios for the US 68 – US 62 Connector over I-24 in Western Kentucky

Summary of the detailed seismic evaluation of bridge#73-0068-00060, I-24 Bridge US 68 – US 60 Connector in McCracken County, KY (Span 1=91.5 ft and Span 2=91.5 ft).		
CAPACITY/DEMAND RATIOS FOR EXPANSION JOINTS/BEARINGS		
		Comment:
2. Displacement Capacity/Demand Ratio, r_{bd}	$1.50 > 1.0$	*Capacity is adequate*
3. Force Capacity/Demand Ratio, r_{bf}	$1.23 > 1.0$	*Capacity is adequate*
CAPACITY/DEMAND RATIOS FOR COLUMNS AND FOOTING		
		Comment:
4. Force Capacity/Demand Ratio for Column, r_{ec}	$0.56 < 1.0$	***Strengthening required*** [a]
5. Force Capacity/Demand Ratio for Footing, r_{ef}	$10.2 > 1.0$	*Capacity is adequate*
6. Anchorage Capacity/Demand Ratio at Bent Cap, $r_{ca(Cap)}$	$= 1.0$	*Capacity is adequate*
7. Anchorage Capacity/Demand Ratio at Footing, $r_{ca(Footing)}$	$= 1.0$	*Capacity is adequate*
8. Splice Capacity/Demand Ratio at Bent Cap, $r_{cs(Cap)}$	N/A[b]	*Not applicable* [b]
9. Splice Capacity/Demand Ratio at Footing, $r_{cs(Footing)}$	N/A[b]	*Not applicable* [b]
10. Transverse Confinement Capacity/Demand Ratio, r_{cc}	$1.12 > 1.0$	*Capacity is adequate*
11. Column Shear Capacity/Demand Ratio, r_{cv}	$1.57 > 1.0$	*Capacity is adequate*
12. Footing Rotation and/or Yielding Ratio, r_{fr}	-	*Not applicable* [c]

[a] As one possible option, the columns' capacity should to be increased to a minimum of 1635 kip-ft over a minimum distance of 4 ft from the top of the web wall shown in the shaded areas of Fig. 2.10

[b] Longitudinal reinforcement extends into the bent cap and footing pedestal

[c] Not evaluated since ref > 0.8 as proposed in the SR Manual

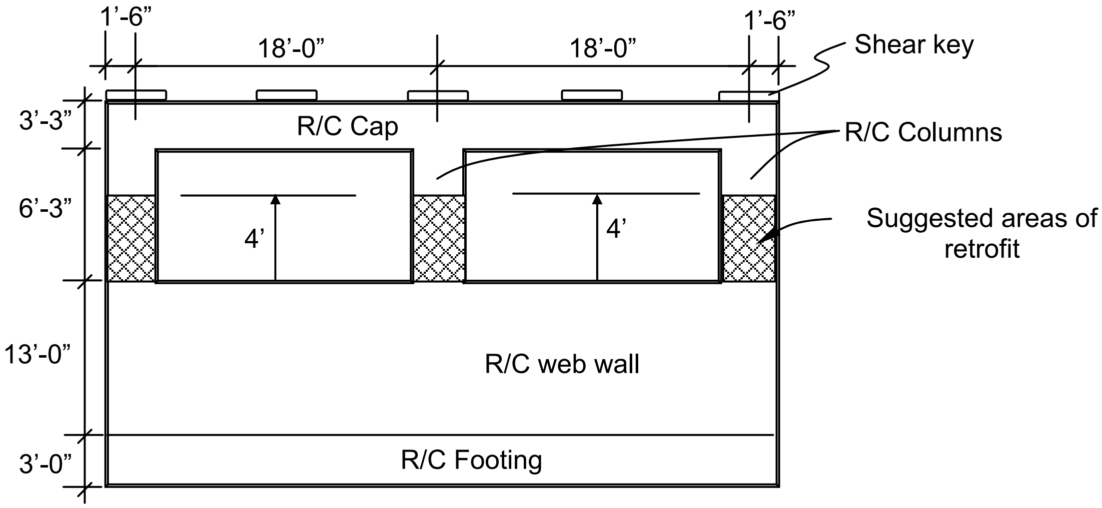


Fig. 10 Required Areas of Retrofit for the US68-US62 Connector Bridge in Kentucky
(an increase of the flexural capacity to 1635 k-ft is recommended for all columns)

8.4 SUMMARY OF THE RESULTS OF THE DETAILED SEISMIC EVALUATION OF THE SELECTED I-24 BRIDGES

Table 8 provides a summary of the seismic deficiencies of the analyzed bridges. Table 9 provides a summary for the seismic evaluation process for the 14 bridges that were considered for the detailed evaluation, with a rating of more than 14. Other details of the results and the required course of action, if any, can be found in the accompanied report, KTC-06-23/SPR206-99-4F that is entitled: "Detailed Seismic Evaluation of Bridges along I-24 in Western Kentucky".

It should be noted that the two pairs of bridges [73-0024-00102 (P) and 73-0024-00120 (P)] with a rank of 29 possess no seismic deficiency. All the other bridges in this investigation contained one or more forms of seismic deficiencies. This indicates that the rating system is an effective means in prioritizing highway bridges for seismic evaluation and retrofit processes. It is recommended that the following measures or course of actions be taken to overcome these deficiencies:

- Bearing seat deficiency – Bearing seat width or length be extended, and/or restrainer be provided to avoid loss of support due to excessive lateral movement;
- Column flexural deficiency – Columns be re-designed, re-sized, and/or strengthened. Isolated bearing seat may be considered to reduced lateral forces;
- Footing flexural deficiency – see column flexural deficiency;
- Column shear deficiency – see column flexural deficiency; and
- Column transverse confinement – see column flexural deficiency.

Table 8 Summary of Seismic Deficiencies of the Selected Bridges along I-24 for projected 250-Year Seismic Events.

Bridge Number (BIN)	Ranking	Seismic Deficiencies
73-0024-00112 73-0024-00112 P	14	- Bearing seat capacity
73-0068-00060 73-0068-00060 P	24	- Column flexural capacity
73-0024-00107 73-0024-00107 P	36	- Column flexural capacity
73-0024-00115 73-0024-00115 P	36	- Bearing seat capacity - Column flexural capacity - Footing flexural capacity
73-3075-00065	48	- Bearing seat capacity - Column flexural capacity
73-0024-00113	48	- Bearing seat capacity - Column flexural capacity - Column shear capacity - Column transverse confinement

Table 9 C/D ratios of the Selected I-24 Bridges along I-24 in Western Kentucky for 250 year event

C/D Ratios / BIN	Joints and/or Bearings		Columns and/or Footings									Bridge ranks
	r_{bd}	r_{bf}	r_{ec}	r_{ef}	r_{ca} (cap)	r_{ca} (footing)	r_{sc} (cap)	r_{sc} (footing)	r_{cv}	r_{cc}	r_{fr}	
73-0024-00112 73-0024-00112 P	**0.61**	4.42	1.30	1.03	1.0	1.0	-	-	2.60	1.97	-	14
73-0068-00060 73-0068-00060 P	1.50	1.23	**0.56**	10.2	1.0	1.0	-	-	1.12	1.57	-	24
73-0024-00102 73-0024-00102 P	1.63	1.90	-	-	-	-	-	-	-	-	-	29
73-0024-00120 73-0024-00120 P	1.07	2.50	1.20	1.74	1.0	1.0	-	-	2.40	2.59	-	29
73-0024-00107 73-0024-00107 P	1.78	8.24	**0.69**	-	-	-	-	-	1.38	3.44	-	36
73-0024-00115 73-0024-00115 P	**0.61**	4.64	**0.69**	**0.96**	1.0	1.0	-	-	1.38	1.41	-	36
73-3075-00065	**0.74**	3.81	**0.81**	1.05	1.0	1.0	-	-	1.62	1.92	-	48
73-0024-00113	**0.67**	1.0	**0.35**	1.13	1.0	1.0	-	-	**0.7**	**0.92**	-	48

Note: When C/D ratio is less than 1.0, retrofitting measure must be performed

9. SEISMIC RANKING OF EMBANKMENTS ALONG I-24 IN WESTERN KENTUCKY

Seismic stability analysis and retrofit of earth embankments, including site remediation, has been, to date primarily, focused on embankment dams and earth retaining structures (Buckle and Friedland, 1995). If a bridge embankment on a priority route is at a high failure risk, soil stabilization may be required depending on the importance of the bridge. The Seismic Retrofit Manual (Buckle and Friedland 1995) demonstrates techniques for assessing the seismic vulnerability of bridges with regard to technical and socio-economic issues. The seismic retrofit manual stipulates that for bridges near unstable slopes, detailed geotechnical investigations should be carried out to assess the potential for slope instability under seismic excitations. The required detailed investigations include material testing, borehole, and trenching to check for unstable layers and vertical fissures. However, for preliminary evaluation of bridges on priority routes the use of detailed geo-technical investigations and sophisticated models are typically limited because of the associated cost and effort.

There is a current interest in careful assessment of the "most critical" embankments along priority routes. In order to achieve this goal, a means of assessing which embankments qualify as "most critical" is required. Other than the work reported by the authors, almost no complete studies have been reported to identify and prioritize highway embankments that are susceptible to seismic failure. Data regarding soil types and depth of bedrock required for detailed seismic analysis and risk assessment are not available for the majority of the bridge embankments. The objective of this part of the study is to provide a simple methodology to conduct preliminary seismic assessment and ranking of bridge embankments in order to identify and prioritize embankments that are susceptible to failure along I-24 in western Kentucky.

Seismic vulnerability ranking and prioritization of embankments became feasible tasks through utilizing the outlines of the "Kentucky Embankment Stability Rating" (*KESR*) model. A ranking model that provides a priority list of embankments with the highest seismic risk of failure was generated. A step-by-step methodology was presented in a flowchart that was generated to assess the seismic vulnerability of multiple bridge embankments simultaneously. The embankment geometry, material, type of underlying soil, elevation of the natural ground line, elevation of upper level of bedrock, and expected seismic event in accordance with the associated seismic zone maps were the variables for each embankment. The methodology resulted in the calculation of the seismic slope stability capacity/demand (*C/D*) ratio, estimated displacement, and liquefaction potential of each bridge embankment. Three categories were identified to represent the failure risk of the embankments. When site-specific data for a bridge embankment was available, the data was used to obtain the list of seismically deficient embankments. When site-specific data for a bridge embankment was not available, the proposed methodology outlined approaches to estimate the information that is required to obtain the priority list.

The proposed methodology was applied to the 127 bridge embankments of I-24 in western Kentucky. The seismic vulnerability during projected 50-year, 250 year seismic events were investigated and the associated seismic performance criteria was examined. The Cumberland River Bridges and the Tennessee River Bridges were evaluated for the 250-year, 500 year seismic events. The embankments were categorized for the designated bridge sites according to their failure risk. A priority list that includes the most critical bridge embankments was then generated. It is understood that the resulting seismic risk of a specific embankment may not be very accurate due to the lack of or limited available data. However, the estimated data and strength parameters that were utilized shall be assessed by a qualified geo-technical engineer in order to ensure valid results.

The ranking model is useful for a quick sensitivity assessment of the effect of various site conditions, earthquake magnitudes, and site geometry on possible movement of designated embankments. The priority list will enable decision makers to decide on either carrying out further detailed evaluation or considering other appropriate actions for the bridge embankments with the highest seismic failure risk.

Based on this preliminary seismic evaluation of the I-24 embankments, it is recommended that the bridge embankments classified as 'critical' in Table 10 and Table 11 be further investigated through carrying out more detailed analysis. All other results of the preliminary seismic evaluation of the I-24 embankments are shown in the accompanied report, KTC-06-26/SPR206-99-7F that is entitled: "Seismic Evaluation and Ranking of Bridge Embankments along I-24 in Western Kentucky".

Table 10 Ranking of Critical Bridge Embankments along I-24 for the 50-Year Seismic Event

County	BIN[1,2]	PGA[3] (%g)	Slope Stability[4]		Liquefaction Potential[7]	Embankment Ranking[8]
			C/D[5] ratio	U^6 in (cm)		
Christian	24-0024-B00125 & 24-0024-B00125P	9	0.81	13.5 (34.2)	High	A1
	24-0024-B00090 & 24-0024-B00090P	9	0.78	1.5 (3.7)	High	A2
	24-0024-B00132 & 24-0024-B00132P	9	0.65	0.8 (2.0)	High	A3
Lyon	72-0024-B00035 & 72-0024-B00035P	15	0.96	0.2 (0.4)	High	A1
	72-5229-B00034	15	0.99	0.1 (0.2)	High	A2
	72-0024-B00044 & 72-0024-B00044P	15	1.14	0.0 (0.0)	High	A3
	72-0024-B00048 & 72-0024-B00048P	15	1.19	0.0 (0.0)	High	A4
	72-0024-B00039 & 72-0024-B00039P	15	1.29	0.0 (0.0)	High	A5
Trigg	111-0024-B00048 & 111-0024-B00048P	9	1.01	0.0 (0.0)	High	A1
Marshall	79-0024-B00117 & 79-0024-B00117P	15	0.77	35.4 (89.8)	High	A1
	79-0024-B00116 & 79-0024-B00116P	15	0.69	2.3 (5.8)	High	A2
	79-0024-B00113 & 79-0024-B00113P	15	0.83	0.8 (2.1)	High	A3
	79-0024-B00115 & 79-0024-B00115P	15	0.83	0.8 (2.1)	High	A4
	79-0095-B00112	15	0.87	0.4 (1.1)	High	A5
	79-0024-B00118 & 79-0024-B00118P	15	0.54	0.2 (0.4)	High	A6
	79-0024-B00114 & 79-0024-B00114P	15	0.96	0.1 (0.3)	High	A7
Caldwell	None of the bridges are ‘critical’.					

[1] As defined in the Kentucky Transportation Cabinet (KyTC) Bridge Inventory
[2] The letter ‘P’ stands for parallel bridges.
[3] PGA is the peak ground acceleration defined Street et al. (1996).
[4] Details for slope stability calculations are presented in Chapter 2.
[5] Capacity/demand ratio is defined in Chapter 2.
[6] Horizontal displacement (*u*) is calculated when C/D ratio is less than 1.0, or else *u* is equal zero.
[7] Details for liquefaction potential calculations are presented in Chapter 3.
[8] Only bridge embankments with a rank classification of A (critical) are listed herein. A bridge embankment with a ranking of A1 is more susceptible to damage than a bridge embankment with a ranking of A2 in that specific county, and so forth.

Table 10 (Cont'd) Ranking of Critical Bridge Embankments along I-24 for the 50-Year Seismic Event

County	BIN[1,2]	PGA[3] (%g)	Slope Stability[4]		Liquefaction Potential[7]	Embankment Ranking[8]
			C/D[5] ratio	U^6 in (cm)		
Livingston	70-0024-B00063 & 70-0024-B00063P	15	0.60	2.0 (5.1)	High	A1
	70-0024-B00062 & 70-0024-B00062P	15	0.85	0.6 (1.5)	High	A2
McCracken	73-0024-B00104 & 73-0024-B00104P	15	0.79	5.6 (14.3)	High	A1
	73-0024-B00103 & 73-0024-B00103P	15	0.81	2.7 (6.9)	High	A2
	73-0068-B00060 & 73-0068-B00060P	15	0.83	1.7 (4.4)	High	A3
	73-0787-B00064	15	0.83	1.7 (4.3)	High	A4
	73-0024-B00107 & 73-0024-B00107P	15	0.83	1.0 (2.4)	High	A5
	73-0024-B00105 & 73-0024-B00105P	15	0.86	0.9 (2.2)	High	A6
	73-0024-B00112 & 73-0024-B00112P	15	0.86	0.5 (1.3)	High	A7
	73-0024-B00102 & 73-0024-B00102P	15	0.90	0.4 (1.0)	High	A8
	73-0131-B00009	15	0.90	0.3 (0.8)	High	A9
	73-0024-B00111 & 73-0024-B00111P	15	0.92	0.3 (0.7)	High	A10
	73-0024-B00100	Bridge over the Ohio River and is beyond the scope of this study				

[1] As defined in the Kentucky Transportation Cabinet (KyTC) Bridge Inventory
[2] The letter 'P' stands for parallel bridges.
[3] PGA is the peak ground acceleration defined Street et al. (1996).
[4] Details for slope stability calculations are presented in Chapter 2.
[5] Capacity/demand ratio is defined in Chapter 2.
[6] Horizontal displacement (*u*) is calculated when C/D ratio is less than 1.0, or else *u* is equal zero.
[7] Details for liquefaction potential calculations are presented in Chapter 3.
[8] Only bridge embankments with a rank classification of A (critical) are listed herein. A bridge embankment with a ranking of A1 is more susceptible to damage than a bridge embankment with a ranking of A2 in that specific county, and so forth.

Table 11 Ranking of Critical Bridge Embankments along I-24 for the 250-Year Seismic Event

County	BIN[1,2]	PGA[3] (%g)	Slope Stability[4]		Liquefaction Potential[7]	Embankment Ranking[8]
			C/D[5] ratio	U^6 in (cm)		
Christian	24-0024-B00125 & 24-0024-B00125P	9	0.81	54.2 (137.7)	High	A1
	24-0024-B00090 & 24-0024-B00090P	9	0.78	5.7 (14.5)	High	A2
	24-0024-B00132 & 24-0024-B00132P	9	0.65	3.1 (7.8)	High	A3
Lyon	72-0024-B00035 & 72-0024-B00035P	15	0.83	3.2 (8.1)	High	A1
	72-5229-B00034	15	0.86	2.1 (5.4)	High	A2
	72-0024-B00044 & 72-0024-B00044P	15	0.96	0.4 (1.1)	High	A3
	72-0024-B00048 & 72-0024-B00048P	15	0.99	0.3 (0.8)	High	A4
	72-0024-B00039 & 72-0024-B00039P	15	1.05	0.0 (0.0)	High	A5
Trigg	111-0024-B00048 & 111-0024-B00048P	9	1.01	0.0 (0.0)	High	A1
	111-6051-B00049	9	2.35	0.0 (0.0)	High	A2
Marshall	79-0024-B00117 & 79-0024-B00117P	15	0.77	145.3 (369.1)	High	A1
	79-0024-B00116 & 79-0024-B00116P	15	0.69	8.9 (22.7)	High	A2
	79-0024-B00113 & 79-0024-B00113P	15	0.83	3.2 (8.1)	High	A3
	79-0024-B00115 & 79-0024-B00115P	15	0.83	3.2 (8.1)	High	A4
	79-0095-B00112	15	0.87	1.7 (4.3)	High	A5
	79-0024-B00118 & 79-0024-B00118P	15	0.54	0.7 (1.7)	High	A6
	79-0024-B00114 & 79-0024-B00114P	15	0.96	0.4 (1.1)	High	A7
	79-0024-B00109	15	2.22	0.0 (0.0)	High	A8
Caldwell	None of the bridges are ‘critical’.					

[1] As defined in the Kentucky Transportation Cabinet (KyTC) Bridge Inventory

[2] The letter ‘P’ stands for parallel bridges.

[3] PGA is the peak ground acceleration defined Street et al. (1996).

[4] Details for slope stability calculations are presented in Chapter 2.

[5] Capacity/demand ratio is defined in Chapter 2.

[6] Horizontal displacement (*u*) is calculated when C/D ratio is less than 1.0, or else *u* is equal zero.

[7] Details for liquefaction potential calculations are presented in Chapter 3.

[8] Only bridge embankments with a rank classification of A (critical) are listed herein. A bridge embankment with a ranking of A1 is more susceptible to damage than a bridge embankment with a ranking of A2 in that specific county, and so forth.

Table 11 (Cont'd) Ranking of Critical Bridge Embankments along I-24 for the 250-Year Seismic Event

County	BIN[1,2]	PGA[3] (%g)	Slope Stability[4]		Liquefaction Potential[7]	Embankment Ranking[8]
			C/D[5] ratio	*U*[6] in (cm)		
Livingston	70-0024-B00063 & 70-0024-B00063P	15	0.60	7.8 (19.9)	High	A1
	70-0024-B00062 & 70-0024-B00062P	15	0.85	2.3 (5.9)	High	A2
McCracken	73-0024-B00104 & 73-0024-B00104P	19	0.75	31.4 (79.8)	High	A1
	73-0024-B00103 & 73-0024-B00103P	19	0.76	15.6 (39.5)	High	A2
	73-0024-B00120 & 73-0024-B00120P	19	0.67	11.3 (28.7)	High	A3
	73-0024-B00118 & 73-0024-B00118P	19	0.77	10.7 (27.3)	High	A4
	73-0068-B00060 & 73-0068-B00060P	19	0.77	10.4 (26.3)	High	A5
	73-0787-B00064	19	0.78	10.1 (25.8)	High	A6
	73-0024-B00115 & 73-0024-B00115P	19	0.79	6.6 (16.8)	High	A7
	73-0024-B00107 & 73-0024-B00107P	19	0.76	6.1 (15.5)	High	A8
	73-0024-B00105 & 73-0024-B00105P	19	0.80	5.7 (14.5)	High	A9
	73-0024-B00112 & 73-0024-B00112P	19	0.79	3.5 (8.9)	High	A10
	73-0024-B00102 & 73-0024-B00102P	19	0.83	2.9 (7.3)	High	A11
	73-0131-B00009	19	0.84	2.5 (6.4)	High	A12
	73-0024-B00111 & 73-0024-B00111P	19	0.85	2.2 (5.5)	High	A13
	73-0024-B00100	Bridge over the Ohio River and is beyond the scope of this study				

[1] As defined in the Kentucky Transportation Cabinet (KyTC) Bridge Inventory

[2] The letter 'P' stands for parallel bridges.

[3] PGA is the peak ground acceleration defined Street et al. (1996).

[4] Details for slope stability calculations are presented in Chapter 2.

[5] Capacity/demand ratio is defined in Chapter 2.

[6] Horizontal displacement (*u*) is calculated when C/D ratio is less than 1.0, or else *u* is equal zero.

[7] Details for liquefaction potential calculations are presented in Chapter 3.

[8] Only bridge embankments with a rank classification of A (critical) are listed herein. A bridge embankment with a ranking of A1 is more susceptible to damage than a bridge embankment with a ranking of A2 in that specific county, and so forth.

10. DETAILED SEISMIC EVALUATION OF THE CUMBERLAND RIVER BRIDGES

The main objective of this part of the study is to assess the structural integrity of the I-24 parallel bridges at the Cumberland River crossing at the borders of Lyons and Livingston counties in western Kentucky (Fig. 11 and Fig. 12). Due to their importance, the bridges were evaluated for the 250-year event and the maximum credible 500-year event. The 250-year and the 500-year events are events that have a 90 % probability of not being exceeded in 250 years and 500 years, respectively. During the 250-year event, the bridges shall remain in the elastic range without any disruption to traffic. During the 500-year event, partial damage shall be permitted to the bridges, but they are to remain accessible to emergency and official vehicles. To achieve this objective, the scope of the work was divided into the following tasks: (1) field testing of the main bridges; (2) finite element modeling and calibration; (3) time-history seismic response analysis; and (4) seismic evaluation/retrofit for both the main and the approach spans of the bridges.

10.1 FIELD TESTING OF THE MAIN SPANS

The free vibration properties of the main bridges were determined through field ambient vibration testing under traffic and wind induced excitation. The purpose of the field-testing was to determine the natural frequencies and the mode shapes. The vibration properties were subsequently used as the basis for calibrating a finite element model that was specifically created for carrying out the seismic response analysis.

10.2 FINITE ELEMENT MODELING OF THE MAIN SPANS

A three-dimensional finite element model of the main bridges was used for free vibration and seismic response analysis. The model was calibrated by comparing the free vibration analysis results with the ambient vibration properties obtained from field-testing.

10.3 SEISMIC EVALUATION OF THE MAIN SPANS

After calibration of the main spans, the model was used for seismic response analysis. The three-dimensional model of the main bridges was subjected to the time histories of the projected 250-year and 500-year events to determine the maximum displacements at joints, stresses in members, and forces on the bearings.

10.4 SEISMIC EVALUATION OF THE APPROACH SPANS

Simple structural models were used to idealize the approach spans depending on the type of bearings that were mounted on the top of the piers. The mathematical models were considered as single degree of freedom (*SDOF*) systems. The mass of the *SDOF* system was considered as the summation of the mass of the superstructure and one-third the mass of the piers. The transverse stiffness and the longitudinal stiffness of the mathematical model was calculated in accordance with the Seismic Evaluation of Highway Bridges in Kentucky (Harik et al., 1997). The seismic response of the approach spans was carried out using the response spectrum method to determine the maximum forces and displacements.

10.5 RESULTS AND RECOMMENDATIONS

10.5.1 The 250-Year Event

The seismic analysis indicated that the main spans of the bridge can resist the 250-year event without yielding or loss-of-span at the supports. Consequently, retrofitting is not required for the main bridge members and bearings for the 250-year event (Fig. 11).

Fig. 11 Capacity of members and bearings of the main spans of the Cumberland River Bridges exceeds demand for projected 250-Year Seismic Event. [Consequently no retrofit is required]

The seismic analysis of the approach spans indicated that pier #1 can resist the 250-year event without yielding or unseating at supports. Consequently, no retrofitting is required. However, the anchor bolts of pier #2 cannot resist the applied shear forces during the 250-year event and retrofit should be considered. Retrofitting can be made by increasing the capacity of the shear bolts or by providing seismic isolation bearings (Fig. 12).

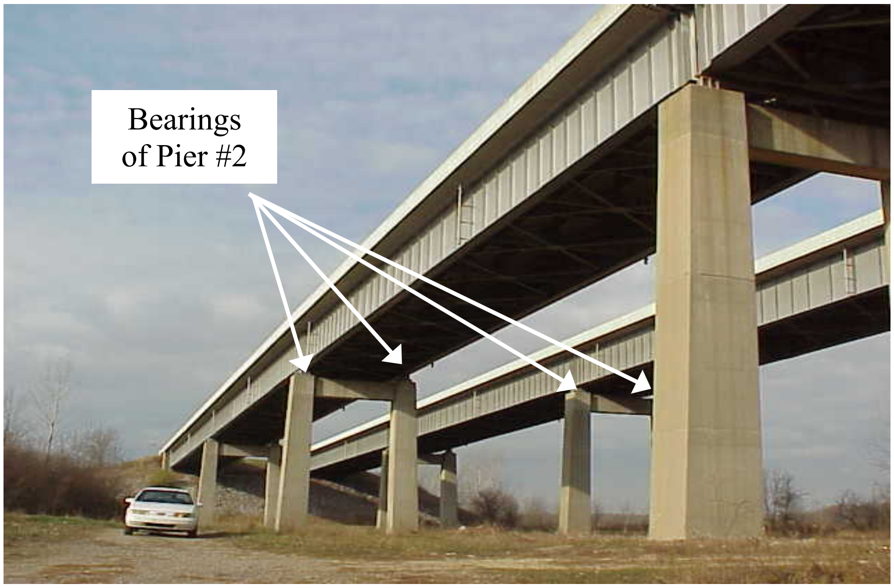


Fig. 12 Capacity of the members exceeds demand but demand of bearings of pier #2 exceeds capacity in the approach spans of the Cumberland River Bridges for projected 250-Year Seismic Event

10.5.2 The 500-Year Event

The seismic analysis indicates that the bridge members # 212 (shown in Fig. 13) of the main spans would yield due to the 500-year maximum credible event. The bearing shear bolts of both pier #4 and pier #5 would fail (Fig. 14). Thus, retrofit has to be provided for these members and bearings. Retrofitting can be made by increasing the capacity of the shear bolts or by providing seismic isolation bearings.

The seismic analysis of the approach spans indicates that pier #1 can resist the 500-year event without yielding or unseating at supports. Consequently, no retrofitting is required. The seismic analysis of the approach spans indicated that the anchor bolts of pier #2 cannot resist the applied shear forces during the 500-year event, and retrofit should be considered (Fig. 15). Retrofitting can be made by increasing the capacity of the shear bolts or by providing seismic isolation bearings.

All details of the seismic evaluation of the two parallel Cumberland River Bridges on the I-24 are shown in the accompanied report, KTC-06-25/SPR206-99-6F that is entitled: “Seismic Evaluation of the Cumberland River Bridges on I-24 in Western Kentucky”.

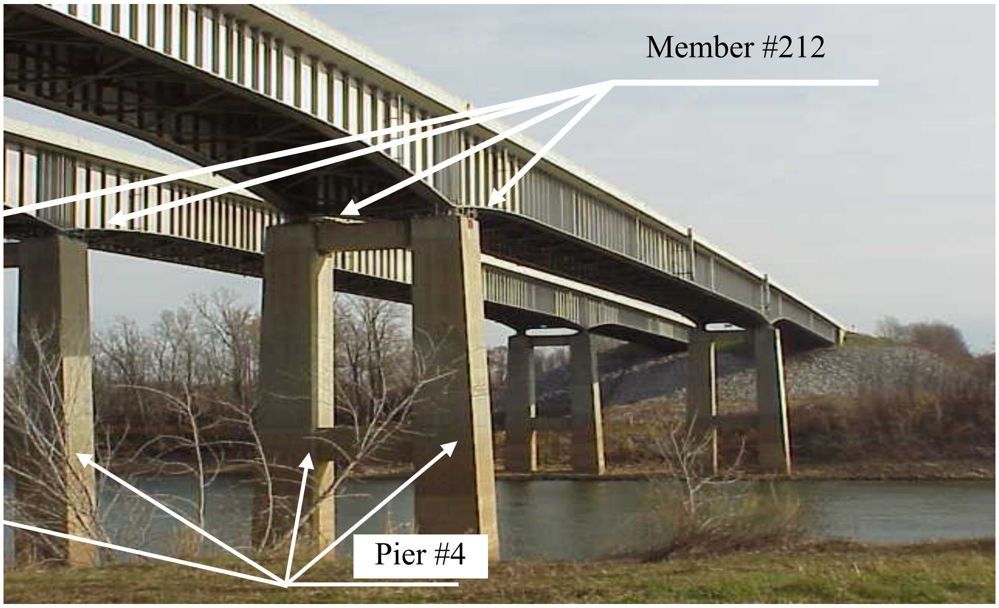


Fig. 13 Demand of the members #212 of the main spans of the Cumberland River Bridges exceeds capacity for projected 500-Year Seismic Event

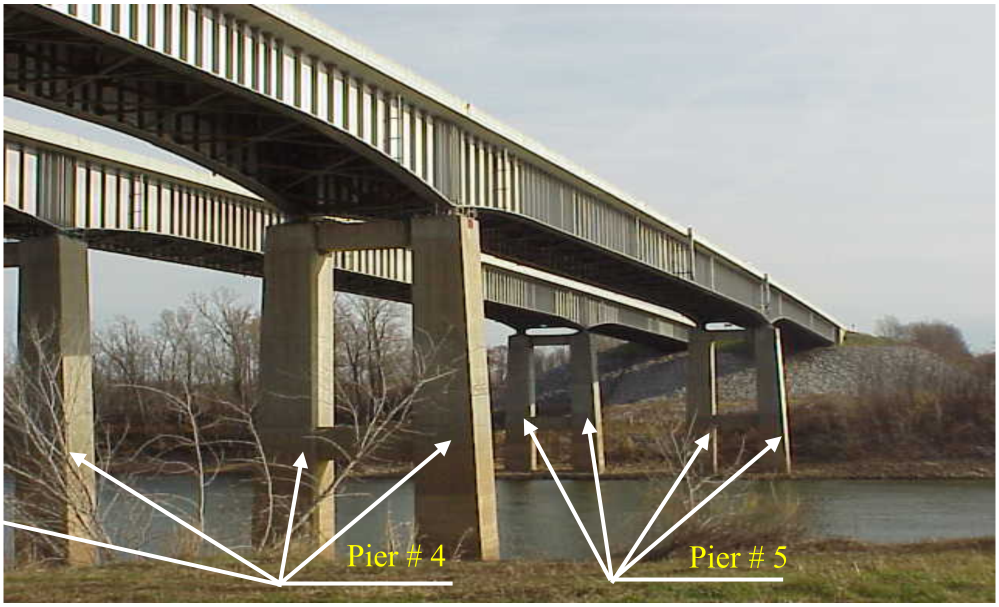


Fig. 14 Demand of bearings of pier #4 and #5 of the main spans of the Cumberland River Bridges exceeds capacity for projected 500-Year Seismic Event

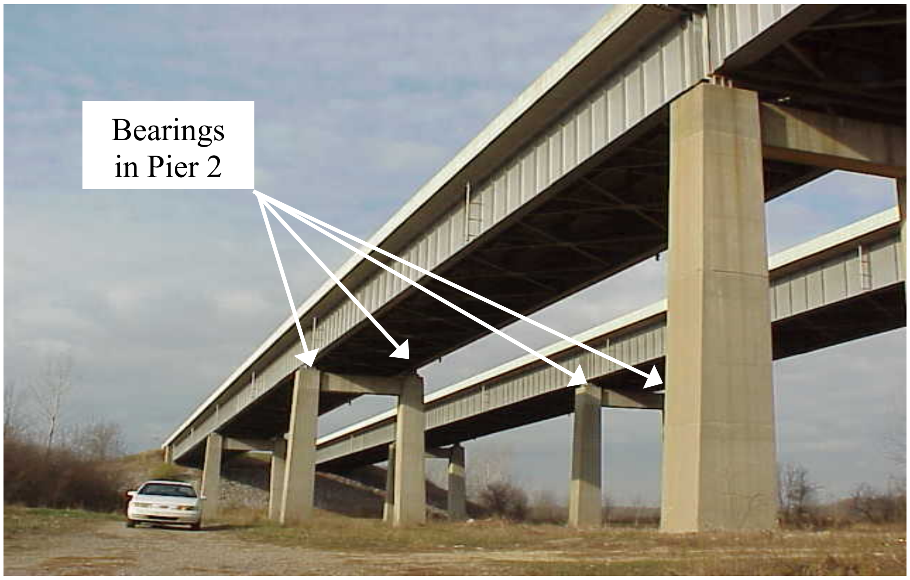


Fig. 15 Demand of bearings of pier #2 of the approach spans of the Cumberland River Bridges exceeds capacity for projected 500-Year Seismic Event

11. DETAILED SEISMIC EVALUATION OF THE TENNESSEE RIVER BRIDGES

The main objective of this part of the study is to assess the structural integrity of the I-24 Bridges over the Tennessee River connecting Marshall and Livingston counties in western Kentucky. Due to their importance, the bridges were evaluated for the 250-year and the 500-year seismic events. The 250-year and the 500-year events are events that have a 90% probability of not being exceeded in 250 years and 500 years, respectively. During the 250-year event, the bridges shall remain in the elastic range without any disruption to traffic. During the 500-year event, partial damage shall be permitted to the bridges, but they are to remain accessible to emergency and official vehicles. To achieve this objective, the scope of the work was divided into the following tasks: (1) field testing of the main bridges; (2) finite element modeling and calibration; (3) time-history seismic response analysis; and (4) seismic evaluation/retrofit for both the main and the approach spans of the bridges.

11.1 FIELD TESTING OF THE MAIN SPANS

The free vibration properties of the main bridges were determined through field ambient vibration testing under traffic and wind induced excitation. The purpose of the field-testing was to determine the natural frequencies and the mode shapes. The vibration properties were subsequently used as the basis for calibrating a finite element model that was specifically created for carrying out the seismic response analysis.

11.2 FINITE ELEMENT MODELING OF THE MAIN SPANS

A three-dimensional finite element model of the main bridges was used for free vibration and seismic response analysis. The model was calibrated by comparing the free vibration analysis results with the ambient vibration properties obtained from field-testing.

11.3 SEISMIC EVALUATION OF THE MAIN SPANS

After calibration of the main spans, the model was used for seismic response analysis. The three-dimensional model of the main bridges was subjected to the time histories of the projected 250-year and 500-year events to determine the maximum displacements at joints, stresses in members, and forces on the bearings.

11.4 SEISMIC EVALUATION OF THE APPROACH SPANS

Simple structural models were used to idealize the approach spans depending on the type of the bearings that were mounted on the top of the piers. The mathematical models were considered as single degree of freedom (*SDOF*) systems. The mass of the

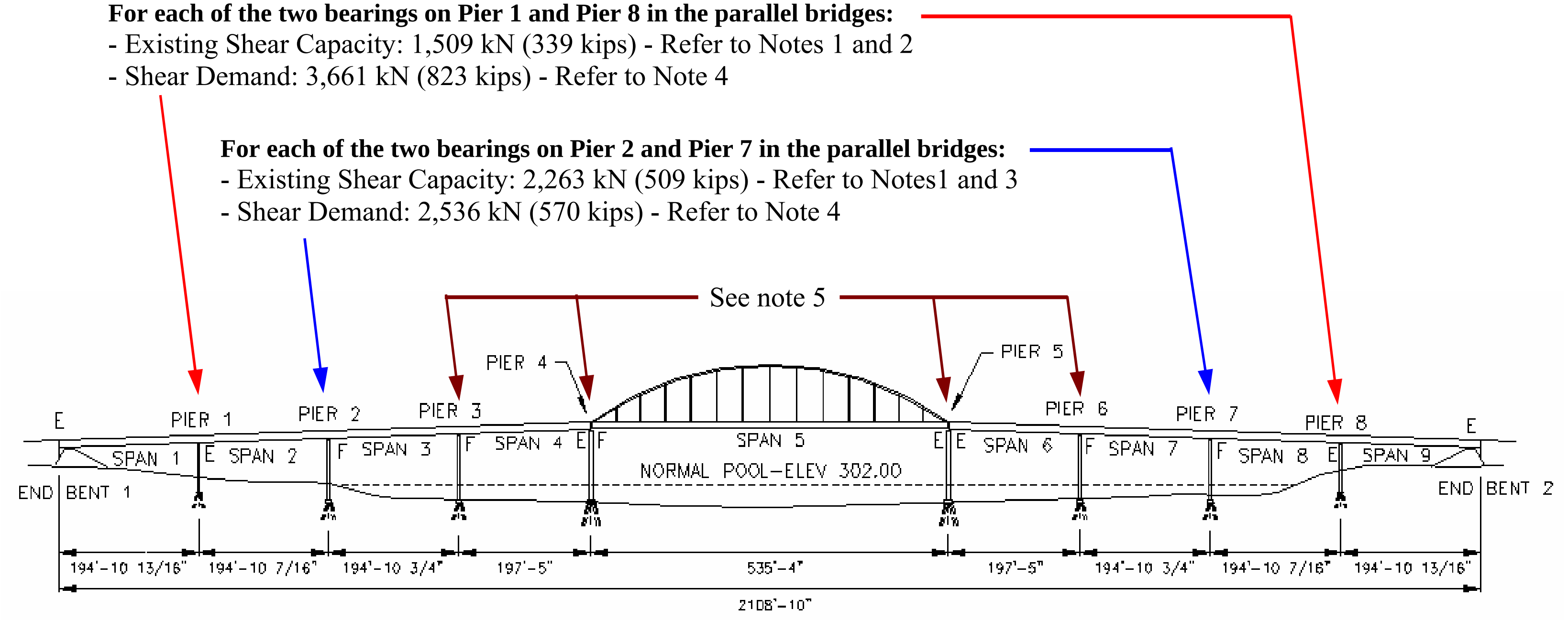
SDOF system was considered as the summation of the mass of the superstructure and one-third the mass of the piers. The transverse stiffness and the longitudinal stiffness of the mathematical model were calculated in accordance with the Seismic Evaluation of Highway Bridges in Kentucky (Harik et al., 1997). The seismic response of the approach spans was carried out using the response spectrum method to determine the maximum forces and displacements.

11.5 RESULTS AND RECOMMENDATIONS

The seismic analyses indicate that the main bridge can resist the 250-year and 500-year earthquake events without yielding of the main structural members or loss-of-span at supports. However, the supports with fixed bearings on the pier of the main bridge need to be retrofitted for the 500-year seismic event.

The analyses for the approach spans showed that few supports on the approach spans are vulnerable to shear failure of the anchor bolts during the 250-year seismic event (Figure 16). Additionally, it is recommended to retrofit all the supports on the piers of the approach spans for the 500-year seismic event (Figure 17).

All details of the seismic evaluation of the two parallel Tennessee River Bridges on the I-24 are shown in the accompanied report, KTC-06-24/SPR206-99-5F that is entitled: “Seismic Evaluation of the Tennessee River Bridges on I-24 in Western Kentucky”.



For each of the two bearings on Pier 1 and Pier 8 in the parallel bridges:
- Existing Shear Capacity: 1,509 kN (339 kips) - Refer to Notes 1 and 2
- Shear Demand: 3,661 kN (823 kips) - Refer to Note 4

For each of the two bearings on Pier 2 and Pier 7 in the parallel bridges:
- Existing Shear Capacity: 2,263 kN (509 kips) - Refer to Notes1 and 3
- Shear Demand: 2,536 kN (570 kips) - Refer to Note 4

See note 5

Note 1: The existing Shear Capacity of the bolts is derived under the assumption that the strength of the bearings remained the same since the bridge was constructed.

Note 2: The two bearings on Pier 1 and Pier 8 in the parallel bridges are expansion bearings in the longitudinal direction and fixed in the transverse direction. The shear capacity and demand are determined for the transverse direction.

Note 3: The bearings on Piers 2, 3, 6 and 7 in the parallel bridges are fixed bearings in both the longitudinal and transverse directions. The shear capacity and demand are determined from the resultant of the capacities in both directions.

Note 4: The shear capacity can be increased by: 1) providing additional bolts, and/or 2) replacing the existing bolts with higher strength bolts, or 3) replacing the bearings with seismic isolation bearings.

Note 5: The bearings at Piers 3, 4, 5 and 6 do not require any retrofit.

Fig. 16 Retrofit Recommendations for the Parallel Tennessee River Bridges on I-24 in Western Kentucky for the 250-Year Seismic Event

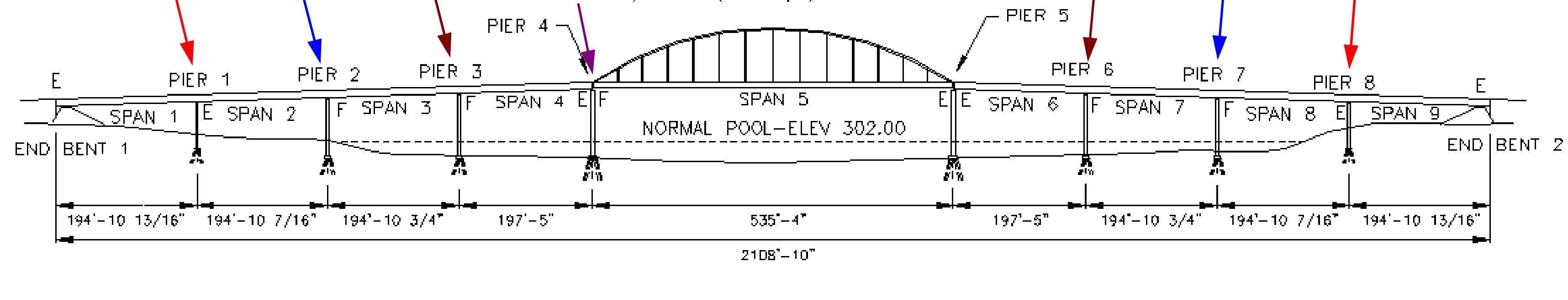
(Note: A 250-year event is an event with 90% probability of not being exceeded in 250 years)

For each of the two bearings on Pier 1 & Pier 8 in the parallel bridges:
- Existing Shear Capacity: 1,509 kN (339 kips) - Refer to Notes1 and 2
- Shear Demand: 7,321 kN (1,646 kips) - Refer to Note 4

For each of the two bearings on Pier 2 & Pier 7 in the parallel bridges:
- Existing Shear Capacity: 2,263 kN (509 kips) - Refer to Notes1 and 3
- Shear Demand: 3,981 kN (895 kips) - Refer to Note 4

For each of the two bearings on Pier 3 & Pier 6 in the parallel bridges:
- Existing Shear Capacity: 2,263 kN (509 kips) - Refer to Notes1 and 3
- Shear Demand: 2,765 kN (622 kips) - Refer to Note 4

For each of the two bearings on Pier 4 of the main span in the parallel bridges:
- Existing Shear Capacity: 2,053 kN (462 kips) - Refer to Notes1 and 3
- Shear Demand: 3,221 kN (724 kips) - Refer to Note 4



Note 1: The existing Shear Capacity of the bolts is derived under the assumption that the strength of the bearings remained the same since the bridge was constructed.

Note 2: The two bearings on Pier 1 and Pier 8 in the parallel bridges are expansion bearings in the longitudinal direction and fixed in the transverse direction. The shear capacity and demand are determined for the transverse direction.

Note 3: The bearings on Piers 2, 3, 6 and 7 in the parallel bridges are fixed bearings in both the longitudinal and transverse directions. The shear capacity and demand are determined from the resultant of the capacities in both directions.

Note 4: The shear capacity can be increased by: 1) providing additional bolts, and/or 2) replacing the existing bolts with higher strength bolts, or 3) replacing the bearings with seismic isolation bearings.

Note 5: The bearings at Pier 5 do not require any retrofit.

Fig. 17 Retrofit Recommendations for the Parallel Tennessee River Bridge on I-24 in Western Kentucky for the 500-Year Seismic Event

(Note: A 500-year event is an event with 90% probability of not being exceeded in 500 years)

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