ABSTRACT
Rapid assessment of a bridge structure’s safety and functionality is a crucial procedure in restoring vital lifeline routes after a hazardous event. However, executing preparatory actions before a hazardous event occurs, and conducting feasible remedial actions during such an event, are also essential to bridge safety. This paper introduces a process for hazard mitigation of highway bridges through the example of an application of earthquake mitigation. Earthquake mitigation consists of three components: pre-earthquake, during-earthquake, and post-earthquake mitigation. Pre-earthquake mitigation consists of a seismic evaluation of all applicable bridges and a prioritization of the seismic vulnerability of these bridges. Simultaneously, pre-earthquake mitigation requires the implementation of earthquake-response training programs for the necessary earthquake-response personnel. Due to the short duration and unpredictability of earthquakes, no form of during-earthquake mitigation is currently possible. Post-earthquake mitigation consists of the use of post-earthquake investigation software that assigns a bridge safety-rating to effected bridges as the first stage of a two-stage approach to guide professional and non-professional personnel in making post-earthquake response decisions. The software is a bridge safety-rating program prepared for the state of Kentucky in the Southeastern United States in order to accelerate bridge investigations following an earthquake. The methodology and concepts presented herein can be extended to other types of hazard mitigation in other states and countries.

1. INTRODUCTION
Two types of hazards that may damage highway bridge structures are man-made hazards and natural hazards. A man-made hazard is an accidental or intentional event of unusual magnitude that threatens the activities of people or the people themselves. As shown in Figure 1, biological or chemical spills, explosions, fires, vehicular impacts, and wars are examples of man-made hazards that may cause damage to highway bridges. A natural hazard is an unexpected or uncontrolled natural event of unusual magnitude that threatens the activities of people or the people themselves. As shown in Figure 2, earthquakes, floods, hurricanes, tornadoes, tsunamis, and volcanoes are examples of natural hazards that may cause damage to highway bridges.

Regardless of the type of hazardous event that occurs at a highway bridge site, every available resource should be utilized to prevent, contain, and assess damage to such structures as they are an essential part of any infrastructure. Hazard mitigation is an effective solution to the integral support required by highway structures before, during, and after a hazardous...
event. As previously mentioned, earthquakes are one type of natural hazard that may damage highway bridges. Earthquakes are very difficult to predict and are unpreventable. Therefore, mitigation of earthquakes requires designing structures (including buildings, roadways, bridges, etc.) that can withstand repeated shaking.\(^1\) In the following, an earthquake mitigation of highway bridges is presented in order to convey the principles and methodologies utilized in any type of hazard mitigation of highway bridges.

Earthquake mitigation is broken into three main components, as shown in Figure 3. The details of each component are described in detail herein.

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**Man-Made Hazards**

- Biological
- Chemical
  - Blast
- Nuclear
  - Impact
  - War
- Other
  - Fire

**Natural Hazards**

- Earthquakes
- Fog
  - El Nino
- Tornadoes
  - Hurricanes
  - Volcanoes
- Other
  - Droughts
  - Floods
  - Tsunamis

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**Earthquake Mitigation of Bridges and Highway Structures:**

- Pre-Earthquake Event
- Post-Earthquake Event
- During-Earthquake Event

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Figure 1. Man-made hazards
Figure 2. Natural hazards
Figure 3. The three major components of the earthquake mitigation of highway bridges
1.1 Background

Kentucky is located in the Southeastern United States, as shown in Figure 4. Kentucky may be affected by earthquakes from several seismic zones in and around the state. The most prominent one is the New Madrid Seismic Zone (NMSZ), in which at least three great earthquakes, each estimated to have been greater than magnitude 8 on the Richter scale, occurred from December 1811 to February 1812. The NMSZ (Figure 4) is potentially one of the most destructive fault zones in the United States. It extends through the Mississippi River Valley and encompasses twenty-six Western Kentucky counties in its strongest area of influence. The U.S. Geological Survey predicts a 20-40% chance of another major earthquake, measuring 7.6 or higher on the Richter scale, within the next fifty years. Thus, earthquakes pose significant seismic hazards and risk to the commonwealth of Kentucky and to other states surrounding the NMSZ.

It is well known that bridge structures are vulnerable to earthquakes. Furthermore, damage to such facilities impacts communities far beyond any immediate death and destruction. For these reasons, the most vital transportation links have been designated priority routes, which must remain open in the event of a major earthquake. In Kentucky, more than 530 bridges on the priority routes are considered essential bridges. With few exceptions, a significant number of them were designed and constructed at a time when seismic-design requirements were unavailable or insufficient by today's standards.

![Figure 4. New Madrid Seismic Zone (after Atkinson, 1989)](image)

2. PRE-EARTHQUAKE MITIGATION

As shown in Figure 5, the major components comprise the pre-earthquake mitigation of highway bridges are Seismic Evaluation & Retrofit, Post-Earthquake Training, Instrumentation & Monitoring, and Other.

2.1 Seismic Evaluation and Retrofit

As shown in Figure 6, Seismic Evaluation & Retrofit is further delineated into five major tasks, which include Seismic Input, Prioritization, Seismic Evaluation, Recommendations, and Seismic Retrofit.
2.1.1 Seismic input: The first task in Seismic Evaluation & Retrofit requires the gathering and organization of a vast amount of data that is acquired from visits to bridge sites as well as from the study of bridge plans. For each bridge, general information such as the geographic location, bridge identification number (BIN), average daily traffic, construction completion date, alignment or skew angle, overall length, overall width, description and date of any prior retrofitting, etc. Information that describes every significant structural member of the bridge with regard to the substructure, superstructure, and bearings is critical to the creation of an effective database. The seismology (seismic activity) and surrounding soil type at the bridge site are also necessary for the creation of a database. The Bridge Inventory database that was developed for the applicable bridges in Western Kentucky is shown in Figure 7.

2.1.2 Prioritization: Each bridge in the Seismic Inventory of Bridges database is assigned a ranking based on the acquired bridge data. The ranking (or preliminary screening) of bridges identifies any that may be seismically deficient. In addition, the ranking identifies the bridges that are in the greatest need of detailed seismic evaluation or seismic retrofit. As shown in Figure 8, the ranking is based on a scale from 0 (Non-Critical) to 100 (Highly Critical). Bridges that receive a Highly Critical ranking require detailed seismic evaluation.
2.1.3 Seismic evaluation: Seismic evaluation is necessary to determine the exact nature of the deficiencies of Highly Critical bridges. Choosing the correct method to perform the seismic evaluation of Highly Critical bridges is important for economic as well as scientific reasons. The American Association of State Highway & Transportation Officials (AASHTO) allows the Uniform Load method, the Single Mode Spectral Analysis method, the Multimode Spectral Analysis method, the Time-History Analysis (THA) method and other methods for seismic evaluation. The Response Spectral Analysis (RSA) method simplifies the solution of a multi-degree of freedom system by reducing the system into a set of single degree of freedom systems wherein each degree of freedom in the structure is represented as single degree of freedom system. Furthermore, the RSA method simplifies seismic evaluation while simultaneously producing maximum (or conservative) response estimates. In contrast, the THA method includes the time dependent characteristics of the earthquake motion and the three dimensional characteristics of the structure. The THA method is complex and time
consuming, however, it does yield significantly more accurate responses than the RSA method [2].

2.1.4 Recommendations: The Seismic Inventory of Bridges, the Seismic Ranking, and the appropriate Seismic Evaluation method identify exactly which bridges should be retrofitted first. In addition, the Seismic Evaluation also identifies exactly where the Highly Critical bridges need remedial action. However, recommendations are required for the type of retrofitting as well as for logistical considerations, such as the time required for the chosen remedial procedures.

2.1.5 Seismic retrofit: Bearings, seats, expansion joints, columns, cap beams, and foundations are included in retrofitting operations. Bridges on hazardous sites may include an even larger number of components. Figures 9 through 11 are examples of common retrofitting techniques. The retrofit of a rocker bearing by replacement with a steel extension and elastomeric bearing pad is shown in Figure 9. An example of a transverse retainer retrofit is shown Figure 10. Energy dissipating devices, such as a torsional beam device and a rolling-bending device are shown in Figure 11. Additional techniques and retrofitting configurations exist, for example, a steel or fiber-reinforce polymer (FRP) jacket may be applied to a column near the column-footing interface.

![Figure 9. Bearing sole plate to girder with catcher retrofit [3]](image1)

![Figure 10. Restrainer anchorage [3]](image2)
2.2 Post-Earthquake Training

The goal of Post-Earthquake Training is to provide rapid assessment of each bridge structure’s safety and functionality after an earthquake event. In addition to training professional and non-professional personnel for earthquake-response procedures, which are described in the section entitled the Two-Staged Approach below, a contingency plan is required to ensure a reliable earthquake-response operation. Mobility issues and the multitudinal number of potentially damaged bridges also affect the earthquake-response plan. An estimated six hours are needed for the post-earthquake damage assessment team to reach Western Kentucky from the base of operations in Frankfort, 250 miles away (see Figure 12). Ultimately, a well-developed contingency plan and a large number of trained personnel are critical to the success of a Post-Earthquake Training Program.

2.3 Instrumentation / Monitoring

Remote sensing or other methods may be used to perform instrumentation and monitoring of particularly important structures. The applications of such monitoring techniques provide a direct and reliable account of bridge conditions. Rapid assessment of bridge structure is easily achieved when such equipment is in place.
3. **DURING-EARTHQUAKE MITIGATION**

Neither geologists nor seismologists can predict earthquakes with respect to time. Additionally, even the greatest earthquakes in recorded history have duration of less than one minute. During-earthquake mitigation is impossible due to the combination of these two obstacles.

4. **POST-EARTHQUAKE MITIGATION**

The most significant challenge to the Kentucky Transportation Cabinet (kyTC), immediately following an earthquake, is to accurately assess the situation and prioritize response needs. One critical task is to rapidly evaluate the condition of all bridges and roadway corridors in the State Highway Priority System. Timely response is important to ensure public safety, aid routing of emergency vehicle traffic, and (re-) establish critical lifeline routes.

Scientists have not yet developed the technology to predict the data, location, and magnitude of an earthquake. Planning a response to an earthquake is even more difficult due to such uncertainties. A key component to any disaster response plan is the proper training and rehearsal drills for qualified personnel, who must possess a variety of backgrounds. Every year, a significant amount of financial and human resources are put into training technical personnel for earthquake response, not only in Kentucky, but also in other states. However, in the central United States, most of the trainees have only a meager opportunity to use such skills, because earthquakes are low probability events during a given human’s life span. As a result, the benefit of training is not proportional to the cost. It has been of great interest to administrators and trainees alike to find a way to solve this dilemma, and simultaneously simplify the response training and the investigation process.

Since the major seismic hazard in Kentucky is located in the rural southwestern portion of the state, it is expected that professional state bridge engineers would be delayed in traveling from the capital (Frankfort) to the damaged locations. The situation is further complicated if the number of effected bridges is large, which would divert inspection resources away from critical needs. Facing more than 500 bridges compounded with other difficulties such as traffic congestion, the completion of investigation could be further delayed.

Regardless of the complications caused by an earthquake, setting up and efficiently carrying out an operation of emergency bridge inspection in remote areas has always been a major concern for the authorities. Currently, the primary method for post-disaster assessment is a thorough onsite inspection by engineers from the KyTC. However, procedures used for establishing inspection priorities are relatively undefined due to the lack of precise information about the distribution of damaging levels. In the absence of such information, attention is dispersed widely within that region to perform initial reconnaissance.

4.1 **The Two-Stage Approach**

Bridge damage assessment and decision-making will be implemented in two stages in Kentucky. The first stage (or triage) includes a preliminary rating of individual bridges and posting pictorial traffic-control signs (“Bridge Closed”, “Emergency Traffic Only”, etc.). This stage is generally conducted by inspectors from the local Highway District bridge maintenance crew who can reach the bridge sites in a short time. At this stage, both safe bridges and collapsed bridges are screened out. It should be noted that these inspectors will not have any training for the post earthquake bridge evaluation. The Inspectors will use a computer program loaded on a PC tablet or personal data assistant (PDA) to conduct the evaluation. The program is capable of considering a vast body of knowledge, reasoning, and
then recommending a course of action. The program has four basic functions: personnel training assistance, bridge inspection guidance, decision making support, and field information collection. Through a simple training process offered by the program, the inspectors will be ready to evaluate the status of bridges on state routes, highways and parkways. The program makes expertise available to bridge inspectors who need answers quickly. In addition, the program ensures standardized evaluations of all bridges.

Based on the information obtained in the first stage, the second stage is initiated. The second stage includes two teams of engineers from the divisions of Maintenance, Structures, Geotechnical, and Constructions of the KyTC in Frankfort. The first team or “Stationary Team” remains in Frankfort and is in continuous contact with the inspectors from stage one as well as the second team. The second team or “Mobile Team” will be en route to the affected areas to evaluate bridges starting with the ones assigned “Bridge Closed” and “Emergency Traffic Only” signs by the inspectors during the stage one.

One of the obstacles that the KyTC has to overcome is the management of information coming from field investigations. To better prepare for seismic events and to provide rapid evaluation and response, the KyTC will be employing recent advances in hardware, software, and methods (such as global positioning systems GPS, personal data assistants PDA, wireless communications technology, and dynamic databases) to improve information collection, analysis, and remote access complications. The incorporation of information technology (IT) tools in reconnaissance efforts permits the analysis of bridge reliability parameters automatically based on an expert support system. The goal is to build a real-time bridge-damage-investigation network in Kentucky as shown in Figure 13. The network allows dynamic exchange of information between the stage 1 inspectors and the stage 2 engineers.

With such a system, bridge inspectors can obtain detailed instructions from headquarters, and make recommendations regarding specific areas, bridges, and subjects that merit further attention. Experts stationed at the headquarters can keep abreast to a situation in the field in real-time, and make strategic planning decisions accordingly. After receiving the first-hand data, the intelligent system will analyze the implications of structural damage, identify any secondary impacts, and send out further instructions to the inspectors. In the future, the four major tasks (seismic monitoring, emergency response, reconnaissance, and disaster processes) will be integrated into one real-time system. Implementation of the system with a bridge database will provide immediate visual representation and routing when some bridges in the system fail or become partially closed to traffic.

4.2 Kentucky Post-Earthquake Investigation Software (KyPEIS)

As a rapid and efficient method to rate damaged bridge structures in a uniform manner, the primary users of the KyPEIS software are intended to be investigators, without any training in post earthquake investigation, who will be performing the initial investigative tasks at the bridge sites (or triage).

The philosophy adopted in KyPEIS is to accept a certain level of expected damage while acknowledging that bridge structures maintain a high degree of residual strength that surpasses typical design levels. The bridge damage specifies four damage states: minor, moderate, major and severe. Definitions of damage states for steel, concrete and timber structural components are proposed based on the expert knowledge of the authors. The architecture of the system is illustrated in Figure 14.

To effectively use KyPEIS, it is necessary to have a comprehensive inventory of the bridges. The structural characteristics are obtained from the Structural Maintenance System (SMS) database compiled and managed by the KyTC. For each bridge, the database includes information on bridge damage and the structural characteristics that are important for a vulnerability assessment. Structural characteristics compiled include the number of spans, type of superstructure and substructure, length and width of the bridge, skew, number of
hinges at joints and bents, bearing types, abutment and column foundation types, retrofit history, and design year to represent design standards (such as column reinforcement and seat width).

The software has been developed using the Microsoft .NET Framework Software Development Kit (SDK) version 2.0. It can run on Windows 2000 and Windows XP operating systems. Since Microsoft Access 2003 provides users with one of the simplest and most flexible Relational Database Management System (RDBMS) solutions on the market today, the software is built with the capability of interfacing with Access 2003. Some major user interfaces of the program are shown in Figure 15.

In the field, the investigators need to observe and record:

- Ground cracks, displacements, liquefaction, settlement;
- Cracking at abutments, piers and retaining walls;
- Signs of movement and/or misalignment;
- Amount of movement at hinges, joints, railings and curbs;
- Condition of foundation piles, noting any exposure;
- Condition of connections;
- Scrape marks, dents, holes, indicating parts of the structure sliding or hitting each other;
- Direction of leaning or falling,
- Deformed or displaced bearings,
- Condition of welds, rivets, bolts, restrainers and shear keys,
- Warping or tearing of steel members.

Data is gathered on damage and impacts to individual bridges, which will be used to prioritize the follow-up inspections by bridge engineers and plan repair efforts. Appropriate posting actions and recommendations are then produced from the inspection results on the computer. The posting categories (e.g. safe for traffic, limited use at reduced speeds, emergency vehicle use only, unsafe for all travel) are used to assure the safety of the traveling
public. It is intended that these results remain consistent with the level of safety appropriate in the immediate post-disaster situation.

![Diagram of Kentucky post-earthquake investigation software components]

**Figure 14. Description of the Kentucky post-earthquake investigation software components**

### 5. CONCLUSIONS

1) The procedures and methods demonstrated in the Pre-Earthquake Mitigation create a solid foundation from which to make decisions regarding the identification and retrofitting measures required of Highly Critical bridges.

2) Also, the Pre-Earthquake Mitigation Post-Earthquake Training program as described in the sections entitled Post-Earthquake Mitigation and Two-Stage Approach enables the necessary personnel to perform a rapid assessment of bridge structure safety and functionality after an earthquake event.

3) Any instrumentation or monitoring that is implemented in extremely important highway structures will provide an excellent opportunity to quickly and accurately determine where retrofitting is needed as a precautionary measure.

4) Due to the unpredictability and brusque nature of earthquakes, no insight is provided into During-Earthquake Mitigation.

5) The procedures and methods demonstrated in the Post-Earthquake Mitigation will expedite the post earthquake response and evaluation of highway bridges in the state of Kentucky. The primary advantage of this two-stage approach is the lack of reliance on continuous training for post EQ evaluation in a part of the country where major
seismic events may not occur in one’s lifetime. The approach relies on a computer expert system and latest communication technologies. The expert system will be continuously modified and updated to ensure its effectiveness following a seismic event.

Figure 15. Screen-shots of the Kentucky post-earthquake investigation software
6) Also, the Pre-Earthquake Mitigation Post-Earthquake Training program as described in the sections entitled Post-Earthquake Mitigation and Two-Stage Approach enables the necessary personnel to perform a rapid assessment of bridge structure safety and functionality after an earthquake event.

7) Any instrumentation or monitoring that is implemented in extremely important highway structures will provide an excellent opportunity to quickly and accurately determine where retrofitting is needed as a precautionary measure.

8) Due to the unpredictability and brusque nature of earthquakes, no insight is provided into During-Earthquake Mitigation.

9) The procedures and methods demonstrated in the Post-Earthquake Mitigation will expedite the post earthquake response and evaluation of highway bridges in the state of Kentucky. The primary advantage of this two-stage approach is the lack of reliance on continuous training for post EQ evaluation in a part of the country where major seismic events may not occur in one’s lifetime. The approach relies on a computer expert system and latest communication technologies. The expert system will be continuously modified and updated to ensure its effectiveness following a seismic event.

10) While continued use of the maximum traffic volume capacities of damaged bridge structures would not be advisable, it is the intent of this study to provide recommendations that are applicable to such structures immediately following a major seismic event. The recommendations rely on residual strength of damaged bridge structures and should only be used as guidance in the short term.

REFERENCES

