

Post-Earthquake Rapid Inspection Planning for Bridges in Western Kentucky

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ABSTRACT: This paper presents a methodology for the rapid assessment of bridge's safety and functionality following a major seismic event in rural areas. The proposed model considers a combination of the bridge ranking prior to the seismic event and a computer assist program to identify the "efficient completion time" strategy for the post-earthquake bridge inspection team to inspect the critical bridge's components damage level. Application of the proposed methodology is conducted on the Purchase Parkway in Western Kentucky. By setting the required inspection time to 40 minutes per bridge, it is estimated herein that a non-trained inspection team and without computer assist would conduct the inspection for all 61 bridges in a period exceeding 40 hours. On the other hand, by setting the time to 20 minutes for a well-trained team with computer assist, it will need 22 hours to inspect all 61 bridges, and 5 hours to inspect provisionally the 9 high risk bridges.

Keywords: Bridge ranking, Inspection Strategies, Post-earthquake inspection, Risk Potential.

1. INTRODUCTION

Bridges have historically presented significant vulnerabilities during major seismic events. Although engineers have taken steps to restore and reinforce bridges against earthquakes, it is inevitable that unexpected damage caused by lack of maintenance, poor design, etc., will occur. Therefore, immediate dispatch for bridge inspection is very important following an earthquake.

To assist in decision making and timely response to ensure safety of the public and restore the transportation system functionality, ShakeCast has been developed and provided freely by U.S. Geological Survey (USGS) for emergency responders[1]. In addition, Caltrans (California Department of Transportation) has developed and implemented a Caltrans-specific version of ShakeCast, a post-earthquake analysis tool for rapid evaluation of potential damages structures[2].

In Japan, post-earthquake response systems for road networks have already been developed. The system is composed with early earthquake alerts which warn about severe earthquake tremors a few seconds before they happen, a GIS database, ground shaking sensors, CCTV monitors and inspection tours by construction office staff [3].

Those post-earthquake response systems above mentioned may be useful in the construction of real time information facilities such as monitors, seismic sensors and communication lines. Although accurate real-time information may be helpful for an efficient inspection tour, it is difficult to extend those systems for a rural area road network. In rural areas, the cost benefit balance of real-time information systems may be lower than one in an urban area. The financial demands for the construction and maintenance of these systems are unavoidable. Consequently, for inspections that take place without real-time information systems, a rapid inspection methodology is very important.

In Japan, post-earthquake inspection systems for building

damage are conducted by architects and building engineers who volunteer to evaluate the building damage and risk to the public. The public sector organizes seminars to train inspectors and registers them as volunteers. The results of inspections, containing comments and remarks from resident and visiting inspectors, are displayed on placards[4]. Following an earthquake in Japan, color inspection stickers are seen at the site of a damaged building. However, this system is not used for bridge structures.

For bridge structures in Kentucky, the rapid inspection system assists in providing a uniform approach for rating the damage that has taken place [5]. The inspection teams can fill out an electronic form for all components of the bridge structure with assistance from sample pictures and key point comments. A computer assist program provides recommendation based on whether the observed damage was none, minor, moderate, or severe for each bridge component. The recommendation is made based on the level of damage in the bridge components. The inspection system interface in Kentucky Transportation Center is composed of a laptop PC that contains all the bridge data in Kentucky and a GPS unit attached to the laptop that identifies the bridge once the inspector is at the site. The inspection system in Kentucky is inexpensive and does not require any special tools or equipment. The system in Kentucky can be used not only by professionals but also by a variety of personnel since it has the tools that assist the inspector embedded in the software. This is an important issue in the limitation of manpower and resources following a disaster.

This study attempts to understand the efficacy of the inspection system with a combination of pre-earthquake investigations and rapid inspections. In addition, scenarios and discussions are presented for the inspection tour planning for safety and road link recovery. The framework of the inspection system is discussed herein through an application example using the Purchase Parkway which is one of the priority routes on the Western Kentucky Parkway System.

2. METHODOLOGY

2.1 Outline of proposed method

The proposed time outline for the rapid inspection planning is shown in Fig.1. Firstly, pre-earthquake investigations should be carried out to ascertain the present condition of bridges. The data from the pre-earthquake investigation is used for forecasting possible damage and ranking the risk. Rapid inspection immediately following an earthquake will be carried out to make recommendations for maintaining public safety and relieving traffic congestion. If the inspection staff has the data from pre-earthquake investigations, their inspection is more effective and rapid. They can check high risk bridges, identified in the pre-earthquake investigation, as a priority.

When making recommendations for traffic relief, inspections should be finished in a short time period, and the shorter the better for rescue activities. However, a few hours may be required for decision making to dispatch the inspection team(s) following the announcement of the magnitude and location of the earthquake.

The objective of this study is to produce a recommendation for a rapid inspection of bridges on priority routes. The areas of interest for this study are underlined in Fig.1.

2.2 Bridge risk ranking

The bridge risk ranking against an earthquake is needed to make priorities for rapid inspection. In general, the risk defines the product of the damage probability by the expected loss. The damage to roadways may vary from minor damage such as slight cracking of road surfaces to the bridge collapse. The expected loss depends on the demand of the road. The demand of the main roads is higher than that of the local roads because the main roads may be used as the evacuation route for residents and as designated routes of the relief teams. Therefore, damage and demand have a direct influence on the risk potential. Consideration of demand for roads which are in different regions is also important. However, a uniform demand can be on road sections that are direct routes. If road sections are awarded a uniform demand, it means that the relative risk potential may be decided only by the damage probability. Since the objective is to create a bridge risk ranking, a relative calculation of the risk potential is sufficient.

The challenge is how to calculate the damage probability. The seismic retrofitting manual for preliminary seismic

evaluation can be used [6]. The manual describes the rating method for a bridge retrofitting program. Since this manual addresses multiple factors such as structural vulnerabilities, seismic and geotechnical hazards, and bridge importance, it is a suitable method to define the post-earthquake inspection ranking. The outline of the method is as follows:

Firstly, the acceleration and importance coefficient are determined. The acceleration is provided by any seismic data. Some patterns of the importance of the bridge are described in the original manual. Since all bridges on the parkways in Western Kentucky are on essential or "priority" roads, the importance coefficient of bridges targeted for application of the proposed methodology can be classified as "essential". The seismic performance category (SPC) is determined by the acceleration and the importance confidence by a table contained in the manual. If the bridge is categorized as SPC A, this is omitted from the inventory. Secondly, the soil profile type (S) and structural vulnerability rating (V) are set. In addition, the seismic hazard rating (E) is modified by the soil profile coefficient (S). Finally, the bridge rank (R) is calculated based on a structural vulnerability rating (V) and a seismic hazard rating (E) as follows:

$$R = V * E \quad (1)$$

In general, a bridge of high R value is more vulnerable than one with a low R value. Since V and E each range from 0 to 10, the value of R will vary from 0 to 100. The R value is easy to understand as a relative index for the vulnerability of the bridge.

2.3 Rapid Inspection system

An essential tool is the inspection assist system, which has been developed by the Kentucky Transportation Center for rapid inspection after an earthquake. Although the target region of the original system development is for the state of Kentucky, if the bridge database of the target area is compiled and installed into the system, its use in any region is possible.

The rapid inspection procedures with the system are as follows:

Firstly, the inspector checks the bridge type. The system provides the 17 types of bridge structure. If the database has

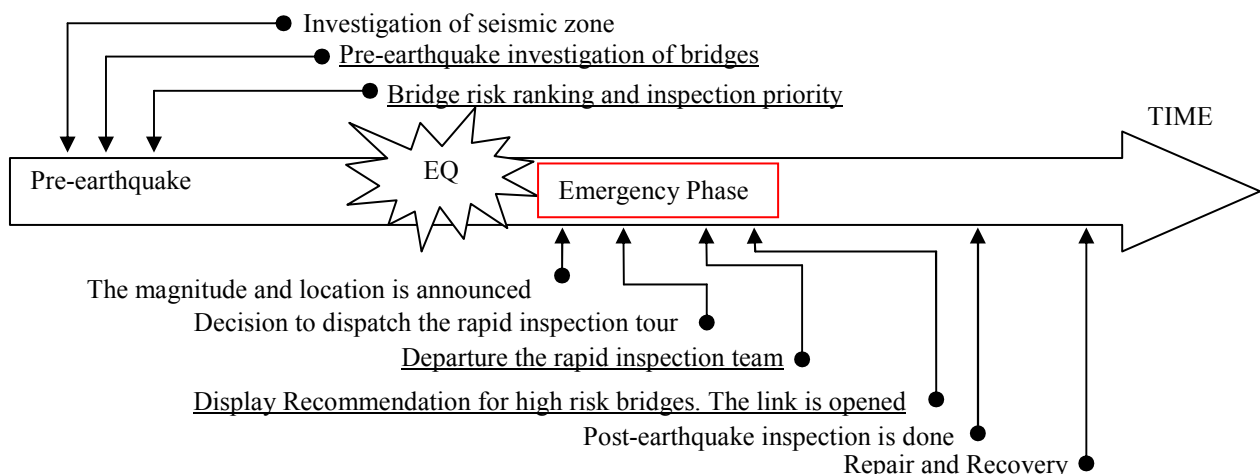


Fig.1. Time outline for rapid inspection planning

already been compiled, the inspector needs to select the bridge code number only. Secondly, the inspector makes a visual inspection. The points of view are embankment, span, deck, abutment, bearing, pier or column, and so on. An internal program will provide an associated recommendation based on whether the observed damage was none, minor, moderate or severe for each component. Thirdly, the recommendation is made through the additional points from each component damage score. The recommendation may be one of five grades- Green, Blue, Yellow, Orange, and Red. Green means "Bridge Open", Blue means "Travel with Caution", Yellow means "Reduced Speed Limit", Orange means "Bridge closed for Traffic Except for Emergency Vehicles at Reduced Speeds" and Red means "Bridge Closed completely". The inspector prints out the recommendation sheets for public awareness. Civil engineers may also find the data as useful information for a follow-up inspection.

If the time required for carrying out the inspection is too long, the efficacy of the system for rapid inspection is decreased, so training and rehearsal drills for qualified personnel and rapid inspection are required.

2.4 The strategy of an inspection tour

If a long time is required to inspect all bridges, the inspection team should limit the inspection to bridges with high priorities. However the risk potential of non-inspected bridges cannot be ignored. Thus, the problem between the risk potential for inspection and the time required can be thought of as a trade-off relation. Normally, all bridges should be inspected immediately following an earthquake. The priority of inspections should be carefully considered. For the strategy of the inspection tour, a check should be made to determine whether the inspection tour can be completed within the time limit for relief activity. If inspection for all bridges is impossible, risk potential can't be decreased. This proposal's methodology defines the sum of the R values as previous risk potential in the region. After inspections and recommendations for each bridge, the risk potential will gradually decrease. When the inspection tour is finished, the sum of non-inspected bridges' R values will be shown as non-inspected bridges' risk potential. The non-inspected bridges' risk potential can be used as an important index for evaluating a post-earthquake bridge inspection strategy.

The time required per bridge is an important parameter. This depends on the proficiency of the system and the bridge structure. Of course the inspection can be carried out without the system; the team needs the handbook and calculation for making the recommendation level by themselves. The team may take a long time. When considering the time required for inspecting and assessing each bridge, this is ample motivation for the training of personnel.

3 CASE STUDY

3.1 Example Area

The study area is in the Western Kentucky region is located in the New Madrid and the Wabash Valley Seismic zones. This is potentially one of the most destructive fault zones in

the United States. The broad impact has direct implications for virtually every aspect of emergency response.

Kentucky's parkways were constructed during the 1960s and '70s to augment the state's interstate highway system. Unlike roads called parkways in other states, Kentucky's parkways are not closed to commercial and recreational traffic. Hence, it is essential that the parkways remain functional and operational following an earthquake, especially, in the Western Kentucky region.

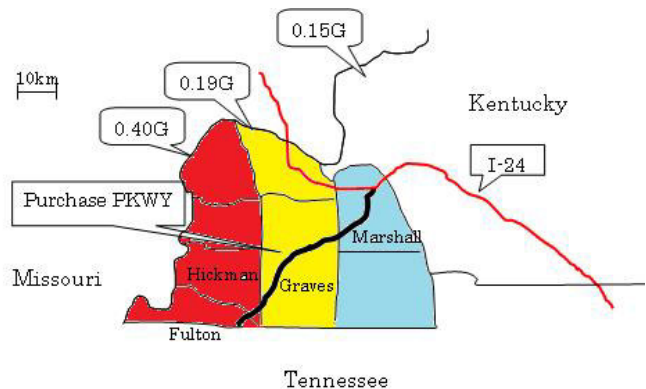


Fig.2. Purchase Parkway in Western Kentucky and PGA for a 250-year earthquake event[8]

I.E. Harik et al. have evaluated bridges on and/or over the parkways in Western Kentucky for seismic events[7], [8]. Their investigation included not only bridges, but also their corresponding approaches and embankments. As a result of their research, the risk to the Julian M. Carroll Purchase Parkway (hereinafter "Purchase PKWY") is higher than other parkways. For the study, I.E. Harik et.al. used the Peak Ground Acceleration (PGA) map showed in Fig.2 for the 250-year earthquake event in Western Kentucky. The 250-year earthquake event implies that there is a 90% probability for the earthquake not being exceeded in 250 years. The PGAs presented in Fig.2 were calculated from a time history response spectra. The result of the investigation, preliminary analysis and ranking, shows that 13 bridges of the Purchase PKWY are deemed critical. These bridges were constructed in the 1960s and seismic design was not taken into consideration. The Purchase PKWY is connected with the state of Tennessee, so it is an important route for response on multi-state issues.

3.2 Strategy and Scenario

One of the important issues of the inspection strategy is the accessibility of inspection teams. However there are no deep ravines and no elevated roads in the area. So, it is considered that the inspection team may be able to move beyond the damage bridge site. Therefore, the inspection team transportation speed may be set at about 48km/h (30miles/h).

There are two primary objectives for the inspections. One is to make a rapid recommendation of bridge safety. The other is to provide road information as to whether people can travel from origin to destination smoothly. To accomplish the first objective, the team goes to bridges which are estimated to have serious damage and displays a recommendation regarding the risk to the public. Although people are able to avoid dangerous bridges, they will be given more detailed road link information later on. If the

second objective takes precedence, the team checks all the bridges in the road section. It is recommended to sweep the road link step by step. However, it will require substantial time, as all bridges should be inspected to ensure that they have only slight damage. It will be difficult to accomplish the two objectives at the same time due to the restriction of human inspection resources. The problem is how to assign priorities and use inspection manpower efficiently. In order to provide both information of bridge safety and road information to the public in a timely manner, the dispatch patterns of the Kentucky Transportation Cabinet personnel are defined under the following strategies:

Strategy 1

The required time of inspection per bridge is varied between 20, 30 and 40 minutes. The time relates to the skill of the inspection team. This will have a large impact on the inspection completion time. In all cases, the inspection team will start from the interstate I-24 junction.

Strategy 2

If the time required to inspect all bridges in one road section is considered to be too long, a more efficient method may be to omit the low risk bridges. The R value can be used for screening in order to shorten the time for inspection in this road section. Since not all bridges are inspected, it is necessary to show how many risk potential of bridges are dispelled by the inspection teams. The inspection percentage (*I*) is defined as follows,

$$I = \frac{S}{T} * 100(\%) \quad (2)$$

Where *S* is the sum of inspected bridge's risk potential, and *T* is the total of all bridges' risk potential

Strategy 3

If two inspection teams can be assigned, deciding how to divide the roles between them is important for the inspection strategy. This study proposes how to share the role based on the R value. One team is the express team that checks the high risk bridges. This team aims to display recommendations for dangerous bridges as soon as possible. This may permit the avoidance of traffic congestion and maintain public safety. To establish safety in this road section, the other team checks all bridges except those which have already been awarded recommendations by the express team. The aim of this method is to share the bridges that have border R value among both teams. Therefore, the R value can be varied for sharing the teams' roles and to create the optimal strategy.

3.3 Result of Bridge Risk Potential

Fig. 3 shows the frequency distribution of the R value versus the Number of Bridges or "Number" of the Purchase PKWY. The original data source is provided by the Kentucky Transportation Center report [9]. Although many bridges are varied between R=0 to 45, 8 bridges are over 75. It means that some specific bridges have a high risk potential and many bridges have a lower probability of being damaged by an earthquake. In addition, two peaks can be seen between R=0 to 45. One peak can be seen in the low level range from 0-10. The second peak is in the range

of 20 to 30. The "Ratio" values in Fig. 3 defines the number of bridges with an R value less than or equal to a specific value of R on the abscissa axis over the total number of bridges.

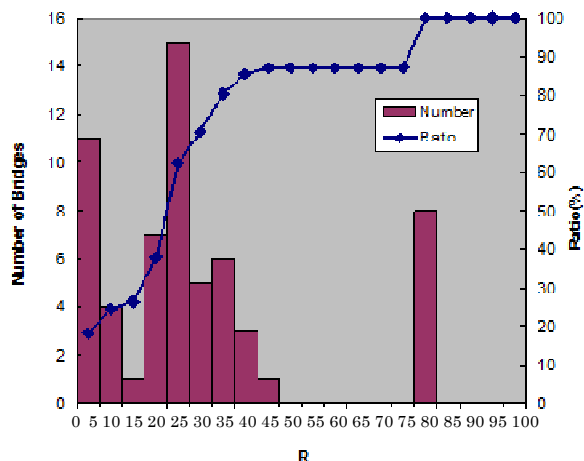


Fig.3. Frequency distribution of the bridge risk potential

4 RESULTS AND DISCUSSION

4.1 Results of Each Strategy

Strategy 1

The fastest case (or 20 minutes per bridge) implies an inspection with a computer assist system conducted by a well-trained team. The middle case (or 30 minutes per bridge) is with computer assistance, but conducted by a non-trained team. The results are shown in Table 1. In all cases, the inspection teams start from the interstate I-24 junction. Cases with the computer assist system can decrease the time of inspection drastically. The improvement of inspection time per bridge is effective for short inspection tours.

Strategy 2

In strategy 1, the recommendation is to check all bridges on the road section. However, there is the possibility that the inspections will take considerable time for all 61 bridges. Therefore, the case for checking all bridges is debatable. Through examination of Fig.3, it is found that high risk bridges are limited in Purchase PKWY. For rapid recommendations, it may not be necessary to inspect all bridges here.

The Kentucky Transportation Center listed bridges having an R >35 as high risk bridges[7]. In addition, Fig. 3 shows that the mid-range bridges' risk potential varies from R=20 to 30. Thus, the target bridges for inspection are selected based on their R value.

Fig.4 shows the risk potential in cases when the inspection team checks bridges based on their risk potential. In the case where the team inspects bridges having R > 20, the inspection will finish within 10 hours. The inspection percentage *I* is approximately 72.8%. The number of bridges inspected is 23 out of 61. This number implies that 37.7 % of the bridges are inspected in this road section. In case bridges having R >35 are inspected, the inspection tour will finish in approximately 5 hours. The inspection percentage *I* is 45.6%, and the number of bridges that have been inspected is 9 out of 61 (or 14.8% of the bridges in this road section).

Table 1. Results of the three post-earthquake inspection strategies

Strategy	Case	Provisional inspection duration for high risk bridges (Hours)	Inspection duration for all bridges (Hours)	Percentage of Inspected Bridges (%)
Strategy 1	Well trained team with computer assist	-	22.1	100.0
	Non trained team with computer assist	-	32.2	100.0
	Non trained tem without computer assist	-	42.4	100.0
Strategy2 (One team)	Bridges with $R > 20$ are inspected	9.4	-	72.8
	Bridges with $R > 35$ are inspected	4.7	-	45.6
Strategy3 (Two teams)	One team inspects bridges with $R > 20$ and another team inspects bridges with $R \leq 20$	9.4	14.4	100.0
	One team inspects bridges with $R > 35$ and another team inspects bridges with $R \leq 35$	4.7	19.1	100.0

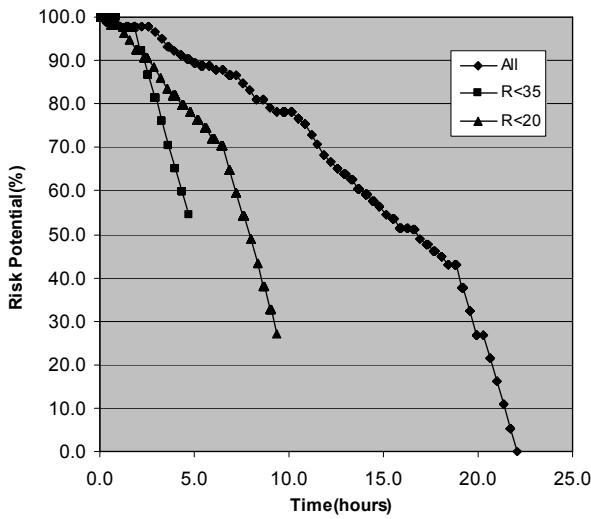


Fig.4. The decrease of the non-inspected bridges' risk potential for different R values

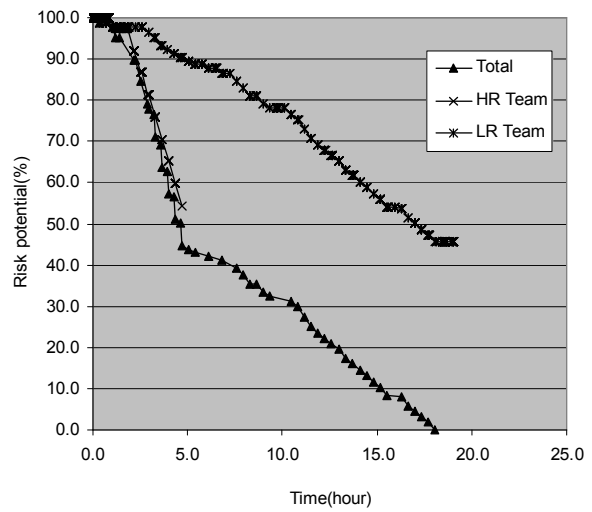


Fig.6. The decrease of the non-inspected bridges' risk potential by the express team for high risk bridges ($R > 35$) and the team for low risk bridges ($R < 35$)

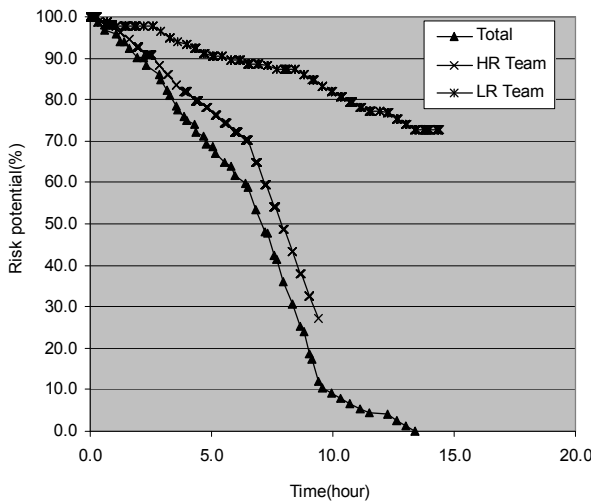


Fig.5. The decrease of the non-inspected bridges' risk potential by the express team for high risk bridges ($R > 20$) and the team for low risk bridges ($R < 20$)

Strategy 3

Fig. 5 shows the results of the inspection of bridges having $R < 20$ and $R > 20$. The express team for high risk bridges

(shown "HR Team") inspects 23 bridges having $R > 20$, and another team for low risk bridges (shown "LR Team") inspects 38 bridges having $R < 20$. The HR team may finish the inspection after 10 hours. At this point in time, because inspection of high risk bridges has been finished, the public may be able to use the road with caution. The other team may finish about 17 hours later. Bridges can receive risk recommendations and the public can travel using the road according to the recommendation displayed at each bridge. Fig.6 shows the result of the inspection of bridges having $R < 35$ and $R > 35$. The HR Team ($R > 35$) inspects only 9 bridges, and the LR team inspects 52 bridges. The HR Team may finish the inspection after 5 hours. The LR Team may finish about 17 hours later.

Comparing the cases when the cutoff values for Rare 20 and 35, the completion time of the comprehensive bridge inspection in the case of the cutoff value is 20 may be faster than in the case when it is 35. This is because the number of bridges inspected is balanced among two teams in the case when the cutoff value is 20. However, in the case when the cutoff value is 35, the inspection of the high risk bridges is faster.

Decision making regarding the inspection strategy is difficult without estimating the magnitude of the

earthquake in the region. For example, if some bridges were to collapse, the road link cannot be opened early by rapid inspection. Rapid inspection for high risk bridges may be required for the public safety. On the other hand, if many bridges suffer damage without collapse, all bridges should be checked early to open the road link. In this scenario, when a severe earthquake occurs, the cutoff value of $R = 35$ is a better to choice.

4.2 Discussion and Adoptable Strategy

Table 1 presents the result of all three strategies, and the following can be deduced:

1. If an inspection team, without training, carries out the inspection for all bridges, an inspection time of over 40 hours may be required. This may prove to be too late for relief activity. By deploying a well-trained team with an assist system, the inspection will be finished in about 22 hours. Training is significant in reducing the inspection time per bridge.
2. In cases when only high risk bridges are inspected by a well-trained team, the inspection will be finished in about 5 hours. Although all bridges may not be able to receive recommendations, people can go through the Purchase PKWY with caution. This may be the swiftest strategy.
3. If two inspection teams are deployed, the high risk bridges can be inspected in about 5 hours, and all bridges within 15 hours.

In conclusion, a well-trained inspection team dispatched to inspect high risk bridges with $R > 35$, travelers can expect to go through the Purchase PKWY within 4.7 hours following a major earthquake. It's the adoptable plan for this area.

5 CONCLUSION AND FUTURE DIRECTIONS

This paper presented a rapid inspection tour planning following an earthquake. The combination of the bridge ranking with pre-earthquake investigation and the computer assist system is our principal proposal in this paper. The proposed model is inexpensive, as daily system maintenance is not required. It may be a useful method for rural areas in which it is difficult to set many telemeter sensors. A sample application for the Purchase PKWY in Western Kentucky region was provided with the recommendation that inspection time will be reduced dramatically by using more than one team with good training and bridge risk ranking information.

As Western Kentucky is a flat land area, accessibility to the bridges' sites by the inspection team is not accounted for in this paper. We have fixed the speed of the inspection team and haven't done a sensitive analysis for this parameter. In cases where ravines and steep cliffs form the landscape of the priority route(s), urban areas, and other characteristics, transportation of the inspection team(s) by helicopter or other special transportation should be considered. Other strategies will need to be formulated to suit the geographical characteristics of each area.

The previous field survey was done in 2002 in Western Kentucky area. And the R value was calculated by Seismic retrofitting manual in 1995 version. However, new manual is published in 2006[10]. Equation (1) hasn't changed in new version. The attempt with 2006 version is need in future.

6 ACKNOWLEDGMENT

We wish to acknowledge Kentucky Transportation Center and the University of Kentucky for their contribution.

7 REFERENCES

- [1] David Wald, Kuo-Wan Lin, Keith Porter, Loren L. Turner, "ShakeCast: Automating and Improving the Use of ShakeMap for Post-Earthquake Decision Making and Response", *Earthquake Spectra*, Vol.24, No.2, 2008, pp.533-553.
- [2] Loren L. Turner, David Wald, Kuo-Wan Lin; Shakecast Caltrans Deploys a Tool for Rapid Post-earthquake Response, *TR NEWS*, No.261, pp.40-41. 2009.
- [3] Yasuhiro Shoji," Developing Earthquake Damage Detection and Information Sharing Tools for Road Administrators", *Society for social management systems 2009*, P.81.
- [4] The Japan Building Disaster Prevention Association," Post-Earthquake Temporary Risk Evaluation of Damaged Buildings", <http://www.kenchiku-bosai.or.jp/english/file/epanfall.PDF>, 2009.
- [5] A.G. Sardo, T.E. Sardo, I.E. Harik," Post Earthquake Investigation Field Manual for the State of Kentucky, Kentucky, Kentucky Transportation Center", University of Kentucky, 2006, KTC - 06 - 30/SPR234 - 01-1F.
- [6] Buckle, I.G., and Friedland, I.M., "Seismic retrofitting manual for highway bridges", Federal Highway Administration, US Department of Transportation. Publication, 1995, No. FHWA-RD-94-052.
- [7] Issam E. Harik et.al," Seismic evaluation of bridges on and over the parkways in Western Kentucky Summary Report", Kentucky Transportation Center, University of Kentucky, 2008, KTC-07-02/SPR246-02-1F.
- [8] R. Street, Z. Wang, I. E. Harik and D. Allen; Source zones, Recurrence rates, and time histories for earthquake affecting, Kentucky, Kentucky Transportation Center, University of Kentucky, KTC-96-4, 1996.
- [9] Jian Xie, Issam E. Harik, Tong Zhao and Jindong Hu, "Preliminary Seismic and Ranking of Bridges On and Over the Parkways in Western Kentucky", Kentucky Transportation Center, University of Kentucky, 2008, KTC-07-04/SPR246-02-3F.
- [10] Ian Buckle, Ian Friedland, John Mander, Geoffrey Martin, Richard Nuttand Maurice Power," Seismic retrofitting manual for highway bridges, Federal Highway Administration", US Department of Transportation. Publication, 2006, No. FHWA - HRT - 06 - 032.

International Journal of GEOMATE, March, 2012, Vol. 2, No. 1 (Sl. No. 3)

MS No. 1249 received August 31, 2011, and reviewed under GEOMATE publication policies.

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