13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2226

SEISMIC HAZARD ASSESSMENT FOR BRIDGE ENGINEERING IN CALIFORNIA

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SUMMARY

Following the considerable damage caused by the 1971 San Fernando earthquake, the California Department of Transportation (Caltrans) embarked on a seismic bridge retrofit program with the goal that bridges withstand Maximum Credible Earthquakes (MCEs) without collapse for "safety" evaluation performance. The MCE is defined as the largest earthquake that a seismogenic fault can produce. With the exception of the definition of a seismogenic fault (late-Quaternary-age faults are considered seismogenic by Caltrans), this parameter is time-independent.

Caltrans also requires a few important bridges in the state to remain "functional" after earthquakes smaller and presumably more frequent than the MCE. These events are defined probabilistically and have Functional Evaluation Earthquake (FEE) magnitudes (Jackson, Liu, Kagan, and Mualchin, 2003, and in progress).

Both ground motion and surface fault rupture displacement hazards are considered in design and planning. Seismic hazard analysis is a critical component for screening of over 24,000 bridges in the state for a major seismic retrofit program with a final cost expected to be more than $4 billion in construction. Fault displacement load is a new feature in bridge engineering; currently Caltrans uses the mean horizontal and vertical displacements expected on a seismogenic fault.

The realistic and conservative nature of the Caltrans seismic hazard assessment method, coupled with its ease for use and revision, is its strength and success. The method is rational, cost effective and defensible for public safety policy. This paper describes the philosophy, history, and future direction of seismic hazard assessment for bridge engineering practice in California.

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INTRODUCTION

The California Department of Transportation (Caltrans) is responsible for designing and constructing bridges to withstand effects from maximum credible earthquakes (MCEs) anticipated from known seismogenic faults. The reason for this position is obvious as stated below. Planning and maintenance of the transportation system require seismic hazard information. Caltrans introduced Seismic Retrofit and Toll Bridge programs to strengthen bridges to withstand the forces of powerful earthquakes in order to meet California needs in the future. In all these efforts, realistic estimates of seismic hazards are necessary and required for public safety and effective earthquake mitigation. While we cannot control or predict the timing of future events, we can design and construct safer structures by using improved engineering.

FACTS ON EARTHQUAKES AND DEFINING THE HAZARDS

We make the following observations. First, the accurate prediction of when and where earthquakes will occur is not possible with current knowledge that is based on a very limited record of earthquake history and the geologic evidence. The famous Parkfield earthquake prediction experiment on the San Andreas fault in Central California is a testimony of this fact. That study has led in fact to an appreciation of the complexities of the earthquake process. Second, the sources of earthquakes are faults, and longer fault ruptures can generate larger magnitudes (for example, Wells and Coppersmith, 1994). Third, earthquake timings or recurrence intervals are not generally reliable for engineering applications (Krinitzsky, 1993). Fourth, larger earthquake magnitude events can produce more damaging effects than smaller events, all other factors being fixed. Thus, consideration of effects from the largest earthquake automatically include smaller events.

Because recurrence intervals of earthquakes are not reliably predictable, time-dependent seismic hazard estimates are inherently not reliable. Thus, the most appropriate method for critical engineering is essentially a time-independent seismic hazard analysis. It must be stressed that whenever damaging earthquakes occur the structures must have been designed to withstand the effects; earthquake timing is immaterial for structural safety.

Based on the above facts, Caltrans has used and will continue to use the concept of quantifying the largest earthquake a seismogenic fault can produce, or the maximum credible earthquake (MCE). Our experience from recent damaging earthquakes in California, such as the Landers, Northridge, and Hector Mines earthquakes, confirm the usefulness of our hazard assessment philosophy. These earthquakes were not unexpected in that we anticipated such earthquake magnitudes to occur on these faults based on physics and geology (Mualchin, 1996b).

This approach has been supported by Stark and Freedman and other researchers (in Mulargia and Geller, 2003). Stark and Freedman state that, “Another large earthquake in the San Francisco Bay Area is inevitable, and imminent in geologic time. Probabilities are a distraction …… They should largely ignore the USGS probability forecast.” Clearly, Caltrans is acting proactively for public safety.

IMPACT OF THE 1971 SAN FERNANDO EARTHQUAKE

Considerable damage to bridges and other structures was caused by the 1971 San Fernando earthquake. Caltrans responded with a modern seismic bridge program to ensure that its bridges could withstand Maximum Credible Earthquakes (MCEs) anticipated from late-Quaternary or presumed active faults. The principle of design criteria based on a dynamic analysis method was presented by Gates (1976). Gates' criteria is currently captured in the Caltrans ARS curve (A is expected peak rock acceleration at the site from an MCE magnitude, R is strong motion spectral shape on rock site, and S is the soil site response factor) which is appropriate and practical for use in bridge engineering. The A factor is estimated using appropriate attenuation curves, the R factor is obtained using either site-specific information or curves first presented in ATC-32 (1996), and the S factor is estimated by either site-specific response calculations or using a standardized site codified value. The Caltrans approach has been used and improved, and reaffirmed recently by Krinitzsky (2002).

To provide peak rock acceleration for design, Greensfelder (1974) developed the first Caltrans seismic hazard map using 77 faults and attenuation relationships developed by Seed and Schnabel (1973). It must be noted that this Caltrans map was successfully used for more than a decade by most industry and public users in California, including designers of hospitals and other critical structures.

After the San Fernando earthquake, improving existing bridge performance during damaging earthquakes was undertaken by Caltrans, with an ongoing bridge retrofit program. 1,262 bridges have been retrofitted at a cost of $54 millions. Seismic retrofit work on bridges has become one of the top priorities of Caltrans. Information on Caltrans Seismic Retrofit Program can be seen at http://svhqsgi4.dot.ca.gov/hq/paffairs/about/retrofit.htm.

UPGRADING DESIGN CRITERIA AND THE SEISMIC HAZARD MAP

Caltrans is upgrading its design criteria and construction standards by using advances in earthquake knowledge and analysis. Mualchin and Jones (1992) produced a revision in Greensfelder's Caltrans seismic hazard map. Note that this map was prepared after spending significant time using the probabilistic approach. The method was demonstrated to be not reliable in general and critical fault data needed for such calculations were not available on a statewide basis, which is still true today. On the Caltrans 1992 map, 234 faults were used, mostly from fault data obtained from the California Division of Mines and Geology (now known as the California Geological Survey). Improved methods for estimating moment magnitudes for MCE were developed and a new set of attenuation relationships prepared for the revised map. Deep-seated faults were included for the first time and a three-dimensional fault geometry was used for preparing peak acceleration contours.

The 1989 Loma Prieta earthquake which caused considerable damage to bridges in the San Francisco Bay area significantly impacted Caltrans. The Caltrans Seismic Advisory Board was formed by the state on the disaster experience and a report was prepared (Housner, 1992). As a result, Caltrans again significantly upgraded its earthquake program, accelerating its ongoing retrofit program (Roberts, 1992) by, for instance, adopting a procedure using steel jackets to increase the strength of single-column bridges. Prior to construction, Caltrans prioritized bridges by screening bridge vulnerability, considering usage of bridges and the seismic hazard factors of the 1992 map (Maroney and Gates, 1992). In the accelerated retrofit program, 1,039 bridges identified as most vulnerable to earthquake damage were to be retrofitted at a cost of $812 million.

MODERN SEISMIC DESIGN CRITERIA AND USE OF GIS

Caltrans continuously improves its standards and practices and seismic hazard analysis is no exception. An innovative GIS seismic hazard map was proposed and developed (Mualchin, 1993), using and advancing ESRA's Arc/Info software. Caltrans officially published the map in 1996 (Mualchin, 1996a) using 273 faults. The map was launched online for internal users and the public for comments and suggestions The map and report can be found at: www.dot.ca.gov/hq/esc/earthquake_engineering/Seismology/seismicmap.html. The map is continously updated with changes posted under "Errata". The superiority of the GIS map is not only its ability to integrate various overlays including bridge locations, but also its analytical capabilities, and practicality for use in a networking environment by users at the office or in the field, and its currency and ease of revision. The potential applications of the GIS map is unlimited.

Another damaging earthquake occurred in 1994 in Northridge, not far from the location of the 1971 San Fernando earthquake. Caltrans had already retrofitted prioritized bridges in the area, but earthquakes do not wait and considerable damage to certain bridges occurred. The Caltrans Seismic Advisory Board was assembled again and prepared another report in the aftermath of this event (Housner, 1994) to assess shortcomings and provide suggestions to Caltrans.

Caltrans oversaw the comprehensive seismic hazard study conducted by private consultants for the toll bridge retrofit program during the 1990s. For this study, probabilistic ground motion response spectra were to be included for comparison purposes only along with standard deterministic Caltrans ARS curves. Caltrans began to introduce performance design using safety evaluation for ordinary bridges and functional evaluation performance levels for important bridges at this time. In this new design criteria matrix, the equivalent return periods of probabilistic strong motion spectra were included for safety evaluation, and functional evaluation design was to be estimated probabilistically.

Caltrans also recognized that the earthquake strong motion spectral shape also depends on its magnitude, i.e., that larger earthquakes have longer periods. This was reflected in the report prepared for Caltrans by Applied Technology Council (1996). The new design criteria require the design individual to consider and compare the effects from several faults and their MCEs to select the design ARS curve which will give the largest response at the structural fundamental period. This is a distinct improvement in selecting appropriate seismic load.

Today, improved estimates of peak accelerations and MCEs are possible with more data. We now use horizonal and vertical motions, as well as fault normal and fault parallel motions because of better information on faults and strong motion characteristics. We can also provide enhanced strong motions on sites towards and above the hanging wall side of thrust and reverse faults.
In the ongoing development of seismic design load criteria, advanced seismological applications are being used. These applications include incorporation of directivity and coherency of seismic waves, fault normal and fault parallel seismic waves, and enhanced strong motions for thrust and reverse faults on or above the hanging wall side. Because of the large uncertainties associated with these factors, especially for future events, Caltrans will continue to exercise appropriate engineering judgements for the final design.

Information on Caltrans seismic design criteria and Engineering standards or services are on the websites given in the references.

SURFACE FAULT RUPTURE DISPLACEMENT HAZARD

It is the policy of Caltrans to avoid siting new bridges across or very near seismogenic faults. This is a realistic and prudent policy to be considered starting with the planning stages of a project. However, certain existing bridges may have been located in such sites. Also, exceptional cases may arise for certain new bridges which because of their locations or lengths must be built across or very near seismogenic faults. Decisions must be made regarding design of such bridges where the hazard cannot be avoided.

Fault rupture displacement estimate is challenging scientifically and also in the basic data gathering process. Caltrans has a more inclusive seismogenic fault database than that included in Hart and Bryant (1997). Faults older than Holocene are well known to be seismogenic worldwide. Thus, Caltrans uses late Quaternary and younger faults for fault hazard considerations.

As fault displacement on a fault rupture plane is multi-valued, from zero to some maxima, there is no objective definition of a single fault displacement. Field methods are limited and precise location of a fault is difficult and must be interpreted by a competent seismic hazards geologist. When a structure is located across a major fault such as the San Andreas, anticipated displacement may be so large that it is beyond current engineering capability.

At this time, the size of earthquake that a fault can generate must be estimated based on thorough geologic and seismologic study, which include geologic mapping and geophysical methods and trenching investigations. The mean displacement anticipated from the predicted magnitude and its sense of motion is recommended for design. The sense of motion includes horizontal and vertical components as well as longitudinal and transverse to the bridge.

FUTURE DIRECTION

1. Caltrans will maintain and improve the MCE-based deterministic seismic hazard map by adding newly discovered seismic sources, revising the map with new information, and completing the list of basic fault parameters. Caltrans will continue to use the deterministic method for estimating seismic hazards for most bridges because of the uncertainties associated with earthquake recurrence intervals required for probabilistic seismic hazard analysis and the high confidence that has been gained from using the deterministic method at Caltrans for more than 30 years.
2. Results for the FEE map, still in development, will be simplified and included in the GIS map overlays.
3. Combined source-specific and site-specific information used for seismic hazard estimates will be attempted when needed, using fault/source data in the GIS map. This will require assumptions regarding rupture propagation, focusing, and other dynamic characteristics of the source. Such information will be developed by Caltrans seismologists, geologists, and engineers when not otherwise available.
4. New, economic and efficient methods for site response estimates will be considered, for example the use of microtremor measurements for soft soil sites and the use of tomography to define subsurface geologic structure for improved models.
5. Simplified seismic hazard zones may be developed for certain regions.
6. Comparison between the design load and recorded strong ground motions with respect to the performance of bridges after damaging earthquakes will be conducted to improve design.

CONCLUSIONS

1. Seismic hazard assessment is an integral part of the design process at Caltrans. We will continue to update and maintain the Deterministic Seismic Hazard Map of California based on Maximum Credible Earthquakes (MCEs).
2. The Caltrans Seismic Safety Retrofit Program is the largest of its kind in the world, created to mitigate earthquake damage of bridges in California. Seismic retrofit work on bridges has become one of the top priorities of Caltrans. The program has addressed approximately 2,200 structures, including toll bridges, with a final cost of expected to be more than $4 billion.
3. Because of extreme complexities in both ground motion and fault displacement hazard distributions, Caltrans will always exercise professional judgments on preferred design values.
4. Though earthquakes are not predictable, Caltrans' position is to be proactive assuring protection against the largest events at any time.

ACKNOWLEGEMENTS

I thank Rob Stott, Deputy Division Chief, Structure Design Services & Earthquake Engineering, and Mike Keever, Chief of Earthquake Engineering, for their continued support and encouragement in my work. I am grateful to my colleague, Martha Merriam for improving the paper. The acceptance of the abstract of my paper by the reviewers is gratefully acknowledged. All errors and shortcomings are my own.

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