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Earthquake Hazard Reduction in the Central and Eastern United States:
A Time for Examination and Action

DEVELOPING A RATIONAL SEISMIC SAFETY POLICY FOR URBAN AREAS WITH FUZZY SEISMICITY

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ABSTRACT

Problems in establishing and mitigating seismic risk in urban areas when seismicity is not confidently based on instrumental records are discussed. Urban Southwestern Ohio is taken as a specific example. Research results pertaining to the seismic vulnerability of recurring constructed facilities are presented. The needs for rigorously establishing seismic risk, developing a realistic mitigation policy and its implementation are discussed.

INTRODUCTION

Urban earthquake risk has been effectively mitigated in the Western U.S. as a result of establishing seismic hazard confidently and developing and implementing realistic preparedness plans. The 1989 Loma Prieta earthquake revealed the realism of the preparedness plans. Many California agencies such as CALTRANS developed further awareness of seismic risk and intensified mitigation measures. Meanwhile, mitigation measures are not in force in most regions of the Midwestern U.S. This is mainly due to apathy arising from the uncertainties in establishing the seismic hazard. Presently seismic hazard distribution throughout the Midwest is based on historic accounts of damage, without instrumental records or a clear understanding of all the possible source mechanisms.

In the case of Southwestern Ohio (SWOH), seismic shocks have been recorded in 1776 and there were accounts of substantial earthquake damage due to the New Madrid seismic events of 1811-1812. The 9 March 1937 seismic event at Anna, Ohio is listed among the notable historic earthquakes in the U.S. [1]. However, as it has been the case

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in most areas East of the Rocky Mountains, seismic provisions were not enforced in SWOH until after the nationally televised 1989 Loma Prieta earthquake.

Seismic risk is not only dependent on seismic hazard, but is also a function of vulnerability and exposed value. Most of the constructed facilities that have not been designed for seismic forces may be vulnerable even to low levels of hazard. Furthermore, the risk to urban SWOH is accentuated due to the size of population and economic and strategic considerations. There is therefore a need to develop a seismic safety policy customized to the social and economic conditions of SWOH and make concerted efforts in order to effectively mitigate the seismic risk. It is important that there is significant payoff in such planning and mitigation, since preparedness for seismic events also improves mitigating other natural disasters such as floods, tornadoes, explosions, etc.

OBJECTIVES

The objectives of the paper are to: (a) Discuss the exposure of SWOH to seismic risk; (b) review the seismic design demands described in the model codes as well as recent developments in characterizing the seismic hazard in SWOH; (c) present recent research findings regarding the vulnerability of constructed facilities in SWOH; and, (d) formulate recommendations for developing a seismic safety policy for mitigating the risk affecting SWOH.

EXPOSURE OF SWOH

In SWOH, Cincinnati and Dayton are adjoining urban areas exposed to seismic risk. The population of the Cincinnati Consolidated Metropolitan Statistical Area (CMSA) and Dayton CMSA are 1.7 million and 0.9 million respectively as on 1989. The annual income of the residents of these two areas add up to $33 billion, 25% of the state's total [2]. The value represented by the physical infrastructure at risk in SWOH is estimated to exceed $25 billion. Cincinnati and Dayton are home to many major industries and federal facilities. SWOH serves as a transportation corridor with three major freeway systems. The Ohio river is a critical transportation artery. Finally, several gas and product pipelines and major electrical transmission lines of the Midwest power pool traverse the Cincinnati CMSA. It follows that SWOH represents a critical exposure in terms of population, physical infrastructure, manufacturing industry and other facilities that are quite critical for the economy and the national security.

SEISMIC HAZARD IN SWOH

Problems in Accurately Establishing the Seismic Hazard

To accurately establish seismic hazard of a region in probabilistic terms, instrumental ground-motion records are needed in sufficient quantity for a statistical data-base. In addition, identification of the potential seismic zone sources are required. On the other hand, no strong-motion records have been retrieved in SWOH since the past destructive earthquakes occurred before the modern instruments were developed. No ground-motion records could be retrieved from the minor shocks which affected SWOH in recent times as the modern seismic instrumentation networks in the Midwest did not extend to this area. Detailed investigation of a pre-Cambrian rift extending through SWOH is underway [3]. Additional geophysical and paleo-seismic studies and seismic instrumentation network are needed in order to scientifically establish seismic hazard in SWOH.

Seismic Hazard Indicated by Model Building Codes

Until the 1980's, the national building codes adopted a seismic hazard map developed by Algermissen [4]. This map was constructed from historic accounts, based on an estimate of the maximum ground shaking experienced by a region without considering the frequency of occurrence of earthquakes. The Ohio Basic Building Code (OBBC) [5] which used this map, placed SWOH in the moderate seismic zone (Zone 2 of 3 zones) until 1989 and AASHTO [6] used this map until 1991. The resulting design base shear coefficient for a mid-rise building with a period of 1.77 second and a reduction factor of one is 0.165, while the equivalent horizontal force coefficient for a bridge with a period of 0.14 second is 0.1.

Algermissen and Perkins [7] developed a new seismic hazard map for U.S. in 1976 by incorporating established source mechanisms, magnitude and frequency of occurrences and proper attenuation relationships based on instrumental data. This map was based on a 10% probability of exceedence within 50 years. This map was adopted after minor modifications by several model codes in the eighties and by OBBC in 1989 and by AASHTO in 1991. Based on this map, SWOH falls within the zone of low seismicity i.e. zone 1 of 4 zones, and the design base shear coefficient for a building with a period of 1.77 seconds reduced from 0.165 to 0.075. The equivalent horizontal force coefficient for the bridge with a period of 0.14 second reduced from 0.1 to 0.07. It follows that the seismic hazard defined by model codes for SWOH was reduced by 30-50% after a probabilistic map was adopted by the codes. This is attributed to a lack of knowledge of the precise earthquake source mechanisms and instrumental recordings for this area as well as the low frequency of occurrence of damaging ground motions in the past.

Another issue related to the hazard map is that it divides the country into four or five broad zones. Each zone covers a large area and an average intensity of ground shaking expected at each zone is specified [8]. It follows that these codes do not assess the actual seismic hazard at the regional and local levels. Therefore, many region-specific and site-specific ground failure hazards such as liquefaction, soil instability etc. go unnoticed. Furthermore, although knowledge on characterizing seismic source zones as well as scientific basis of hazard assessment have been improved significantly in recent years, there is a natural time lag before these advances are introduced into model codes.

Recent Changes in Seismic Hazard Depicted for SWOH

In 1988, Federal Emergency Management Agency (FEMA) issued seismic hazard maps for two levels of earthquake [9]. The new maps characterize the hazard corresponding to a maximum credible earthquake (10% probability of exceedence in 250 years) in addition to a design earthquake (10% probability of exceedence in 50 years). For SWOH, the maximum credible earthquake has about 3 times higher damage potential than the design earthquake. However, the discrepancy between the design forces for the design and credible earthquakes is considerably less in the Western U.S. As per the performance criteria employed, the structures designed for the design earthquake should generally resist the maximum credible earthquake with repairable structural damage. In SWOH, on the other hand, the performance of the structures even if these were designed for the design earthquake may be catastrophic in the event of the maximum credible earthquake. The fact remains that most structures have not been designed even for the design level earthquake. Presently, designers still omit the earthquake provisions if the total wind loads exceed the design earthquake base shear.

The maximum credible earthquake corresponds to a constructed facility service life of 250 years. Seismic hazard maps in the current codes that are based on a 50-year service life are significantly underestimating seismic hazard to certain constructed facilities that need to be designed for an extended service life. It should be noted that many important, essential or critical constructed facilities need to be designed for an extended service life.

The Electric Power Research Institute (EPRI) recently conducted an extensive study to assess the seismic hazard in the Central U.S. for designing nuclear power plants [10]. Seismic source zones were identified based on tectonic features and seismotectonic regions. The study indicated that the seismic hazard in SWOH may be considerably greater than what is indicated by model codes when return periods of 1000 years or longer are considered.

SEISMIC VULNERABILITY IN SWOH

Since the seismic design provisions were not enforced in Cincinnati until recently, and the lack of enforcement still prevails in the case of most local governments, a majority of the existing mid-rise buildings have not been designed and detailed for seismic forces. These buildings may not perform satisfactorily even in the event of the expected earthquake and therefore, pose a threat to life safety.

According to the Ohio Department of Transportation, none of the highway bridges in SWOH have been designed and constructed considering any seismic effects until this year. Certain bridge types such as continuous steel-stringer bridges supported on roller-rocker bearings without any lateral restraint, may be particularly vulnerable. These are exemplified in the following.

CASE STUDIES

Vulnerability of a Mid Rise Building

A 27-story RC flat slab-core building which was located at Cincinnati was utilized as a specimen for evaluation. The structural system represented a large stock of mid rise RC construction in the Midwestern U.S. Closed-loop modal tests were performed for structural identification. The dynamic characteristics and lateral flexibility were identified from the measured acceleration responses. A comprehensive 3D analytical model was developed based on the ETABS program [11] and this was calibrated against modal test results. Foundation flexibility was carefully measured and simulated in the model.

Rigorous seismic vulnerability evaluation was performed using the FEMA-178 handbook [12]. Response spectra were constructed as per the FEMA-178 and also for the maximum credible earthquake as per the NEHRP 1988. Response spectrum analyses were performed using these spectra and demands were computed at the element level. The capacities of elements were calculated and the demand-to-capacity (D/C) ratios were computed for both FEMA-178 and 1988 NEHRP seismic forces. The building was vulnerable even for the reduced level of seismic forces prescribed by FEMA-178. The exterior slab-column connection was found to be the weakest link in the building. Due to the influence of the gravity load on the strength of the connection transferring the unbalanced moment, the connection was found vulnerable to failure by flexure followed by punching shear. The building was found susceptible to a progressive collapse due to the lack of adequate anchorage of the bottom bars at slab-column and slab-wall connection regions.

The implosion of the building in June 1991 provided an evidence of its failure behavior. Films of implosion and debris revealed that implosion resulted in a progressive collapse and pancaking of all the floor slabs. A brittle fracture failure mode at the slab-column and slab-core connections was the governing mechanism which led to a complete pancaking and collapse.

Mid-rise flat slab buildings which are typical in the Midwestern U.S., if they possess similar vulnerability, should be considered as potentially hazardous buildings. The risk posed by this type of building due to its catastrophic failure nature is unacceptable. Therefore, efforts for evaluation and upgrading of this type construction is needed in order to effectively mitigate the seismic risk.

Vulnerability of Highway Bridges

Two steel-stringer highway bridges representing typical bridge in the Ohio system were tested. The superstructure of both bridges comprised of reinforced concrete slab supported on steel girders. The superstructure of the first bridge constructed in 1990 is supported on elastomeric pads at the piers and integral-abutments. The superstructure of the second bridge constructed in 1973 is supported by bolsters and rockers over the piers and abutments.

For each bridge, a complete 3D finite element model was developed using the SAP90 program [13] and calibrated through structural identification. Modal tests as well as controlled truck-load tests were conducted for the experimental components of structural identification. Response spectra were then developed as per the AASHTO [6]. Response spectrum analyses were performed for both expected and maximum credible earthquakes. Following the ATC-6-2 [14], the D/C ratios were computed. The D/C ratio of the bolster bearing which is critical for this type of bridge was investigated. The lateral capacity of this bearing is equal to the tributary weight on it as per a previous experimental investigation [15].

The first bridge was found to be safe for both levels of earthquakes. For the second bridge, D/C for bolster bearing is 0.71 and 1.42 for the design and maximum credible earthquakes respectively. This bridge is therefore vulnerable to the maximum credible earthquake. This indicates that other similar types of bridges may be vulnerable to the maximum credible earthquake in SWOH and therefore, careful evaluations are needed.

EARTHQUAKE HAZARD MITIGATION POLICIES

The basic policies for hazard mitigation that are currently implemented in the U.S. prior to an occurrence of earthquakes are shown in Table 1 [16]. Such measures are completely ignored or the measures implemented are inadequate for providing a contemporary level of seismic safety in many urban areas of the Midwestern U.S. Implementation of seismic design provisions in the building codes is important for mitigation in the case of new buildings. A problem regarding codes is that national building/bridge codes consider SWOH as a region of "low" seismicity based on the "expected" earthquake, ignoring the potential of a "maximum credible" earthquake. The seismic provisions of these codes do not address many design /detailing issues which may become critical when the maximum credible earthquake is considered. For example, there is a lack of information on the design and detailing of the connections between the diaphragm and the vertical elements in a flat slab building. This is due to the fact the codes do not recommend this type of building in high seismic regions. However, the flat slab building is common in the Midwestern and Eastern U.S. Therefore, for satisfactory seismic performance of this type of building, the connections should be adequate to transfer the lateral loads to the vertical elements.

The connections which are important include the beam-column joints, slab-column connections, and slab-core connections. The design and detailing of the beam-column have been well established and incorporated in the seismic codes. However, although the ACI 352 committee presented recommendations in 1988 [17] for the design of slab-column connections which were based on recent research, these have not yet been incorporated in the building codes. Furthermore, there is a lack of clear understanding of the behavior of slab-core connections. At present, this connection is treated as a moment-free pinned connection. However, the typical monolithic connection would act as rigid and it should have the capacity to transfer the shear and axial forces from the

Table 1. Policies for hazard reduction prior to occurring of earthquakes [16].

Policy		Affected Parameter
Direct	Indirect	
Building code development, land use planning, and zoning Warning systems Soil stabilization Land modification Strengthening of existing high-risk structures and facilities	Earthquake insurance Quality control of construction Licensing of design professionals Education of the public Prediction/warning procedures Emergency plan	Exposure Risk Primary and secondary hazards Vulnerability

diaphragm to the vertical elements following cracking and yielding of the diaphragm reinforcement in flexure. Since these connections are critical for satisfactory seismic performance, it is essential to incorporate provisions for the proper design and detailing of these in the building codes. The connections between facade elements and the structures are important even for mitigating the effects of tornado or hurricane [18].

At present, if the design seismic forces are less than the design wind forces, seismic design and detailing provisions are completely ignored by SWOH engineers. The designers do not realize that the nature of seismic loading and philosophy of seismic design differ significantly from those of the wind. The design seismic forces as per the codes are based on the assumption that the buildings will resist earthquakes by inelastic energy dissipation. The actual seismic forces are reduced by a reduction factor which depends on the energy dissipation capacity of the structural system. The nonstructural, structural, and foundation systems should be conceptually designed to provide desirable seismic attributes, and properly detailed for seismic performance. If the seismic design and detailing are ignored, the performance of the building would not be satisfactory in the event of the expected earthquake even if the design seismic forces are lesser than the wind forces. Therefore, the building codes should provide guidelines to address this problem.

Another component of hazard reduction is the development of zoning maps. In SWOH, the presence of deep-fills and sporadic recurrence of lake-bed layers indicate the possibility of ground failures including liquefaction and landslides during an earthquake. Geological information should be utilized in identifying hazardous areas. To reduce the risk, land use planning should be implemented which is necessary for the selection of sites for facilities, particularly critical facilities and lifelines.

Seismic safety is not possible just by enforcing the codes. It is necessary to control the quality of construction and implement emergency plans. Furthermore, education of design professionals and public officials regarding seismic hazard mitigation is needed.

The public should also be educated for awareness of the actual seismic risk in terms of loss of life and economic losses.

CONCLUSIONS AND RECOMMENDATIONS

According to the maps issued recently by FEMA, as well as studies by EPRI, the seismic hazard in SWOH is considerably higher than what has been depicted by the model building codes based typically on a 10% probability of exceedence in 50 years. The new hazard maps issued by FEMA indicate that the damage potential of a maximum credible earthquake with a 10% probability of exceedence in 250 years is 2-3 times higher than the seismic loads that are being considered in designing ordinary construction with a typical 50-year service-life.

The performance criteria adopted for ordinary constructed facilities is that these are expected to survive a major earthquake with only repairable structural damage and without any casualties. This may be satisfied in Western U.S., since the magnitude of the design earthquake is of the same order as that of the maximum credible earthquake. However, in SWOH, the damage potential of a maximum credible earthquake is 2-3 times higher than that of the design earthquake. Therefore, the performance of the constructed facilities designed for the design earthquake would be catastrophic in the event of the maximum credible earthquake. This nature of hazard compounds the seismic risk due to existing facilities that have not been designed for any level of seismic forces. This has been verified by recent site-and-facility specific research on the seismic performance buildings and bridges in SWOH. It follows that there is an urgent need for evaluating and upgrading existing facilities.

It is not practical to expect life safety performance criteria in SWOH in the event of the maximum credible earthquake for all the facilities as it is demanded in the Western U.S. Although such performance is technically possible, it would not be possible to upgrade all the vulnerable facilities considering social, political, and economic factors. It follows that the performance criteria adopted in SWOH would have to be different than that adopted in the Western U.S. if a realistic mitigation policy is to be established. At least, the important, critical, and essential facilities and lifelines that should remain serviceable should survive the maximum credible earthquake without structural damage and casualties. These facilities are essential facilities such as hospitals, police, firehouses; important facilities with large population concentrations such as schools; critical facilities such as power plants, dams, hazardous waste containment facilities; and, lifelines such as water, sewer, communication, power distribution lines, and certain bridges. These facilities should be evaluated and retrofitted to guarantee a minimum acceptable performance.

There is public apathy for seismic risk mitigation in the Midwestern U.S. in view of the absence of a past destructive earthquake in the contemporary history of this region. Although research has revealed the extent of vulnerability of existing structures, it is difficult to convince the officials to take any action to upgrade these facilities. It is necessary to minimize the uncertainties in assessing seismic hazard and to prove the catastrophic failure nature of hazardous existing structures. It follows that considerable region-specific research, education and engineering applications are necessary before accomplishing a contemporary level of seismic safety in SWOH.

In the Midwestern U.S., the local governments should implement the basic earthquake mitigation policies such as building code implementation, land use planning and zoning, quality control of construction, education of the public, and emergency planning. The building codes should provide guidelines for proper seismic design, particularly the design and detailing of the connections between diaphragms and vertical elements.

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