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CHARACTERISTICS OF SEISMICITY IN STABLE CONTINENTAL REGIONS IMPROTANT FOR SEISMIC HAZARD ASSESSMENT

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ABSTRACT

Subjective evaluations of seismic sources and seismicity parameters are required as basic inputs for probabilistic seismic hazard assessments. In stable continental regions which are characterized by very low seismicity, these input evaluations are highly uncertain because of limited geological and geophysical indicators of earthquake activity coupled with limited seismicity data. The regional data bases can be significantly expanded however, by treating low seismicity stable continental regions world-wide as tectonically analogous. The world-wide data provide insights regarding correlation of seismicity with tectonic features, aiding the interpretation of seismic sources, and may be used to constrain seismicity parameter interpretations (recurrence rates and maximum magnitudes) for probabilistic seismic hazard assessments in these regions.

INTRODUCTION

State-of-practice methods for assessing seismic hazard at a site rely on subjective evaluations of earthquake sources, of earthquake sizes and recurrence rates (if probabilistic assessments are desired) associated with each seismic source, and account for the variability in ground motion attenuation (EPRI, 1989). These subjective interpretations constitute a basic requirement for every seismic hazard assessment whether deterministic or probabilistic approaches are used to model the vibratory ground motion hazard at any particular site. Thus, the geological, geophysical and seismological data on which all evaluations must depend are of fundamental importance. The more sparse the data and the weaker our understanding of their significance as indicators of earthquake activity, the more uncertain our interpretations must be. Consequently, interpretations are generally less certain in tectonically stable continental interior regions, which are characterized by low seismicity and sparse, poorly developed geologic indicators of seismogenic activity, than in interplate regions, which typically have relatively high seismicity and reasonably well developed geologic indicators of seismic activity. Recent experience is that it is necessary and most productive to use the broadest available data (geological, geophysical and seismological) in an integrated interpretation for evaluating seismic sources (EPRI, 1989). Similarly, use of multiple estimation approaches are needed for assessing the maximum earthquakes associated with seismic sources and use of multiple ground motion attenuation relationships can result in more complete estimates of vibratory ground motion and its variability. To expand the generally sparse data base for low seismicity regions, data from analogous tectonic regions world-wide can be used (EPRI, 1994).

SEISMIC SOURCES

Seismic sources for the purpose of a seismic hazard analysis, represent locations within the earth that are interpreted to have uniform tectonic and seismicity characteristics (EPRI, 1989; Coppersmith, 1995). Seismicity characteristics are those seismic source parameters that are important for a probabilistic seismic hazard assessment (PSHA): probability of activity (e.g., of alternative source interpretations), rate of earthquake recurrence, and maximum magnitude. The resolving power of various data for evaluating seismic sources is closely linked with characteristics of a tectonic regime. In this context, the boundaries of lithospheric plates and the stable plate interiors can be considered the first order tectonic regimes of the earth. Plate boundaries are characterized by geologically rapid differential movement between lithospheric blocks, local sources of tectonic stress (the differential movement of adjoining plates), and the highest rates of seismicity. In contrast, the interiors of the plates are remote from the loci of differential movement between lithospheric plates, generally do not contain local sources of tectonic stress, and have the lowest seismicity rates among tectonic regimes of the world. As an example, the North American lithospheric plate interior appears to behave tectonically as ridged block within which tectonic stresses are caused by gravitationally imposed compressive forces at Atlantic ridge spreading zone (Zoback, 1992a). This imposed tectonic stress field may be locally perturbed by crustal structure, or regionally where glacial rebound is taking place, but it can be considered nearly constant in magnitude and orientation of principal maximum components over the entire interior of the plate. The North American plate, consistent with other lithospheric plate interiors, may be further subdivided into an oceanic plate region and a stable continental region (SCR), as defined in EPRI (1994). Because SCRs are tectonically similar they can be considered world-wide tectonic analogs for the purpose of evaluating seismic sources and seismicity perimeters.

The fundamental differences between plate boundary and stable continental region tectonic regimes are reflected in very different seismic source and seismicity parameter characteristics. Seismic sources within plate boundary tectonic regimes generally are faults of various tectonic order, including first order plate boundary fault systems that are the loci of differential movement between the plates. These faults can be mapped on the basis of their recognizable displacements at the earth's surface during the Holocene or Quaternary, or as active folds reflecting buried faults. Although geophysical and seismological data are important for determining the geometries and seismicity characteristics of plate boundary seismic sources, these sources often can be adequately evaluated for PSHA using geological data alone. In contrast, while large-scale tectonic features exist in the brittle crust throughout SCRs, they are relics of previous tectonic episodes and do not act as loci for large scale differential movement between crustal blocks in the current tectonic regime. Further, world-wide studies of tectonic features within SCRs show that when reactivitation does occur, it usually involves only portions or segments of the relic feature (EPRI, 1994). While earthquakes within SCR tectonic regimes are considered to be caused by brittle failure on faults within the seismogenic depth of the earth's crust (Zoback, 1992b), just as in highly active interplate tectonic regimes, the determination of which of the many candidate relic tectonic features may be active is highly uncertain and, with notable exceptions, they can be given only a likelihood or probability of being active (termed activity (EPRI, 1989)). Thus within SCRs, tectonic activity usually is not strongly reflected in any geological or geophysical data set, except in rare instances where fault displacements have occurred in the Quaternary. Consequently, an integrated interpretation of geological, geophysical and seismological data is required to assess the seismogenic potential (activity) of tectonic features. Similarly, methods used to evaluate seismicity parameters (especially maximum magnitudes) for seismic sources within plate boundary tectonic regimes are not generally adequate to characterize the seismicity parameters for seismic sources in stable continental tectonic regions. To make these evaluations it is helpful to make use of world-wide SCR seismicity data (EPRI, 1994).

To be adequately complete and credible, interpretations of seismic sources in low seismicity SCRs must be based on an integrated evaluation of physical criteria that indicate seismogenic activity, using all available geological, geophysical and seismological data. Relevant geophysical criteria for activity may vary among experts because of uncertain knowledge about the process of tectonic strain release in SCR crust, and the relative importance given various criteria for activity also may differ, often depending on the expert's discipline training. This is simply a part of the knowledge (epistemic) uncertainty about earthquake processes (Budnitz, et al., 1995). In addition, the available data, although extensive for many areas in SCRs, usually must be considered incomplete, further contributing to uncertainty in seismic source interpretations. Thus, to account properly for the uncertainty in seismogenic activity criteria and for, usually, incomplete available date, consistent seismic source interpretation procedures are required (EPRI, 1989). In applying seismic source evaluation procedures, alternative interpretations must be provided to fully express the uncertainty.

The level of effort and procedures required to evaluate seismic sources depend on the intended use of the results (Budnitz, et al., 1995). Given the range of earth-science disciplines required and the diverse data sets that must be evaluated, current practice when the evaluations are for critical facilities is to require multiple seismic source interpretations (as many as six). Seismic source interpretations intended for use in a national building code would require a lesser level of effort and, perhaps, different procedures. The reason for the different requirement is that structures built to national building code requirements are typically designed to withstand earthquake motions expected to reoccur once in about 500 years, while critical industrial facilities must be designed to withstand earthquake motions expected to reoccur only once in about 10,000 years. To demonstrate the higher level of safety for seismic design of critical industrial facilities a greater level of effort and more rigorous procedures are required to evaluate seismic sources (as well as for the remainder of the seismic design process) and fully capture the uncertainty.

SEISMICITY PARAMETERS

The estimation of seismicity parameters (earthquake recurrence frequency and maximum magnitude) for seismic sources in regions of low seismicity is greatly aided by data from analogous regions of the world (EPRI, 1994). Consider the application of the world-wide SCR seismicity data base to the SCR region of eastern North America, east of the Rocky Mountains. This region is one of nine SCRs of the world (EPRI, 1994). Like the other eight SCRs its crust is geologically old and tectonically stable, lacking internal sources of tectonic stress, although glacial rebound appears to shift the relative magnitude of stress among principal components (Zoback, 1992b). Another characteristic that the eastern North America SCR shares with other SCR tectonic regions of the world is its low rate of seismicity. The average annual strain rate for SCRs is about three orders of magnitude lower than that for plate boundary tectonic regimes. For non-extended SCR crust, the difference is about four orders of magnitude (EPRI, 1994). In consequence of such low seismicity, the historic earthquake data bases for most SCRs is not considered adequate to confidently assess seismicity parameters. However, because of tectonic similarities (relic tectonic features, tectonic stability, and tectonic stresses imposed at the oceanic boundary of the plate), it is reasonable to use world-wide SCR data to aid in evaluating the seismicity parameters of seismic sources in eastern North America.

The recently completed EPRI studies show also that the seismic potential of SCR crust is not uniform but varies depending on the degree of rifting or crustal extension that it underwent in its most recent tectonic deformation in the geologic past and to some extent, its age (EPRI, 1994). In eastern North America, three types of crust are identified: unrifted - the craton and the Appalachian fold belt; failed intracontinental rifts - the St. Lawrence rift complex, including the Ottawa-Bonnechere and Saguenay grabens, and the Reelfoot rift complex; rifted passive continental margin - the Atlantic passive margin, produced by the present opening of the Atlantic Ocean in late Mesozoic, and a relic passive margin produced by the rifting of the Iapetan Ocean at the beginning of the Paleozoic (Johnston, 1995). The Atlantic passive margin includes the continental-oceanic crust boundary and its associated thinned and faulted inboard continental shelf. World-wide, Precambrian rifts such as the Midcontinent rift of Grenville age, appear to be incorporated into the cratonic crust and do not localize seismicity above the background levels (EPRI, 1994, Johnston, 1995).

Seismicity data form analogous SCR crust can be used for the estimation of maximum earthquakes for the various types of SCR crust in eastern North America. World-wide, rifted continental margins such as the Atlantic passive margin, have experienced some of the largest SCR earthquakes. Nine of 15 known SCR earthquakes of moment magnitude ≥ 7.0 occurred on tectonic features within passive continental margin crust. Four of these occurred on continental-oceanic crust boundaries, the largest being the 1933 Baffin Bay earthquake, which had a moment magnitude of 7.3 to 7.7. The two largest earthquakes known to have occurred in inboard extended passive margin crust were both historic; their estimated moment magnitudes are 7.4 and 7.6 (EPRI, 1994, Johnston, 1995).

In eastern North America, the relic Iapetan rift is not distinguished from the Appalachian fold belt on the basis of maximum earthquakes. The largest earthquake associated with the Appalachian fold belt is the 1897 Giles County, South Carolina earthquake which had a moment magnitude of 5.8. Major earthquakes larger than moment magnitude 7.0, similar to those that occur in rifted crust, are not known in fold belt crust. Similarly, major earthquakes are not observed in unrifted cratonic crust. The 1989 Ungava, Canada earthquake of moment magnitude 6.0 (Johnston and Bullard, 1990) appears to be characteristic of the maximum earthquakes that occur in unrifted cratonic crust. Intracontinental rifts such as the St. Lawrence rift complex and the Reelfoot rift, like rifted continental margins, support large earthquakes. The St. Lawrence rift includes the Charlevoix seismic zone which is second in eastern North America only to the New Madrid seismic zone within the Reedfoot rift, in producing large earthquakes. The maximum earthquake associated with the St. Lawrence rift occurred in the Charlevoix seismic zone in 1663. Its moment magnitude has been estimated to be 6.6, with an estimation error of about ± 0.5 magnitude units. The largest earthquakes associated with the Reelfoot rift were centered in the New Madrid seismic zone in 1811 - 1812. The three largest earthquakes of this sequence had estimated moment magnitudes of 7.8 to 8.1, the largest earthquakes known in SCR crust (EPRI, 1994, Johnston, 1995).

Probabilistic seismic hazard results are strongly correlated with the frequency of earthquakes and their distribution with magnitude. For seismic sources in eastern North America and similar SCRs where earthquake recurrence is extremely low, these parameters are often difficult to estimate for specific seismic sources using local data alone, introducing large uncertainty. To augment the sparse data and obtain more certain results, seismicity data from analogous SCR crust world-wide can be used to aid in estimating seismicity rates and to provide constraints on the rates for specific seismic sources. The normalized rate (normalized on area) of earthquakes in eastern North America larger than moment magnitude 5 is not significantly different from the global SCR rate and the normalized rate for eastern North America rifted crust in nearly twice that for unrifted crust. Globally, the normalized rate for rifted crust exceeds the rate for unrifted crust by a factor of 4, The recently completed EPRI studies show also that the seismic potential of SCR crust is not uniform but varies depending on the degree of rifting or crustal extension that it underwent in its most recent tectonic deformation in the geologic past and to some extent, its age (EPRI, 1994). In eastern North America, three types of crust are identified: unrifted - the craton and the Appalachian fold belt; failed intracontinental rifts - the St. Lawrence rift complex, including the Ottawa-Bonnechere and Saguenay grabens, and the Reelfoot rift complex; rifted passive continental margin - the Atlantic passive margin, produced by the present opening of the Atlantic Ocean in late Mesozoic, and a relic passive margin produced by the rifting of the Iapetan Ocean at the beginning of the Paleozoic (Johnston, 1995). The Atlantic passive margin includes the continental-oceanic crust boundary and its associated thinned and faulted inboard continental shelf. World-wide, Precambrian rifts such as the Midcontinent rift of Grenville age, appear to be incorporated into the cratonic crust and do not localize seismicity above the background levels (EPRI, 1994, Johnston, 1995).

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CONCLUSIONS

Some of the uncertainty in the assessment of seismic hazard in low seismicity SCR regions can be reduced by using seismicity data from analogous regions world-wide. Information on the correlation of seismicity with tectonic features can provide valuable guidance in interpreting seismic sources. The world-wide SCR seismicity data, while not definitive, provides valuable constraints on the assessment of seismicity rates and maximum earthquakes associated with specific seismic sources.

REFERENCES

Budnitz, Robert J., George Apostolakis, David M. Boore, Lloyd S. Cluff, Kevin J. Coppersmith, C. Allin Cornell, and Peter A Morris (1995). Recommendations for Probabilitic Seismic Hazard Analysis: Guidance on Uncertainty and Use of Experts. NUREG/CR-6372, U. S. Nuclear Regulatory Commission, Washington, DC.

Coppersmith, Kevin, J. (1995). Methods and Procedures for Determining Seismic Sources Based on Geological and Seismological Information. In: Atomic Energy Control Board Workshop on Seismic Hazard in Southern Ontario, June 19 - 21, 1995, Ottawa, Canada.

Electric Power Research Institute (EPRI) (1989). Seismic Hazard Methodology for the Central and Eastern United States, Volume 1, Part 2: Methodology. NP-4726A, Electric Power Research Institute, Inc., Palo Alto, CA.

Electric Power Research Institute (EPRI) (1994). The Earthquakes of Stable Continental Regions, Volume 1: Assessment of Large Earthquake Potential. TR-102261s, Electric Power Research Institute, Inc., Palo Alto, CA.

Johnston, A. C. (1995). Stable Continental Earthquakes and Seismic Hazard in Eastern North America. In: Atomic Energy Control Board Workshop on Seismic Hazard in Southern Ontario, June 19 - 21, 1995, Ottawa, Canada.

Johnston, A. C., and T. Bullard (1990). The Ungava, Quebec, earthquake: Eastern North America's first modern surface repture (abs.). Seismological Research Letters, 61, 3-4, 152-153.

Zoback, Mary Lou (1992a). "First and second-order patterns of stress in the lithosphere: The World Stress Map Project". Journal of Geophysical Research, 97, B8, 11,703-11728.

Zoback, Mary Lou (1992b). "Stress field constraints on intraplate seismicity in eastern North America. Journal of Geophysical Research, 97, B8, 11,761-11,782.