AN INTRODUCTION TO PREDICTING EARTHQUAKE HAZARDS AND LOSSES IN THE PACIFIC NORTHWEST

By Albert M. Rogers[1] *and* George R. Priest[2]

INTRODUCTION

The articles in the Earthquake Hazards section of the professional paper discuss ground-shaking and ground-failure hazards and the estimation of losses associated with these hazards. Ground shaking and ground failure are the major factors in loss of life and property during earthquakes. The delineation of these hazards by mapping and site-specific prediction techniques is an important step in the process of reducing the effects of earthquakes. Ground-shaking and ground-failure maps, for example, can be valuable in land-use-policy development, siting or relocation of local government emergency facilities, and urban-renewal decisions. Furthermore, hazard maps can aid in the design and siting of lifelines (see volume 1, Glossary) and ordinary structures and in emergency planning and response, each requiring advance information about the likelihood of earthquake damage to infrastructure. Estimates of the magnitude of economic losses and mortality during future earthquakes are also partly based on hazard maps. Loss estimates are not only useful in planning for earthquakes but also serve decision makers in establishing preventive actions and determining the rate at which resources should be expended to reduce earthquake effects.

Preparation of hazard maps requires extensive regional development of databases, a process that is far from complete in the Pacific Northwest. Useful hazard maps, for example, are based on detailed mapping of geologic deposits and measurement of their physical properties and on topography, sediment thickness, basin geometry, water-table depth, attenuation of ground motion, and the seismic and geologic mapping of young faults capable of producing damaging earthquakes. A new earth-science field called paleoseismology has emerged that provides information about recurrence rates on faults and the time since the last earthquake, data that can be incorporated into probabilistic ground-motion maps or used to forecast the probability of the next earthquake during a chosen time interval. Database development will also be of great value in continued research to improve hazards-prediction methodology.

Site-specific hazard estimates are most useful in the design of critical facilities and high-occupancy buildings such as bridges, power plants, hospitals, and high-rise structures. The information used for site-specific estimates is generally more detailed than that required to produce hazard maps. Such estimates are commonly based on borehole measurements at the site and modeling of local ground motions based on these measurements and also on data such as regional ground-motion attenuation and fault locations.

Estimating ground-shaking and ground-failure hazards in this region is complicated by three factors. First, several types of earthquakes are likely (see Rogers and others, volume 1, for a discussion of earthquake types), and each type is expected to produce damage that differs in geographic distribution and level of intensity. Second, very few strong-motion records exist that would permit calibration of models or generalization about the characteristics of ground shaking for the region. Furthermore, no records exist for the types of Pacific Northwest earthquakes having the greatest potential for destruction, that is, the great Cascadia thrust-fault earthquake and the shallow continental-crust earthquake. Third, the types of data needed to produce microzonation maps for strong motion, ground failure, and losses are not yet available except in limited areas.

Nevertheless, some estimates of these factors are possible. This volume presents work to develop several types of databases, research to predict site-specific estimates of ground shaking for several earthquake types, research to map limited areas that depict some types of ground failure, and the estimation of one type of economic loss. In the following, we review the reports that contribute to the

[1]U.S. Geological Survey, Box 25046, MS 966, Federal Center, Denver, CO 80225.

[2]Oregon Department of Geoscience, 910 State Office Building, 1400 S.W. 5th Ave., Portland, OR 97201.

understanding of these problems. A review of earlier work on this topic is presented in the introduction to this professional paper (Rogers and others, volume 1).

GROUND FAILURE

One of the first steps in the development of a ground-failure prediction capability is the assessment of past ground failures. This assessment is important in two respects. First, we know from experience elsewhere that ground failure is likely to recur in many of the same locations during successive earthquakes, given the same conditions. Second, past ground failures tell us about the local conditions, earthquake magnitudes, and epicenter distances likely to produce ground failures in the future. Chleborad and Schuster (this volume) present a study of ground failures associated with the 1949 and 1965 Puget Sound earthquakes. Failures from these events were spread across a large part of the Puget Sound region and northwestern Oregon and included landslides, ground settlement, ground cracks, and liquefaction effects such as sand boils and lateral spreading. Other miscellaneous effects that may have been related to ground failure, such as broken and bent underground pipes, are also mapped. These maps demonstrate the widespread susceptibility of this region to earthquake-induced ground failure and the concentration of these effects near bodies of water, along bluffs, and in lowland areas with a high water table. For larger earthquakes or earthquakes with shallower focal depths than the 1949 and 1965 events, the effects are expected to be more widespread and intense.

Grant and others (this volume) present a map showing the estimated liquefaction hazard for Seattle based on standard penetrometer measurements in more than 300 borings, depth to the water table, geologic maps of surficial units, and unit thickness. They develop two sets of criteria for liquefaction that in combination permit the delineation of areas of high, moderate, low, and very low liquefaction potential. This map shows that the zones of high and moderate liquefaction are concentrated along shoreline areas, in areas of fill, and along the Duwamish River tide flats and Interbay (Smith's Cove) areas. The map should help in development of land-use policies, estimation of future losses, recognition of the need for site-specific studies for some types of structures, disaster planning, and other decision making by local governments and citizens.

GROUND-MOTION ESTIMATION

DATABASE DEVELOPMENT

That near-surface geologic conditions can influence the level of strong ground shaking is well known (for example, see Kanai, 1952; Gutenberg, 1957; Borcherdt and others, 1975; and Rogers and others, 1985). The effects can be large at some places; consequently, any attempt to estimate future ground motions must account for the influence of site conditions in some manner. Several methods are available to predict these effects. In one method, detailed geologic maps are prepared that discriminate between the youngest geologic units that are most likely to influence shaking levels. From such information, hazard maps can be prepared that depict relative changes in expected shaking levels that can be expressed in terms such as low, medium, and high. Other methods might express these changes in terms of maps of Modified Mercalli intensity increments (or any other earthquake-intensity measure) associated with specific surficial sediments or Modified Mercalli intensity for hypothetical earthquakes on specific faults. Linear or nonlinear models of sediment responses can be used to calculate ground-shaking levels relative to rock if data for these calculations are available. Measurement of the actual response of each geologic unit using strong-motion recordings or recordings of local earthquakes and blasts can also provide a measure of spectral levels relative to rock. If calculations or measurements of this kind are available for enough sites that can be correlated with surficial geologic conditions, maps can be constructed depicting the relative changes.

King and others (1990) and Carver and others (this volume) have collected data that partly establish the influence of near-surface sediments on the level of ground shaking in Olympia and Seattle, Wash. In these studies, local earthquakes and blasts were recorded on a variety of geologic units and at sites for which the intensity of shaking in the 1949 and 1965 Puget Sound earthquakes could be established. The studies establish a correlation between shaking intensity in damaging earthquakes and relative spectral levels for typical sediment types. Amplification of shaking by as much as 800 percent has been observed in the Pacific Northwest on some alluvium types for some spectral bands. Because soils respond nonlinearly when subjected to very strong motion, such large amplifications are not commonly experienced in large earthquakes. However, these levels can be used to determine a qualitative measure of the relative geographic variation in shaking. For some alluvium types and for low to moderate shaking levels, relative factors determined from small regional earthquakes and blasts may accurately predict variations in strong-motion levels (for example, see Borcherdt and others, 1975; Borcherdt and Glassmoyer, 1992; and Rogers and others, 1985).

Madin (this volume) compiles maps of faulting and thickness of surficial sediments in the Portland, Oreg., region that depict alluvial units likely to affect ground-shaking levels. These maps have as a basis compilations of earlier geologic mapping combined with existing borehole logs. Such maps are the first step in studies to evaluate the ground-shaking, ground-failure, and faulting potential in this region. Based on this work, maps depicting these hazards are, in fact, in progress for the Portland area (George R. Priest, Oregon Department of Geology and Mineral Industries, written commun., 1992).

SITE-SPECIFIC GROUND-SHAKING ESTIMATES

Cohee and others (this volume) compute strong-motion time histories and spectra at sites underlain by both rock and soil for a moment magnitude (M_W) 8 subduction-zone rupture on the Cascadia thrust fault using a theoretical earthquake source model. The calculations were made on a geographic grid that includes the Portland and Seattle regions for two independent hypothetical M_W 8 earthquakes, one west of Seattle and the other west of Portland. These postulated earthquakes would produce damaging ground motions over large areas of western Oregon and Washington. Although the highest values, equaling about 0.6*g* (see **Acceleration** in the glossary) at soil sites, are computed near the outer coast of Oregon and the Olympic Peninsula, significant damaging ground motions of about 0.1*g* near Portland to 0.3*g* near Seattle are indicated at sites underlain by alluvium. These calculations show that strong motions at this level can be expected to last 10 seconds or more. Unfortunately, the calculations do not model the part of the ground-motion spectrum that would affect structures taller than about 10 stories. These long-period ground motions are dependent on sediment geometry and near-surface sediment properties, which are only partly modeled in the calculations. Considerable research is needed to evaluate the long-period shaking levels in the major urban areas in a manner that realistically accounts for the effects of geologic deposits and basin geometry.

Silva and others (this volume) model both Benioff-zone and Cascadia thrust-fault ruptures using a band-limited white-noise earthquake source. The model is tested by comparing model predictions against the strong-motion records available from the 1949 and 1965 Puget Sound earthquakes. In modeling the thrust-fault earthquake, Silva and others (this volume) assume a M_W 8.5 event. This simulation yields peak acceleration values of about 0.15*g* at Seattle, considerably smaller than that determined by Cohee and others (this volume). This discrepancy is due to assumptions about the extent of downdip rupture. Silva and others (this volume) assume downdip rupture is limited to a point near the outer coast, whereas Cohee and others (this volume) assume rupture occurs farther downdip, to points well within the Olympic Peninsula. This result demonstrates the importance of improving our understanding of thrust-fault properties and slip mechanisms. At present, these issues are unresolved.

These studies provide a valuable first step toward our goal to evaluate the degree of hazard and risk due to earthquakes in the Pacific Northwest. Nevertheless, it is clear that much additional work is needed. With respect to ground-failure and site effects, more detailed geologic maps of young deposits are needed in urban areas by measuring the properties of such geologic units using standard penetrometer measurements or borehole shear velocities. The estimation of site effects in records of regional earthquakes recorded at different basin locations and on different geologic units should also be continued to fully understand the effects of geology on shaking levels. These records would also serve as a database for modeling such effects in order to estimate ground motions at other locations. Probabilistic ground-shaking estimates for this region need revision to incorporate the potential Cascadia thrust-fault earthquake, newly discovered continental-crust earthquake sources, and new information on paleoseismicity recurrence rates.

LOSS ESTIMATES

In a demonstration of Geographic Information System (GIS) techniques for loss estimation, Wang and others (1991) calculated earthquake-induced losses to water and sewer systems in Portland. Their study includes development of methods for inventory of facilities and formulation of an empirical loss-estimation algorithm that depends on earthquake shaking and liquefaction effects. They modeled two possible earthquakes, a surface-wave magnitude (M_S) 8.4 subduction-zone event and a M_S 6.5 local event, for their demonstration project. Dollar losses were tabulated by sewer- and water-pipe size, type of construction, materials, shaking intensity, and soil conditions. The subduction-zone earthquake was predicted to cause more than $4 million damage to both water and sewer pipelines in one drainage basin. Just as important, however, is that this type of study and methodology can quickly show the location of probable damage in map form, which can be important for emergency planning and eventual system redesign.

Much additional work is needed to extend the study of potential earthquake damage to water and sewer systems in other urban areas and to begin studies of damage to other infrastructure elements such as roads, power-distribution systems, bridges, pipelines, and other facilities. In addition, updated regional loss studies are needed in light of much new data concerning the earthquake hazards in the Pacific Northwest (for example, see Rogers and others, volume 1).

CONCLUSION

The studies reported in this volume, though only partial, show some of the types of research that can increase our understanding of earthquake effects and expected losses in the Pacific Northwest. It is clear from such studies that economic loss, life loss, and disruption of urban infrastructure is expected to be high for most earthquake-occurrence hypotheses. It is important to continue such studies in order to understand the hazards and to make realistic plans that minimize the effects and facilitate responses to future earthquakes. The long-term effect of mitigation based on these plans will be to reduce the economic burden of damaging earthquakes and to save lives.

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