EARTHQUAKE HAZARD MICROZONATION METHODS

DEPREM TEHLİKESİNİN MİKROBÖLGELENDİRİLMESİ METODLARI

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SUMMARY

The purpose behind a review of earthquake hazard microzonation practices lies in ascertaining the potential applications and favored methodologies of this type of research. Microzonation has been used as a way to subdivide a small region into areas or zones that have a relatively similar degree of exposure to various earthquake-related dangers. Hazards can be clearly illustrated in microzonation maps, which in turn, with vulnerabilities, can be used for conducting risk assessments. Such maps can be utilized for the earthquake resistant design of structures and can form the basis for development of local land-use policies at the government level, in order to reduce loss of life and property from future disasters.

ÖZET

Deprem tehlikesinin belirlenmesi için kullanılan mikrobölgelendirme yöntemlerini inceleyen bu makalenin amacı bu konu ile ilgili potansiyel uygulamaları ve önemli metodolojileri tanıtmaktır. Mikrobölgelendirme verilen bir sahanın herbiri kendi içerisinde benzer deprem tehlikesi seviyesine maruz küçük bölgelere ayırılması işlemidir. Hasargörebilirlik bilgileri ile beraber, mikrobölgelendirme haritaları deprem riskinin belirlenmesinde kullanılır. Mikrobölgelendirme haritaları yapıların depreme dayanıklı olarak projelendirilmesine yönelik bilgileri sağlar ve depremlerdeki can ve mal kayıplarını azaltmak maksadıyla yerel yönetim tarafından uygulanan arazı kullanım politikalarının temelini teşkil eder.

INTRODUCTION

Microzonation has been described by many authors as a technique for defining geographic areas that have different potential severity for each geologic hazard, thus permitting improvement of estimates for design through an awareness of local site

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conditions. A thorough review of the literature shows that most studies are conducted specifically with regard to earthquake-induced hazards. Microzonation maps depicting individual or groups of earthquake hazards are usually the primary goal of seismic hazard assessments, while vulnerability and risk assessments are often valuable extensions of microzoning studies. Microzoning is most definitive and useful when the effort is multidisciplinary, combining information and interpretations from the geologic, seismologic, tectonic, geotechnical, and engineering disciplines. The objective of a review of microzonation practices is to ascertain not only the potential applications of this type of investigation, but what are the favored methodologies to date and how and why they are implemented in practice. Microzonation evolved in the 1970's as an application of relatively simple methods for approximating the potential for seismic disaster, into an effective tool in the 1990's for mitigating such disasters. Today microzoning is a fundamental tool used in preparation of earthquake hazard scenarios, for conducting vulnerability and risk assessments, and ultimately for planning land-use strategies. Based on microzonation maps as well as historical (or recent) earthquake information, it should be possible to recognize urban areas which should either be bypassed or carefully planned and designed for where damage to constructed areas is expected to be the worst.

Most investigations begin with the identification of variations in local geologic and seismic conditions, and a subsequent classification of natural hazards. Various microzoning methods have been proposed and attempted to accomplish these ends (UNESCO, 1978; NSF and UNESCO, 1982; Vaciago, 1989; TIT, 1991). Microzonation usually results in the production of maps depicting the areal limits of the potential for any one or a combination of earthquake-related hazards, including surface rupture, amplification, ground shaking, soil failure, peak ground acceleration (PGA), velocity (PGV) or displacement (PGD), or damage to the built environment. From experience with past earthquakes, it is evident that the most severe damage to urban areas is caused by soil-structure resonance, liquefaction and surface displacements, and factors related to the quality, design and arrangement of the structures involved (Hays, 1992). Thus according to most authors, microzoning should ascertain and incorporate the applicable ground motion parameters and geologic information into maps. Ideally, these maps should also designate the location, relative severity, recurrence interval, and probability of exceedance of an earthquake (of a particular magnitude) for the study area (Cluff, 1978; Coburn et al., 1992). Many researchers are recommending that the use of microzonation be increased in building codes, in pre-earthquake hazard mitigation and post-earthquake preparedness, countermeasure and land-use planning, even so far as suggesting litigation for extremely high risk areas. Integration of technical databases which include the results of microzonation studies on local, national and international levels is also recommended.

EARLY MICROZONATION MAPS

Microzonation began in the 1970's as a way to quantitatively assess the potential damage which could be caused by seismic activity on a site-by-site basis (Kaneko et al., 1992). For microzoning purposes, this was accomplished primarily by considering parameters of seismic intensity, damage to structures, and the number of deaths and injuries (Figure 1). Initial methodologies for regional scale seismic zonation concentrated mainly on the identification and delineation of soils likely to amplify ground motion, or to fail via landslides or liquefaction (Hays, 1992). The resultant maps were often limited in regards to information on regional seismic wave propagation (i.e. strong ground motion at the base rock in relation to epicentral distance), duration of strong shaking, source parameters (i.e. magnitude), spacial and temporal approach to earthquake recurrence, and uncertainty (UNDP and UNESCO, 1974; Hays, 1992). These early maps presented primarily ground shaking hazard, showing variations of the local site response based on the effects of the most recent earthquakes. Although some early investigators were concerned about the lack of application of microzonation results to the actual design of structures, the scope of many of these initial studies was substantial considering the available resources (i.e. computers).

Frequently notable advances in the state of practice of microzonation have been accomplished only after damaging earthquakes, since usually it is only then that public officials desire competent scientific knowledge (as well as prompt monetary investment) to reconstruct the affected communities, so that the chances of repeating the catastrophe are diminished. Post-earthquake investigations typically included geological, seismological, engineering and sociological studies, either individually or in combination. One of the most important developments in microzoning has been the tendency for these studies to be interdisciplinary, and integrate the various geoscience and engineering disciplines in all aspects of the seismic hazard assessment. Gradually over the years the possibilities have increased with improved scientific techniques, individual project organization, and international cooperation; the inclusion of risks (i.e. damage to lifelines) into these studies has also opened up the range of obtainable objectives (Kaneko et al., 1992).

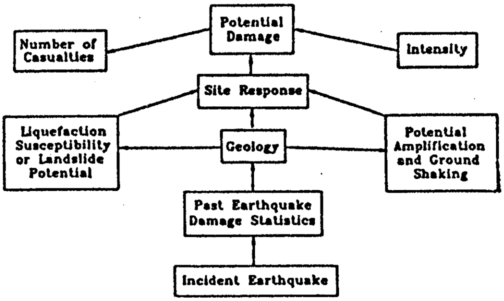

Figure 1. Early microzonation input information and results. *Onceki mikrobölgelendirme girdi bilgileri ve sonuçları.*

CURRENT UNDERSTANDING

Presently investigators all over the world are acting on the premise that pre-earthquake microzonation studies are an effective weapon toward mitigation of earthquake disasters (Figure 2). In the initial stages of a microzonation study, most researchers are primarily concerned with identifying variations in local ground conditions, which can be used to distinguish zones of differing degrees of earthquake hazard potential. These conditions usually directly influence the practicality of a site for a particular structure or urban development. The following list comprises the ground conditions sited by many authors (Cluff, 1978; Coburn et al., 1992; Erdik, 1993) as to be the most important: 1) Types and thicknesses of surficial soil deposits; 2) Variable topography; 3) Sites prone to soil failure; 4) Areas susceptible to permanent ground deformations; and 5) Coastal sites vulnerable to wave inundation from tsunamis, seiches, or dam failures.

Soil conditions of the most concern are those which can cause amplification (or relative shaking response between different geologic units) of ground motions, over particular frequency ranges (i.e. in narrow bands), or simply in general. It is well documented that for any one earthquake, the distribution of damage is usually site-dependent, and the amplification effects of soft, unconsolidated ground can be much higher than those of hard rock or well-consolidated material. Hence, the built environment residing on unconsolidated, reclaimed or alluvial deposits repeatedly suffers the greater damage than those on firmer land. The thickness of surficial soil layers also affects the amplitude and frequency content of the ground motions; thick deposits of softer soil overlying more rigid formations can trap the seismic waves to an even greater extent than would a thin surficial cover, again causing significant amplification. In addition, the contact zones and lateral discontinuities between highly contrasting geologic units (i.e. possessing high impedance contrast) are other areas where significant amplification may be anticipated. It is important to consider whether correlation between such semi-quantitative parameters and damage is appropriate between different localities with analogous but not identical attributes. Variations in topography can also cause significant amplification due to focusing and diffraction of earthquake vibrations, especially along the top of isolated hills, elongated crests and the edges of plateaus and cliffs.

The most destructive soil failures due to earthquakes include liquefaction, densification and loss of shear strength. Liquefaction and landsliding processes include rock falls, topples, slumps, slides, subsidence, lateral spreads and flow failures of soil and rock, etc... Liquefaction occurs when the shear stress generated by seismic motion during and earthquake causes and increase in the pore pressure within loose, fine grained soils (usually sand), and the soil layers ultimately loose their strength to the point where the ground behaves as a liquid. Strong shaking can cause densification (or settlement) of loose soils, involving compaction and sinking. Liquefaction can in turn can also result in settlement and subsequent tilting of structures on a site-by site basis as well as initiate large-scale landsliding events (i.e. the Nigata earthquake of 1964). Large permanent ground

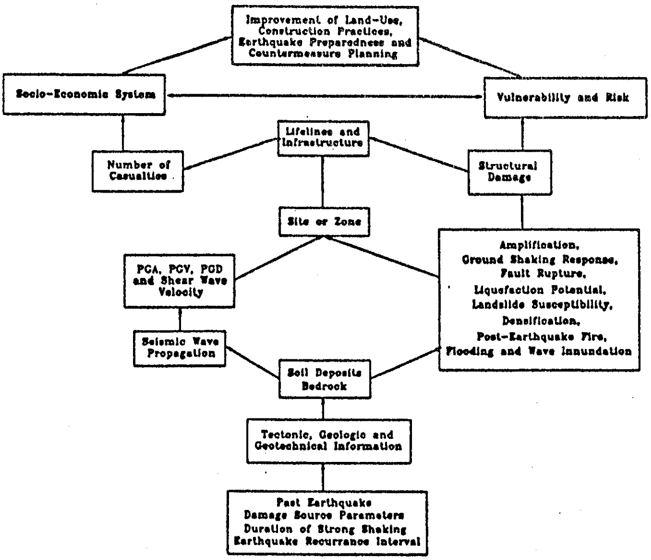

Figure 2. Current microzonation input information and possible output. *Şuanki mikrobölgelendirme girdi billgileri ve muhtemel sonuçları.*

deformations are often associated with surface faulting or shallow faulting. If such features show evidence of Quaternary motion, most researchers consider them to be active with a possibility of rupture. Other types of permanent soil failures which may occur as a result of an earthquake include torsional and lateral displacements, and compaction of loose granular soils, which can result in large and differential settlements of the ground surface.

Tsunamis, seiches and dam failures may immediately proceed an earthquake in many seismically active regions; each event alone might comprise an additional major catastrophe whose damage would probably rival the initial destruction caused only by the earthquake. Tsunami zonation requires data on long term-tsunami hazard, such as run-up heights and distances for estimating recurrence. High resolution mapping of areas susceptible to inundation necessitates accurate prediction of water run-up heights and water`velocities affected by the interaction of onshore structures and topography (Sanchez et al., 1991). In regards to failures of earthen and concrete dams due to earthquakes, the historical percentage is low. Most failures are the result of inadequate site selection, deficient design and/or poor construction practices. Criteria must be generated for any specific dam inundation area regarding the relative failure risk, in order to regulate site-selection and construction.

Approaches to Microzonation

Urban (or microzonation) scale probabilistic seismic zonation maps were not produced until after the 1970's, yet by the 1990's they began to replace deterministic maps on urban, regional, and national scales. The strategy employed for any one particular microzonation study is usually a function of the resources of the investigators (i.e. funding, field expertise, scientific knowledge base), how recently a damaging earthquake occurred, accessibility of the earthquake-prone area, and the socio-economic and political situation. In order to make microzoning more feasible to those of limited resources, several alternative methods which have been proposed by various investigators (i.e. Vaciago, 1989) are outlined herein.

One strategy for determining ground motion characteristics is to record microtremors and other low amplitude ground motions (i.e. aftershocks) and investigate them across the region or zone of interest. A pioneer in this research area, Kanai (et al., 1961) determined that the time and frequency domain wave shapes of microtremors are distinctly different for different soil conditions. This method is commonly used for estimating amplification factors between a hard rock reference location and another site of interest, which can be calculated via several different methods. This information can provide some understanding about what portions of a region or zone should expect the most significant ground motion during future earthquakes. In studies conducted in Turkey (UNDP and UNESCO, 1974), for example, there was close agreement between areas of high amplification determined through weak motion instrumentation and localities of significant damage from the associated earthquakes. In another case in Greece, investigators were able to compare the results of a microzonation study (based on microtremor measurements and small earthquake records) conducted in 1977 in the Korinth-Loutraki area with the damage caused by the February 24, 1981 (M6.7) earthquake; the authors found that the soil classification presented in their microzonation map of the Corinth-Loutraki area was in good agreement with the earthquake damage distribution. However, methods employing the use of weak ground motions in order to predict the local effects of strong ground motions have been disapproved of, since the waves may originate at the surface and follow different propagation paths from earthquakes, leading to sampling of shallow site characteristics. Also, if the low amplitude vibration sources are located at the ground surface, measurements can be nonstationary over different periods of the day and provide more detail about the sources of excitation than about the ground conditions. Due to the nature of these sources, the weak ground motions display low-strain behavior and require careful interpretation if the intention is to estimate the strong motion performance of a site. Many authors believe that existing techniques based on consideration of local site conditions resolved from previous structural damage, microtremor and small earthquake studies are not reliable enough for determination of seismic design parameters without additional evidence of the effects of different levels of excitation on the local geology, i.e. multiple recordings of ground motions caused by earthquakes or explosions.

One of the most credible methods for mapping factors relevant to engineering purposes is, of course, use of strong motion records, since these provide direct measurements of the site response of local (site-specific) geologic conditions to representative earthquake ground motions. Engineers and seismologists have recognized the significance of utilizing response spectra in the characterization of strong ground motions and their effects on structures since the 1940's. Either direct extrapolation (i.e. by scaling a set of statistically normalized acceleration spectral curves representative of different site conditions (Seed et al., 1976)) or probabilistic methods can then be used for predicting the ground motion characteristics of an earthquake of a particular size, for instance by modeling the expected response spectra based on known geologic, tectonic and seismic conditions and previously recorded strong motion records. Microzonation maps portraying the distribution of parameters of engineering significance (i.e. peak recorded ground acceleration, velocity and displacement) can be prepared specifically for seismic design purposes. Seismic impedance pertaining to site geology can be promptly determined using the known propagation velocity of body waves, especially if records exist along profiles crossing the area of interest (Medvedev, 1965). Nevertheless, there are major obstacles to this approach: 1) It is obviously not very practical to wait several decades for a sizable earthquake, 2) Even if records of multiple events exist there is no way to discern the homogeneity of the sources, and 3) Strong motion instrumentation is expensive and requires trained maintenance staff. At present these applications are often hindered due to a lack of applicable data, i.e. base rock records with respect to magnitude, hypocentral distance, depth of focus, and earthquake mechanisms.

Another method involves defining individual seismic hazard scenarios based primarily on characterization of phenomena triggered by a natural hazard, such as those interpreted from current geological information and field observations (Erdik, 1993). For example, Bressan (et al., 1986) describes four groups of qualitative scenarios: 1) Amplification of ground motion due to soil behaviour; 2) Amplification of ground motion due to morphological features; 3) The potential for permanent ground deformations; 4) The potential for (or active) conditions of slope instability; and 5) Simulation of post-earthquake wave inundation and fire. Due to the relative simplicity of these approaches, they are recommended only for use in preliminary microzoning.

A fourth approach to microzonation mapping involves an empirical estimation of the impact of subsurface geology on an intensity parameter determined for each specific measurement location. In the 1960's, for example, Medvedev (1965) attempted to relate an increment of seismic intensity to water table elevation and seismic site rigidity, where a site impedance parameter is found for each individual site which equals the product of subsoil density and longitudinal wave velocity. Today, many researchers are correlating empirically or experimentally derived parameters such as transfer functions and shear wave velocity to provide a first approximation of relative shaking response. In recent studies by Boore and Joyner (1994) and Borcherdt (1994), utilizing estimated site amplification factors, peak accelerations and response spectra, sites were characterized by dividing the site geology into different classes, depending on the average shear-wave velocity in the upper 30 m. This technique can be applied directly to the assessment of intensity variations.

Microzonation Mapping

Many researchers are advocating the compilation of microzonation information into GIS maps and databases, which would ultimately be accessible to other professionals (i.e.

engineers, city planners) who require the material for siting, design and land-use planning purposes. Microzonation projects usually produce one or more maps showing the potential for any of the following circumstances: 1) Ground rupture due to faulting; 2) Buried faults; 3) Peak ground acceleration, velocity, or displacement; 4) Ground shaking; 5) MSK intensity; 6) Ground motion amplification; 7) Shear wave velocity; 8) Liquefaction potential; 9) Potential densification and settlement; 10) Landslide susceptibility; 11) Damage to particular buildings or types of structures; 12) Damage to lifelines; 13) Post-earthquake flooding or wave inundation; 14) Post-earthquake fire; and 15) Casualty statistics. The spacial extent of any one (or a combination) of these parameters or events should be explicitly portrayed on the respective map. The maps sited above may be based on the damage distribution of historical earthquakes, current geologic information and analogous ground motion measurements, or on the probability of a particular earthquake occurring in a certain location sometime in the future. The latter map might indicate the variation of damage at the location of interest from an earthquake of a particular size, depending on the site conditions as well as the distance from a major fault. Thus, these maps can help identify the most vulnerable areas within a specified region.

RECOMMENDATIONS AND CONCLUSIONS

When microzonation maps are used to quantify and illustrate primary earthquake-related hazards, generally some combination of the following is accomplished using the current approaches: 1) Categorization of geologic and geotechnical information, with particular emphasis on seismic vibration and soil dynamics; 2) Determination of local and/or regional amplification of ground motion; 3) Evaluation of attenuation relationships on a regional scale, using strong ground motion, weak ground motion, and intensity data; 4) Calculation of the intensity of ground shaking using probabilistic methods; 5) Estimation the probability of exceedance of an earthquake of a particular magnitude for the entire study area; 6) Survey of earthquake catalogues and historical damage statistics; and 7) Construction of maps depicting individual or combinations of hazards, based on the occurrence of a hypothetical earthquake (Bresson et al., 1986).

In the current state of practice in seismic microzoning, maps which provide estimates of parameters necessary for the siting and earthquake resistant design of civil engineering systems are generally the main goal. These maps describe either specific conditions which may be triggered by an earthquake, or provide geologic, geotechnical or seismic parameters of similar relative magnitude for the given zones, or a combination of several such elements (as sited above). Recent studies have established reliable correlations between semi-quantitative geotechnical parameters and damage sustained by structures during earthquakes, indicating that their usefulness for seismic microzoning purposes (Hodder et al., 1993). Researchers conducting pre- as well as post-earthquake investigations are usually interested in whether the majority of the damage caused by ground motion could be due primarily to tectonic and geologic (soil) conditions, construction practices, or a combination of both.

In general, the state of microzonation practices today requires the following: 1) Extensive seismic and strong motion data bases; 2) Comprehensive geologic and geotechnical data bases, including tectonic (i.e. structural geology, geodetics) and structural engineering information; and 3) Ability to analytically model the principal physical processes such as nonlinear soil behaviour and earthquake source mechanisms (Hays, 1992). However, meeting these requirements is sometimes difficult for communities in developing countries.

Unfortunately, at present many countries consider seismic zonation on any scale to be a local research problem, not a practice accepted on an international scale. Efforts are now under way toward a worldwide network of organizations which will cooperate together in order to encourage the practice of seismic zonation (on a regional scale) as part of the International Decade for Natural Disaster Reduction (IDNDR). The network includes such organizations as the International Fora on Seismic Zonation (IFSZ) (sponsored by the USGS and UNESCO), the Hazard Mapping Program in California (State of California, 1990), and the Cooperative program for Seismic Risk Reduction (SEISMED). These organizations promote technical activities such as post-earthquake investigations, a significant source of basic information and an incentive for increasing the professional ability to perform seismic zonation as a part of earthquake risk management. It would be beneficial to many countries with limited resources to be able to collaborate and coordinate their research with such organizations, for example by organizing periodic seminars and workshops.

Other recommendations for the future include legislation of pre-earthquake preparedness programs and emergency response measures, with microzonation as a viable tool, in seismically active areas. Microzoning could decrease potential disasters by improving building regulations at a local level for areas known to be at high risk, if requirements were included in construction and design regulations for specific hazard information. Perhaps microzonation studies may also be used to promote pre-earthquake inspection of structures at risk. According to many authors, during the 21st century worldwide zonation practices should be based on integrated technical databases, perhaps employing expert systems, to perform pre- as well as post-earthquake zonation studies.

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