13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 1428

SEISMIC MICROZONATION FOR EARTHQUAKE RISK MITIGATION IN TURKEY

A. ANSAL[1], M. ERDIK[2], J. STUDER[3], S. SPRINGMAN[4], J. LAUE[5], J. BUCHHEISTER[6], D. GIARDINI[7], D. FAEH[8], D. KOKSAL[9]

SUMMARY

As a tool to improve the state of land use management in Turkey and to better mitigate earthquake risk in the future, a microzonation project was initiated after the 1999 Kocaeli earthquake. The project had two components (a) drafting a microzonation manual [1], (b) conducting pilot case studies in the selected two regions affected by the 1999 Marmara earthquakes [2]. The main purpose of the study was to test and demonstrate the applicability of the methodology proposed in the Seismic Microzonation Manual prepared for the project. The major contributions of the study are the probabilistic assessment of the regional earthquake hazard, interpretation of the microtremor records, and interpretation of the available geological and geotechnical data based on a grid approach. All the available data was transformed to GIS format and the results are evaluated to obtain a microzonation with respect to site amplification, liquefaction susceptibility and landslide hazard. An attempt will be made to summarize the results of the pilot study conducted for the Gölcük region to give an overview of the proposed methodology.

INTRODUCTION

The microzonation studies were conducted in two pilot areas (1) Adapazari, (2) Gölcük, Ihsaniye and Degirmedere. The location and general geology of the pilot areas are shown in Figure 1. The related activities concerning the microzonation studies were carried out in several partly simultaneous and partly consecutive phases.

The first phase involved the compilation of the available geological and geotechnical data that was previously obtained for different purposes. A major portion of the available data was supplied by

---

[1] Kandilli Observatory and Earthquake Research Institute, Bogazici University, Istanbul, Turkey
[2] Kandilli Observatory and Earthquake Research Institute, Bogazici University, Istanbul, Turkey
[3] Studer Engineering, Zurich, Switzerland
[4] Institute for Geotechnical Engineering, Swiss Federal Institute of Technology, Zurich, Switzerland
[5] Institute for Geotechnical Engineering, Swiss Federal Institute of Technology, Zurich, Switzerland
[6] Institute for Geotechnical Engineering, Swiss Federal Institute of Technology, Zurich, Switzerland
[7] Institute of Geophysics, Swiss Federal Institute of Technology, Zurich, Switzerland
[8] Institute of Geophysics, Swiss Federal Institute of Technology, Zurich, Switzerland
[9] World Institute for Disaster Risk Management- DRM, Virginia, USA

Sakarya University [3]. Limited numbers of additional subsurface explorations were also carried out to supplement the available data. The second group of data was supplied by General Directorate of Disaster Affairs. These data were analyzed and evaluated by the Institute for Geotechnical Engineering of the Swiss Federal Institute of Technology in Zurich. At the same time, all the available geotechnical data was converted to GIS format at the General Directorate of Disaster Affairs.

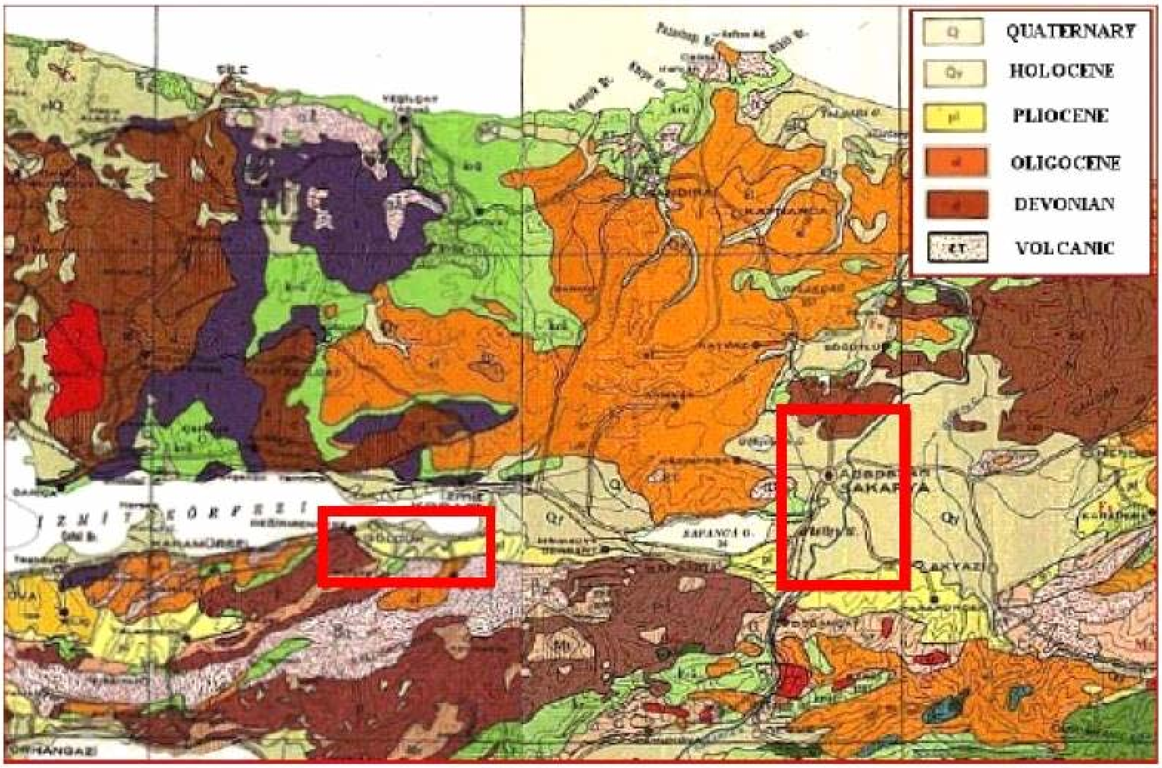

Figure 1. Location of the pilot areas over the Geology Map of the region

The second phase of the study was the evaluation of the earthquake hazard for the microzonation study. In this phase, both pilot areas were divided into approximately 500m x 500m cells to evaluate earthquake hazard parameters in terms of spectral acceleration ordinates for each cell. The determination of the regional hazard for the pilot areas was one of the important contributions of this study to the state-of-the-practice of microzonation in Turkey. Since the region has experienced a very severe earthquake in the near past, basically two types of assessment were carried out. The first assessment was the estimation of the hazard parameters with respect to the Poisson model for a probability of exceedance of 10% and 40% in 50 years. The second assessment was the estimation of the hazard parameters with respect to time dependent probability by a renewal model taking into account the recent earthquakes of 1999.

The third phase of the study involved microtremor measurements in the pilot areas and interpretation of the results obtained. The fourth phase of the study was the evaluation and analysis of the available geotechnical data to determine the necessary parameters for conducting the microzonation with respect to different parameters. Representative soil profiles and site conditions for each cell were determined. Site response analyses were conducted for each cell point using the acceleration spectra compatible simulated earthquake time histories obtained for each cell separately based on the seismic hazard study. The fifth phase involved the evaluation of the liquefaction susceptibility and landslide hazard based on the results obtained in the fourth phase of the study. The last phase involved the final evaluation of all the findings obtained from the studies conducted for specifying the microzonation with respect to site amplification, liquefaction susceptibility and landslide hazard.

The microzonation studies in the pilot areas were carried out by the participation of researchers from Bogazici, Middle East Technical, and Sakarya Universities and Directorate of Disaster Affairs from Turkey, Institute of Geophysics and Institute for Geotechnical Engineering of the Swiss Federal Institute of Technology in Zurich, Structural Engineering Institute of the Swiss Federal Institute of Technology in Lausanne, Studer Engineering from Switzerland, and the World Institute of Disaster Risk Management. The procedure adopted was based on the consensus reached among the researchers involved in the study during the Concept [4] and Synthesis [5] meetings held at Kandilli Observatory and Earthquake Research Institute of Bogazici University, in Istanbul.

The project is organized and managed by the World Institute for Disaster Risk Management (DRM), and funded by the Swiss Agency for Development and Cooperation (SDC). A close cooperation was established among the scientific and technical staff and with the governmental authorities responsible for microzonation in Turkey to provide a suitable base for the implementation of the results in the future microzonation projects in Turkey.

BACKGROUND

Seismic microzonation requires multi-disciplinary contributions as well as comprehensive understanding of the effects of earthquake generated ground motions on man-made structures. It can be considered as the process for estimating the response of soil layers under earthquake excitations and thus the variation of earthquake ground motion characteristics on the ground surface. The key issue behind a microzonation study is to use the obtained variation of the selected parameters for land use and city planning. Therefore it is crucial that the selected microzonation parameters should be meaningful for city planners as well as for public officials and should not lead to controversial arguments among the property owners and city administrators.

The purpose of seismic microzonation is to minimize the damage to the man-made environment. Thus, selection of the zonation parameters should be in accordance with this objective. Different zones could be delineated with respect to selected parameters to provide city planners with some guidelines for specifying population and building density, and more specifically, building characteristics. All of these analyses have to be considered within a probabilistic framework in order to account for all possibilities that may arise due different earthquake source mechanisms, which will have relevant exceedance probabilities (risk) levels attached, that are suitable for the purpose.

The national seismic zoning maps are mostly at small scales such as 1:1,000,000 or less and are mostly based on seismic source zones defined at similar scales. However, seismic microzonation for a town requires 1:5,000 or even 1:1,000 scale studies and needs to be based on seismic hazard studies at similar scales. One purpose of the seismic microzonation could be to supply input for the structural design by replacing national macrozonation maps. However, the applicability of this approach is questioned by engineers and scientists as well as by public officials in charge of design and construction control, because the reliability and uniformity of these microzonation studies can not be assured. While the country wide macrozonation maps are produced by national experts and go through a careful review process, the same approach can not be followed for the large number of seismic microzonation studies. One possible solution for this scale incompatibility is to increase the scales of seismic macrozonation maps steadily with the accumulation of geological and seismological data as implemented by USGS in USA [6, 7].

Geological formations, local site classification, equivalent shear wave velocity, spectral acceleration, spectral amplification and their variation are some of the parameters studied during a seismic microzonation. A consistent approach has to be implemented to assess each parameter with respect to all other parameters. The objective of seismic zonation is to establish a seismic hazard map at a scale of 1:5000 taking into account earthquake source and local site conditions. Thus estimation of the earthquake induced forces and their variation in the investigated area must be the main target in seismic microzonation. Even though seismic microzonation contains important information for city and urban planning, considering different structures with different functions, site specific studies need to be performed at each site to evaluate the effects of local soil conditions.

GÖLCÜK CASE STUDY

Seismic Hazard Assessment

The study involves a probabilistic estimate of the expected ground motions at the sited locations for the next 50 years. The methodology used in this study is similar to the one used by the U. S. Geological Survey to develop the current seismic hazard maps for the United States. The program utilized in the assessment of the seismic hazard is also the code developed by A. Frankel and used by USGS [8].

The fault segmentation model used in this study is based on a compilation of data from various studies [9, 10, 11, 12, 13] and is presented in Figure 2. The historic and instrumental seismicity of the Marmara region has been thoroughly investigated [14]. The earthquake hazards in the region are assumed to be the result of the contributions, computed in following two steps:

a. Ground motions that would occur as the result from the earthquakes in the magnitude range from 5.0 to 6.9.

b. Ground motions that would result from larger magnitude events in the magnitude range 7.0 and higher.

Figure 2 Fault segmentation model developed for this study.

Part (a) is termed as “background activity”, i.e. the activity not associated with the main tectonic entities. In the computation of part (a), an earthquake catalogue of magnitude 5.0 and higher events are used.

These events are not assigned to specific faults (the resolution of the neo-tectonic studies that we have compiled from literature does not allow such an association), but they are assigned to cells of a grid (of size 0.005º x 0.005º), in other words each cell of the grid is assumed to be a potential source for moderately sized events. It is also assumed that a Gutenberg-Richter type recurrence relationship governs the earthquake recurrence in the background.

To compute the seismic activity in each cell first an overall "b" value is calculated for the entire region. Although the maximum likelihood method [15] yielded a "b" value of 0.8 for the Marmara region, mainly to account for the deficiently reported earthquakes at lower magnitudes, a "b" value of 1.0 is preferred for the analysis. Following that, the "a" value in each source cell is obtained using the earthquake catalogue considered to be complete since 1900 and 1940 for magnitudes greater than 5.5 and 5.0 respectively. As such, the background activity is assumed to be Poissonian. The grided rates are spatially smoothed with a two-dimensional Gaussian filter with a decay distance of 50 km.

Part (b) is related to the seismic energy release along well-defined faults. For this part, a fault segmentation model is developed and it is assumed that energy along these faults is released by characteristic events characterized by magnitude and recurrence time. Two models have been used to determine the seismic activity along these linear source zones: these are a Poisson model using a characteristic earthquake recurrence relationship and a time dependent (renewal) model. The Poisson and the renewal models differ in that in the Poisson model, the probability of occurrence of the characteristic event does not change in time, whereas in the renewal model it increases as a function of the time elapsed since the last characteristic event.

The characteristic earthquake recurrence rates are determined by assigning characteristic magnitude and recurrence intervals to each fault segment in the region. The model assumes that seismic energy along the segments is released by characteristic earthquakes. In this study, the Youngs and Coppersmith [16] model is used to determine the magnitude distribution. In this model, the fault generates moderate magnitude earthquakes as well as characteristic earthquakes.

For the renewal model, the conditional probability for each fault segment is calculated from the mean recurrence interval of the characteristic earthquake determined as explained previously, the elapsed time since the last major earthquake and the exposure period (taken as 50 years). The probabilities are said to be conditional since they change as a function of the time elapsed since the last earthquake. A lognormal distribution with a covariance of 0.5 is assumed to represent the earthquake probability density distribution.

The ground motion parameters used in the quantification of the earthquake hazard for this study are the peak ground acceleration (PGA) and the spectral accelerations (SA) for natural periods of 0.2 and 1.0 seconds. The ground motions are determined for soft rock (NEHRP B/C boundary) conditions. Boore et al. [17], Campbell [18] and Sadigh et al. [19] have proposed the attenuation relationships that was used in the assessment of PGA, and those of Boore et al. [17] and Sadigh et al. [19] have been used for the assessment of SA. Although the initial choice of these attenuation relationships follow those of USGS studies for California, nevertheless, these Western US based attenuation relationships have been found to provide good correlation with the attenuation characteristics of ground motion in the Northwestern Anatolia [14, 20].

Since the major purpose for the microzonation study is for land use and city planning, it was decided to determine the required earthquake hazard parameters based on the Poisson model for a return period of 100 years that corresponds approximately to 40% probability of exceedance in 50 years. The results for PGA and SA at 0.2 sec natural periods at NEHRP B/C boundary site class for the Poisson model are presented in Figure 3 for the Gölcük region.

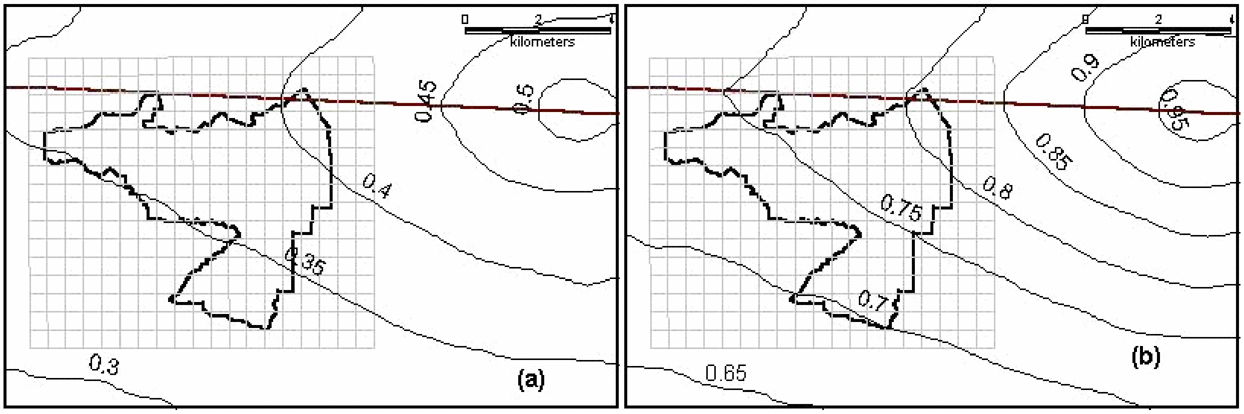

Figure 3. (a) PGA (b) SA (T=0.2 sec) contour maps at NEHRP B/C boundary site class for 40% probability of exceedance in 50 years for Gölcük region (Poisson model)

Site Characterization

The aim is to define hypothetical boreholes, which can be assumed to be located at the centre of the cells. A hypothetical borehole should be an idealized borehole, which will be the most representative for the soil conditions in the specific area of interest. For the identification of the local soil conditions, an approach was chosen by taking available existing data into account. Data were available from different sources for the two project areas, with varying degree of information on the site investigations being conducted, reliability and quality of the derived data. Thus this information should be dealt with great care, and a plausibility check of the available data is essential prior to carrying out the microzonation procedure. Direct use of this kind of data from such a variety of different sources might lead to an unrealistic scenario, and might not be comparable or even withstand a subsequent confirmation of this approach in terms of the hypothetical boreholes. Nonetheless data from different sources should be taken into account if the quality appears to be acceptable so that it is possible to benefit from an independent view of the soil conditions in overall terms and the reliability of a single site investigation in particular.

In total, 97 sets of borehole data with additional 6 CPT loggings were available for Gölcük. Not all of these data sets cover a single 500m x 500m grid point. In some cases, there is more than one borehole available for each cell. Other cells of the original pilot study area were not covered.

The geology is slightly variable in the Gölcük region. A large portion of the area is covered by stiffer geological formations. Site characterization was conducted based on the boreholes and other related information available for each cell. Each selected soil profile was classified according to the Turkish Earthquake Code and NEHRP site classification, and equivalent shear wave velocities were calculated for each grid point. The site classification according to the Turkish Earthquake Code for the Gölcük region is shown in Figures 4 with respect to the surface geology. The majority of the area is classified as Z1 or Z2 according to the Turkish Earthquake Code [21], indicating the dominance of stiffer and denser deposits in the region. As can be observed there are significant variations in each geological unit in term of site classification, demonstrating the limitations of using only surface geology for microzonation.

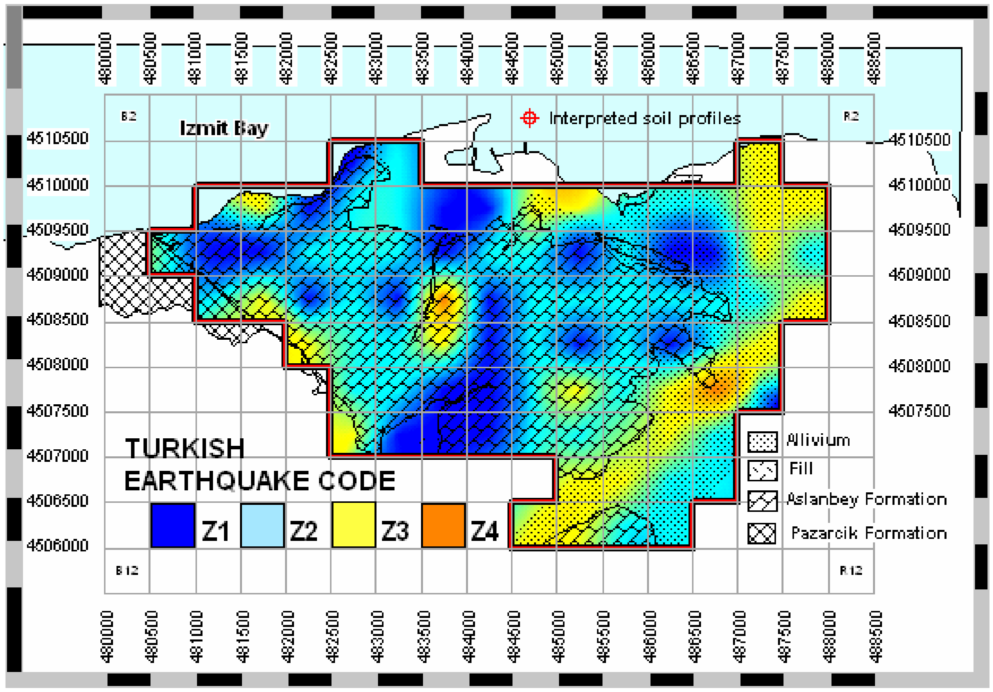

Figure 4. Site Classification according to Turkish Earthquake Code for Gölcük

Site Amplification

Site response analyses were conducted for the pilot area using EERA [22] Excel routines for the selected soil profiles and the input time histories obtained for each cell from the regional probabilistic earthquake hazard study. The basic intention of the site response analysis is to estimate the effect of local site conditions in assessing the site amplification with respect to ground shaking. It would be logical to base this decision on all the available results obtained from site identification based on equivalent shear wave velocity, site response analysis as well as from microtremor measurements conducted in the region. In the case of site response analysis, a suitable parameter is considered to be the average spectral acceleration between 0.5 and 1.5 second periods based on the consensus reached among all parties including the project's Technical Advisory Board (TAB) of experts [23]. Thus, instead of giving all the parameters obtained by site response analysis, such as peak ground or maximum spectral accelerations, only the variation of the average spectral accelerations was mapped.

The approach adopted in the assessment of the calculated zonation maps involves the division of the area into three zones as (A, B, and C) as defined in the Microzonation Manual [1]. Since the site characterizations, as well as all the analysis performed, require various approximations as well as some assumptions, it was preferred not to present the numerical values for any parameter. In all cases, the variations of the calculated parameters are considered for each area separately and their frequency distributions were calculated. Thus the zone A shows the most unsuitable 33 percentile (e.g. low equivalent shear wave velocities, high spectral accelerations or high spectral amplification), zone B the medium 34 percentile and zone C shows the most favorable 33 percentile (e.g. high average shear wave velocities, low spectral accelerations or low spectral amplifications).

The peak spectral amplifications based on equivalent shear wave velocity were calculated using the empirical relationship given by Midorikawa [24] and the peak spectral amplifications were evaluated and the variations were also mapped, as in the case of average spectral accelerations obtained by site response analyses.

Even though it is generally accepted that H/V ratios obtained from microtremor records would not lead to very reliable spectral amplification values, they can still be taken into consideration when finalizing the microzonation with respect to site amplification. Therefore, the results obtained from the microtremor study were utilized to map the variation of the spectral amplifications.

Seismic Microzonation with respect to ground motion

The final mapping with respect to ground shaking can be accomplished by comparing the average spectral accelerations obtained by site response analyses with the peak spectral amplifications calculated using equivalent shear wave velocity. After studying the soil profiles and site classifications, it was observed that at some grid points the site amplifications were relatively high, and at some grid points the peak ground accelerations were very low, based on the site response analyses. The site response analysis, whether it is conducted by EERA or Shake [25], would sometimes give unrealistically high spectral amplifications or very low peak ground acceleration values depending on the thickness of the deposit, estimated initial shear moduli, and also on the characteristics of the input acceleration time histories. On the other hand, even though they are more empirical, the spectral amplifications calculated using equivalent shear wave velocities tend to give more consistent values that appear to be more realistic when compared with the selected soil profiles.

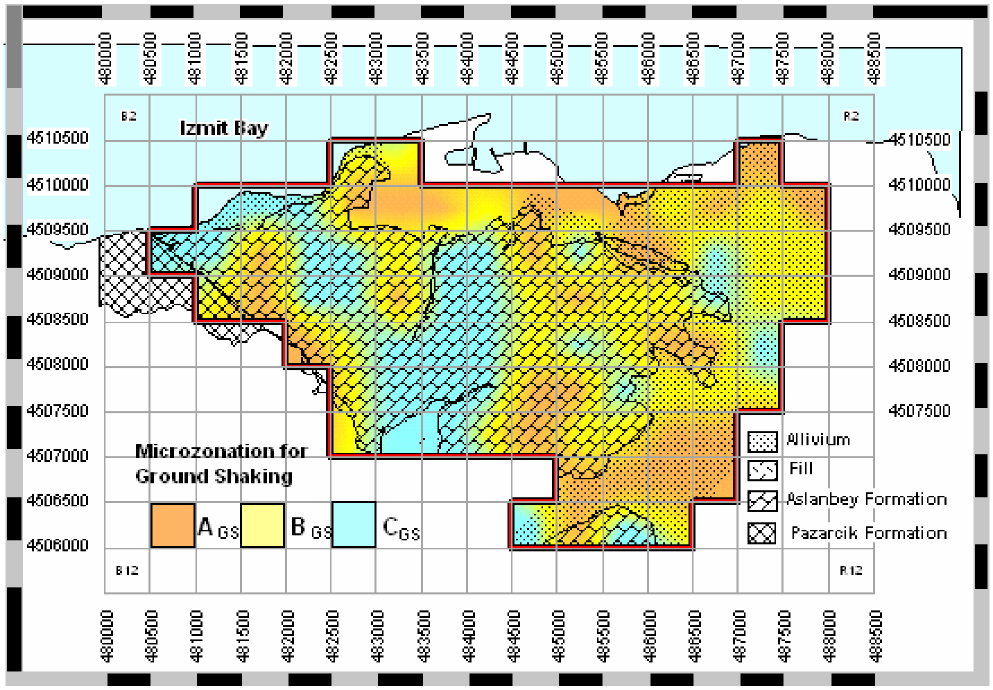

Figure 5. Comparison of ground shaking map with geological formations

The comparison between the average spectral accelerations obtained by site response analysis and peak spectral amplifications obtained from equivalent shear wave velocities were conducted for each cell numerically by adopting the above criteria to determine the three zones and then perform the mapping using the new data. As a last step, the estimated map for the ground shaking is compared with the geology map for Gölcük, as shown in Figure 5. It is evident from this map that most part of the alluvium deposit, as expected, is in the zone A of high intensity of ground shaking. However, it is important to observe that certain sections of Aslanbey Formation, which was described by Önalp [26] as "It consists of loose and lightly cemented sandstones-siltstones-claystones and gravelstones (conglomerates). It often behaves as soil due to past extensive weathering and degradation. Its thickness is in the order of 100 m." are also located in zone A. This example demonstrates that zonation with respect to geological formations may not be very accurate due to different factors, whereby in the case of the Aslanbey formation, it is very likely that the differences in the weathering and degradation requires different zones to be defined within the same formation for microzonation purposes.

Liquefaction Susceptibility

The approach adopted to perform microzonation map in terms of the liquefaction susceptibility was based on the method developed by Youd et al. [27] and Iwasaki et al. [28] as recommended in the Manual [1] and as suggested by the TAB [23]. For the purpose of demonstrating the applicability of the proposed approach, the liquefaction susceptibility microzonation map was produced for the Gölcük region.

In the approach adopted, the variation of the safety factors with depth were determined for each representative borehole for the Gölcük region based on the method proposed by Youd et al. [27]. It may be appropriate to review the basic steps followed in estimating the liquefaction susceptibility for each cell.

Step 1. The induced stress ratio CSR is calculated from Seed and Idriss [29] as,

$$CSR = \frac{\tau_{av}}{\sigma'_v} = 0.65 \frac{a_{\max}}{g} \frac{\sigma_v}{\sigma'_v} r_d \tag{1}$$

where a_{max}= peak horizontal ground surface acceleration; g = acceleration of gravity; σ_v = total vertical overburden stress; σ'_v = effective vertical overburden stress; r_d = stress reduction factor. The average value of r_d is calculated by the expression [27],

$$r_d = \frac{(1.00 - 0.4113z^{0.5} + 0.04052z + 0.001753z^{1.5})}{(1.00 - 0.4177z^{0.5} + 0.05729z - 0.006205z^{1.5} + 0.001210z^2)} \tag{2}$$

where, z is the depth below ground surface in meters.

Step 2. Corrected $N_{1,60}$ values are calculated as,

$$N_{1,60} = NC_N C_R C_S C_B C_E \tag{3}$$

where N = measured standard penetration resistance, C_N = factor to normalize N to a common reference effective overburden stress; C_R = correction for rod length, C_S = correction for non-standardized sampler configuration, C_B = correction for borehole diameter, C_E = correction for hammer energy ratio.

C_N was calculated from Kayen et al. [30], which limits its maximum value to 1.7. Taking into consideration the average borehole drilling experience in Turkey, it was assumed that C_E=0.5, C_B=1, C_S=1.1. C_R is corrected as suggested by Youd et al [27] with respect the depth of the each individual location (C_R =0.75 for d<3 m, C_R =0.8 for d=3-4m, C_R =0.85 for d=4-6m, C_R =0.95 for d=6-10m, C_R =1 for d=10-30m).

Step 3. Even though the proposed method recommends a further correction to account for the influence of fines content, since there was not sufficient information, this correction was not applied for the present study. However, it is highly recommended that fines correction should be applied in the future microzonation studies. Therefore it is crucial that fines content should be determined for all liquefiable soil layers.

Step 4. The resulting $N_{1,60}$, is used with modified 5% or less fines content curve of Seed et al. [31] to evaluate liquefaction resistance CRR using the equation of the curve as given by Youd et al. [27];

$$CRR_{7.5} = \frac{1}{34 - N_{1,60}} + \frac{N_{1,60}}{135} + \frac{50}{\left(10N_{1,60} + 45\right)^2} - \frac{1}{200} \tag{4}$$

Step 5. Since the curve given by Eq.(4) is valid only for magnitude 7.5 earthquakes, a magnitude scaling factor MSF need to be applied to adjust to the other magnitudes where MSF would be chosen from a range of recommended values [27]. For the Gölcük case study, the MSF is taken as 1.

The safety factors were calculated along the whole depth of the borehole for all liquefiable soil layers based on the available SPT-N blow counts using the surface peak ground accelerations calculated from site response analysis. The liquefaction potential for each borehole was calculated based on the procedure proposed by Iwasaki et al. [28] using the variation of the safety factors with depth. Iwasaki et al. [28] quantified the severity of possible liquefaction at any site by introducing a factor called the liquefaction potential index, PL, defined as

$$P_L = \int F(z)w(z)dz \tag{5}$$

where z is the below the ground water surface, measured in meters; $F(z)$ is a function of the liquefaction resistance factor, FL, where $F(z)=1- FL$ but if $FL>1.0$, $F(z)=0$; and $w(z)=10-0.5z$. Based on the results reported by Iwasaki et al. [28] and in accordance with the Microzonation Manual [1] and TAB [23], three zones (A, B, and C) were identified with respect to liquefaction potential index. Zone A is the where the liquefaction potential index is $PL>15$, zone B is the intermediate zone where the liquefaction potential index is $5>PL>15$, and zone C is the safest zone where liquefaction potential index is $PL<5$ The microzonation map for liquefaction susceptibility determined by this approach is shown for Gölcük region in Figure 6.

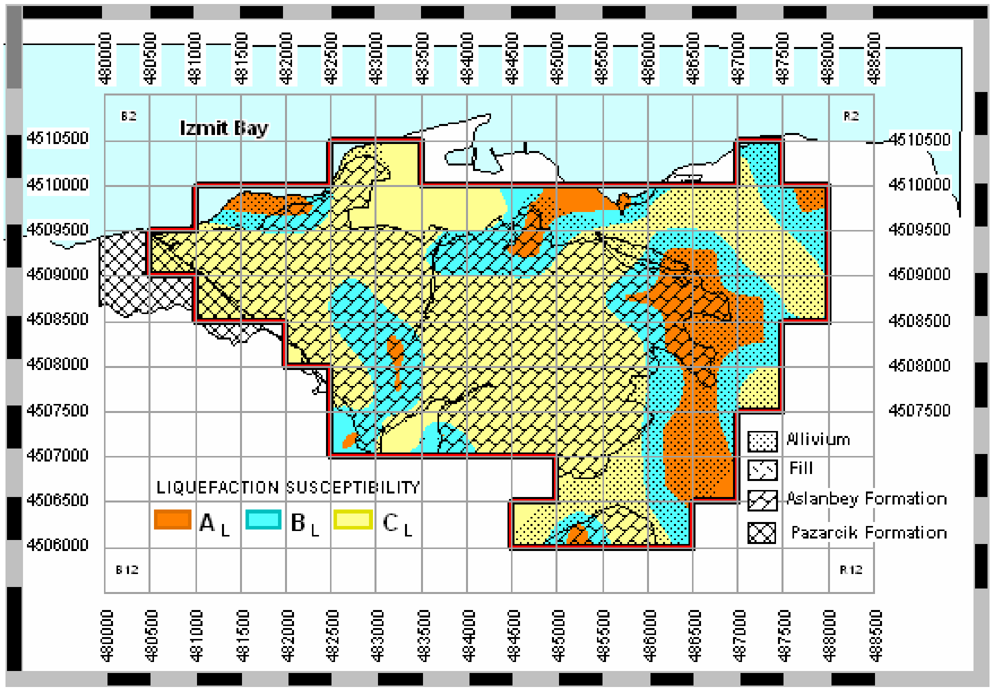

Figure 6. Comparison of liquefaction susceptibility map with geological formations

CONCLUSIONS

Seismic microzonation can be considered as being composed of three main phases. In the first phase, the earthquake source characteristic for the study area needs to be determined more accurately in a probabilistic manner to satisfy the requirements of the civil engineering and urban planning. The second phase is the investigation of the geological and geotechnical site conditions, taking into consideration all the relevant factors (i.e. topographical and basin effects, variations in the soil stratifications, soil nonlinearity, etc.). This information is an essential ingredient for the assessment of site dependent seismic hazard studies. The third phase is the analysis and interpretation of the accumulated data in the first two phases to establish suitable and applicable microzonation parameters that could be utilized for urban planning and thus for earthquake risk mitigation.

In seismic microzonation, the variation of earthquake ground motion is studied by taking the earthquake source and path characteristics into account in a probabilistic manner, as well as geological and geotechnical site conditions. Due to the damage distributions observed during past earthquakes, it became evident that earthquake zonation maps prepared at small scales do not yield the necessary information for risk mitigation at a city level. With the increase in the analytical, in-situ and laboratory investigation capabilities, there has been significant increase in the accumulated databases concerning the regional geological formations, earthquake source mechanisms, seismic activity and earthquake ground motion records. In the light of these scientific and technical advances, it became possible and feasible to conduct seismic zonation studies at regional and microzonation at local levels with continuously increasing scales. The main objective is to estimate more accurately the ground motion characteristics during possible earthquakes taking into account all the main controlling factors.

Within the framework of the pilot microzonation studies conducted for Adapazari and Gölcük regions, a methodology is developed for adoption as a guideline for seismic microzonation investigations in Turkey. The proposed methodology is based on the regional estimation of the earthquake hazard, detailed investigation of geological and geotechnical site conditions and analysis of the ground motion characteristics based on a grid layout.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to the Swiss Agency for Development and Cooperation (SDC) for funding and to the World Institute for Disaster Risk Management (DRM) for conducting the project. The very significant support of the Directories of Disaster Affairs namely (M.Taymaz, E.Demirbas, O.Gökçe, M.K.Tüfekçi, K.Özener, S.Demir, A.Demir, S.Kök, S.Yagci, I.Kayakiran, E.Nebioglu, A.Güldemir, M.E.Durgun) is highly appreciated. The authors would also like to express their gratitude to all the partners and young researchers who contributed to the project as a whole namely A.Önalp, P.Gülkan, M.Elmas, B.Siyahi, Ö.Çetin, S.Bakir, Y.Fahjan, P.Lestuzzi, K.Sesetyan, M.Demircioglu, H.Akman, A.Christen, A.Yakut, T.Yilmaz, U.Yazgan, Ü.Gülerce, C.Greifenhagen and R.Panduri. Last but not the least, grateful thanks are offered to the members of the Technical Advisory Board: R.Whitman, L.W.Finn, R.Meli, A.Marcellini, J.P.Bard, S.Yasuda for their careful review and valuable recommendations.

REFERENCES

1 Studer J, Ansal A. “Seismic Microzonation for Municipalities, Manual.” Research Report for Republic of Turkey, Ministry of Public Works and Settlement, General Directorate of Disaster Affairs, World Institute for Disaster Risk Management, Inc., 2004.

2 Ansal A, Springman S, Studer J, Demirbas E, Önalp A, Erdik M, Giardini D, Sesetyan K, Demircioglu M, Akman H, Fäh D, Christen A, Laue J, Buchheister J, Cetin Ö, Siyahi B, Fahjan Y,

Gülkan P, Bakir S, Lestuzzi P, Elmas M, Köksal D, and Gökce O. “Seismic Microzonation for Municipalities, Pilot Studies: Adapazari, Gölcük, Ihsaniye and Degirmendere.” Research Report for Republic of Turkey, Ministry of Public Works and Settlement, General Directorate of Disaster Affairs, World Institute for Disaster Risk Management, Inc., 2004.

3 Önalp A, Geotechnical Data for Adapazari and Gölcuk Regions, Sakarya University, Internal Report, 2003.

4 Ansal A, Çetin KÖ, Demirbas E, Elmas M, Erdik M, Fäh D, Giardini D, Köksal D, Laue J, Lestuzzi P, Önalp A, Siyahi B, Springman S, Studer J. “Report of the Meeting on Concepts for Analyses and Interpretation of Results in DRM-MERM Project.” World Institute for Disaster Risk Management, Inc., 2002.

5 Ansal A, Balamir M, Bakir S, Buchheister J, Christen A, Çetin KÖ, Demirbas E, Durgun M, Erdik M, Fäh D, Giardini D, Gülkan P, Hammer J, Köksal D, Krimgold F, Laue J, Lestuzzi P, Önalp A, Siyahi B, Springman S, Studer J, Yasuda S. “Report of the Synthesis Meeting for the Research and Manual Task Groups in DRM-MERM Project” Research and Manual Task Groups, World Institute for Disaster Risk Management, Inc., 2003.

6 Frankel AD, Mueller CS, Barnhard TP, Leyendecker EV, Wesson RL, Harmsen SC., Klein FW, Perkins DM, Dickman NC, Hanson SL, Hopper MG. “USGS National Seismic Hazard Maps.” Earthquake Spectra 2000; (16)1:1-15.

7 Leyendecker EV, Hunt RJ, Frankel AD, Rukstales KS. “Development of Maximum Considered Earthquake Ground Motion Maps.” Earthquake Spectra 2000; (16)1:21-40.

8 Frankel AD, Mueller C, Barnhard T, Perkins D, Leyendecker EV, Dickman N, Hanson S, Hopper M. “National Seismic Hazard Maps: Documentation June 1996.” Open File Report 96-532, U. S. Geological Survey, Denver, Colorado, 1996.

9 Barka AA, Kadinsky-Cade K. “Strike-Slip Fault Geometry in Turkey and its influence on earthquake activity.” Tectonics 1988; 7(3): 663-684.

10 Saroglu F, Emre Ö, Kuscu I. “Active Fault Map of Turkey.” Mineral Res. Explor. Inst. Turkey, 1992.

11 Akyuz HS, Barka AA, Altunel E, Hartleb R, Sunal G. “Field Observations and Slip Distribution of the November 12, 1999 Duzce Earthquake (M=7.1), Bolu-Turkey.” Barka AA, Kozaci O, Akyüz S, Altunel E, Editors. The 1999 Izmit and Duzce Earthquakes: Preliminary Results. Istanbul Technical University Press, 2000: 61-70.

12 Le Pichon X, Sengör AMC, Demirbag E, Rangin C, Imren C, Armijo R, Görür N, Çagatay N, Mercier de Lepinay B, Meyer B, Saatçilar R, Tok B. “The Active Main Marmara Fault.” Earth and Planetary Science Letters 2001; 192 (4): 595-616.

13 Yaltirak C. “Tectonic evolution of Marmara Sea and its surroundings.” Marine Geology 2002; 1-37.

14 Erdik M, Aydýnoglu N, Barka A, Yuzugullu O, Siyahi B, Durukal E, Fahjan Y, Biro YA, Akman H, Birgören G, Demircioglu M, Ozbey C, Sesetyan K. “Earthquake Risk Assessment for the Istanbul Metropolitan Area.” BU Kandilli Observatory and Earthquake Research Ins., Dept. of Earthquake Engineering, 2002.

15 Weichert DH. “Estimation of the Earthquake Recurrence Parameters for Unequal Observation Periods for Different Magnitudes.” BSSA 1980; 70: 1337-1346.

16 Youngs RR, Coppersmith KJ. “Implications of Fault Slip Rates and Earthquake Recurrence Models to Probabilistic Seismic Hazard Estimates.” BSSA 1985; 75: 939-964.

17 Boore DM, Joyner WB, Fumal TE. “Equations for Estimating Horizontal Response Spectra and Peak Acceleration from Western North American Earthquakes: A Summary of Recent Work.” Seismological Research Letters 1997; 68(1): 128-153.

18 Campbell KW. “Empirical Near-Source Attenuation Relationships for Horizontal and Vertical Components of Peak Ground Acceleration, Peak Ground Velocity, and Pseudo-Absolute Acceleration Response Spectra.” Seismological Research Letters 1997; 68(1) .

19 Sadigh K, Chang C-Y, Egan JA, Makdisi F, Youngs RR. “Attenuation Relationships for Shallow Crustal Earthquakes Based on California Strong Motion Data.” Seismological Research Letters 1997; (68)1: 180-189.

20 Ozbey C, Sari A, Manuel L, Erdik M, Fahjan Y. “An empirical attenuation relationship for Northwestern Turkey ground motion using a random effects approach.” Soil Dynamic and Earthquake Engineering 2004, (24): 115-125.

21 Ministry of Public Works and Settlement, Government of Republic Turkey “Specification for Structures to be Built in Disaster Areas.” English Translation, Kandilli Observatory and Earthquake Research Institute http://www.koeri.boun.edu.tr/depremmuh/, 1997.

22 Bardet JP, Ichii K, Lin CH. “EERA, A computer program for equivalent linear earthquake site response analysis of layered soils deposits.” University of Southern California, Los Angeles, 2000.

23 TAB, Technical Advisory Board. “Report of Technical Advisory Board, Zurich, Switzerland.” World Institute for Disaster Risk Management, Inc., 2003.

24 Midorikawa S. “Prediction of Isoseismal Map in the Kanto Plain due to Hypothetical Earthquake.” Journal of Structural Engineering 1987; 33B: 43-48.

25 Idriss IM, Sun JI. “User’s Manual for Shake91, A Computer Program for Conducting Equivalent Linear Seismic Response Analysis of Horizontally Layered Soil Deposits Modified based on the original SHAKE program Published in December 1972 by Schnabel, Lysmer and Seed.” 1992.

26 Önalp A, “The Geology and Geotechnical Characteristics of the Pilot Areas.” Chapter 2 of “Seismic Microzonation for Municipalities, Pilot Studies: Adapazari, Gölcük, Ihsaniye an Degirmendere.” Research Report for Republic of Turkey, Ministry of Public Works and Settlement, General Directorate of Disaster Affairs, World Institute for Disaster Risk Management, Inc., 2004.

27 Youd TL, Idriss IM, Andrus RD, Arango I, Castro G, Christian JT, Dobry R, Finn WDL, Harder LF Jr, Hynes ME, Ishihara K, Koester JP, Liao SSC, Marcuson WFIII, Martin GR, Mitchell JK, Moriwaki Y, Power MS, Robertson PK, Seed RB, Stokoe KHII. “Liquefaction Resistance of Soils: Summary Report from the 1996 NCEER and 1998 NCEER/NSF Workshops on Evaluation of Liquefaction Resistance of Soils.” ASCE, Journal of Geotechnical and Geoenvironmental Engineering 2001; 127(10):817-833.

28 Iwasaki T, Tokida K, Tatsuoka F, Watanabe S, Yasuda S, Sato H. (1982) “Microzonation of Soil Liquefaction Potential Using Simplified Methods.” Proceedings of 3rd International Conf. on Microzonation, Seattle, 1982; 3: 1319-1330.

29 Seed HB, Idriss IM. “Simplified Procedure for Evaluating Soil Liquefaction Potential.” ASCE Journal of the Soil Mechanics and Foundations Division 1971; 97(SM9): 1249-1273.

30 Kayen RE, Mitchell JK, Seed RB, Lodge A, Nishio A, Coutinho R. “Evaluation of SPT-, CPT-, and Shear Wave-Based Methods for Liquefaction Potential Assessment Using Loma Prieta Data.” Proceedings of 4th Japan-US Workshop on Earthquake-Resistant Design of Lifeline Facilities and Countermeasures for Soil Liquefaction, 1992; (1):177-204.

31 Seed HB, Tokimatsu K, Harder LF, Chung RM. "Influence of SPT Procedures in soil liquefaction resistance evaluations." ASCE Journal of Geotechnical Engineering 1985; 111(12): 1425-1445.