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Evaluation of Liquefaction Susceptibility for Microzonation and Urban Planning

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Evaluation of Liquefaction Susceptibility for Microzonation and Urban Planning

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Abstract
Various procedures were developed to evaluate liquefaction susceptibility of soil layers for implementing engineering remediation measures. The approach that has gained wide acceptance within the framework of urban planning is to establish microzonation maps with respect to liquefaction susceptibility to mitigate possible earthquake damage related to liquefaction. In this context, microzonation maps were produced recently for six municipalities in Turkey as a part of a major Pilot Project.

Two variables are required for the assessment of liquefaction resistance of sandy soil layers; the seismic demand expressed in terms of cyclic stress ratio, CSR; and the capacity of the soil layers to resist liquefaction, expressed in terms of cyclic resistance ratio, CRR. The approach adopted to perform microzonation maps for liquefaction susceptibility was based on the procedure proposed by Youd et al., 2001 and Iwasaki et al., 1982. The variation of the safety factors with depth were determined for each representative borehole where CSR is calculated using stress reduction factor and CRR based on SPT blow counts. In addition CSR was calculated based on site response analyses. The results are compared and the source of uncertainties and the effects of the two approaches are discussed in terms of the final microzonation maps.

Introduction
Liquefaction of soil layers has been a major cause of damage to soil structures, lifeline facilities and building foundations during the past earthquakes. Significant efforts have been made to evaluate the mechanics of the soil behaviour during cyclic excitations and to determine the factors affecting liquefaction susceptibility based on laboratory and field tests. The approach that has gained wide acceptance within the framework of urban planning is to establish microzonation maps with respect to liquefaction susceptibility to mitigate possible earthquake damage related to liquefaction (Ansal and Tonuk, 2005; Todorovska, 1998, Kavazanjian et al., 1985).

Liquefaction susceptibility microzonation maps were produced recently for six municipalities in Turkey as a part of a major Pilot Project to be used for urban planning. The local soil stratifications and soil characteristics were determined based on previously and recently conducted soil borings. The investigated municipalities were divided into cells by a grid system of 500m×500m and site characterization was performed for each cell based on the available borings and other relevant information by defining a representative soil profiles (Ansal et al., 2005).

Site Response Analysis
The latest version of Shake (Shake91), the site response analysis code, originally developed by Schnabel et al., 1972 that was updated by Idriss and Sun, 1992 was used to evaluate the effects of local soil stratification and to calculate the peak

horizontal accelerations. Three previously recorded acceleration time histories compatible with the earthquake hazard assessment in terms of probable magnitude, distance and fault mechanism were selected as the input outcrop motion. The input acceleration time histories were scaled for each cell with respect to the peak accelerations obtained from earthquake hazard study since this approach was practical and gave consistent results as observed by Durukal et al., 2006. The three scaled acceleration time histories for each cell were used for site response analyses and the average of the PGAs at the ground surface was determined for each cell. An effort was made to select acceleration time histories that are more compatible with the NEHRP spectra calculated in the earthquake hazard study as shown in Figure 1.

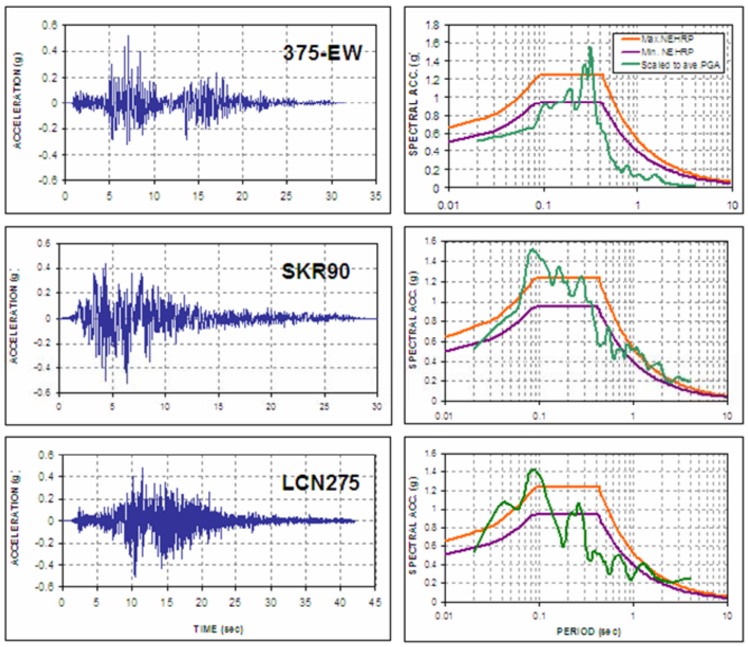

Figure 1. Three average PGA scaled acceleration time histories and the comparison of the corresponding response spectra with the minimum and maximum NEHRP spectra calculated in the hazard study for all cells in Bandırma city

Evaluation of Liquefaction Susceptibility

Two variables are required for the assessment of liquefaction susceptibility: (1) seismic demand on the soil layers, expressed in terms of cyclic stress ratio, CSR; and (2) capacity of the soil layers to resist liquefaction, expressed in terms of cyclic resistance ratio, CRR. Cyclic stress ratio is defined as the ratio of the cyclically applied shear stress to the effective normal stress acting at the beginning of shaking on the plane where shear stress is applied.

A detailed approach to determine liquefaction potential of saturated sand deposits requires cyclic tests, preferably, on undisturbed samples. However, the use of laboratory testing is complicated due to difficulties associated with sample disturbance during both sampling and reconsolidation. Thus empirical approaches based on the in-situ penetration test results gained popularity in the engineering practice as well as in the engineering codes.

As summarized by Youd et al., 2001, the oldest and still the most widely used approach is the simplified procedure for assessing liquefaction susceptibility originally proposed by Seed and Idriss, 1971 based on SPT N-values and cyclic stress ratio calculated using stress reduction factor. The cyclic stress ratio, CSR, is expressed as;

$$\mathrm{CSR} = \frac{\tau_{av}}{\sigma_v^{'}} = 0.65 \frac{a_{max}}{g} \frac{\sigma_v}{\sigma_v^{'}} r_d \qquad (1)$$

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

$$r_d = \frac{(1.00 - 0.4113z^{0.5} + 0.04052z + 0.001753z^{1.5})}{(1.00 - 0.4177z^{0.5} + 0.05729z - 0.006205z^{1.5} + 0.00121z^{2})} \qquad (2)$$

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

The second alternative is obtaining the variation of average shear stress with depth based on site response analyses. As shown in Figure 2, there are differences between the ones determined by site response analyses and conventional r_d procedure. The differences are not consistent and it depends very much on the properties of the soil stratification, shear wave velocity profiles and peak ground accelerations. The observed general trend indicates that the variation of CSR, calculated by site response analysis is higher compared to CSR calculated using the simplified stress reduction factor.

There have been various studies concerning the definition of stress reduction factor in the literature (Cetin, et al., 2004; Idriss and Boulanger, 2003). In most of these studies, different formulations were proposed to calculate rapidly the variation of cyclic stress ratio that would be induced by the design earthquake and almost all of them are only dependent on the depth in the soil profile. In the recent formulation proposed by Cetin et al., 2004 the effect of other factors such as peak acceleration on the ground surface, magnitude of the design earthquake, and soil stiffness at the top 12m in addition to the depth from the ground surface were considered as factors controlling the variation of stress reduction factor or in more general terms variation of maximum shear stresses with depth.

The comparison of the variation of CSR calculated using the formulation proposed by Youd et al., 2001, Cetin et al., 2004 and site response analyses given in Figure 2 indicate significant differences among the three approaches. In general, CSR calculated by site response analyses gave higher or similar values and the formulation suggested by Cetin et al., 2004 gave lower values.

The CSR calculated by the procedure suggested by Youd et al., 2001 depends only on depth of the element and ground water level and incapable to account for the changes in the soil profile. Depending on the soil stratification and stiffness of the soil layers the variation of CSR obtained by site response analysis could be considered more reliable. Thus based on the results obtained in this study, the formulation suggested by Youd et al., 2001 in general yielded values on the unsafe side.

It was also interesting to observe that the variation of CSR calculated using the r_d formulation given by Cetin et al., 2004 expressed as dependent on average shear wave velocity at top 12m, earthquake magnitude and peak ground acceleration in addition to depth gave even lower values in comparison to site response analyses as shown in Figure 2.

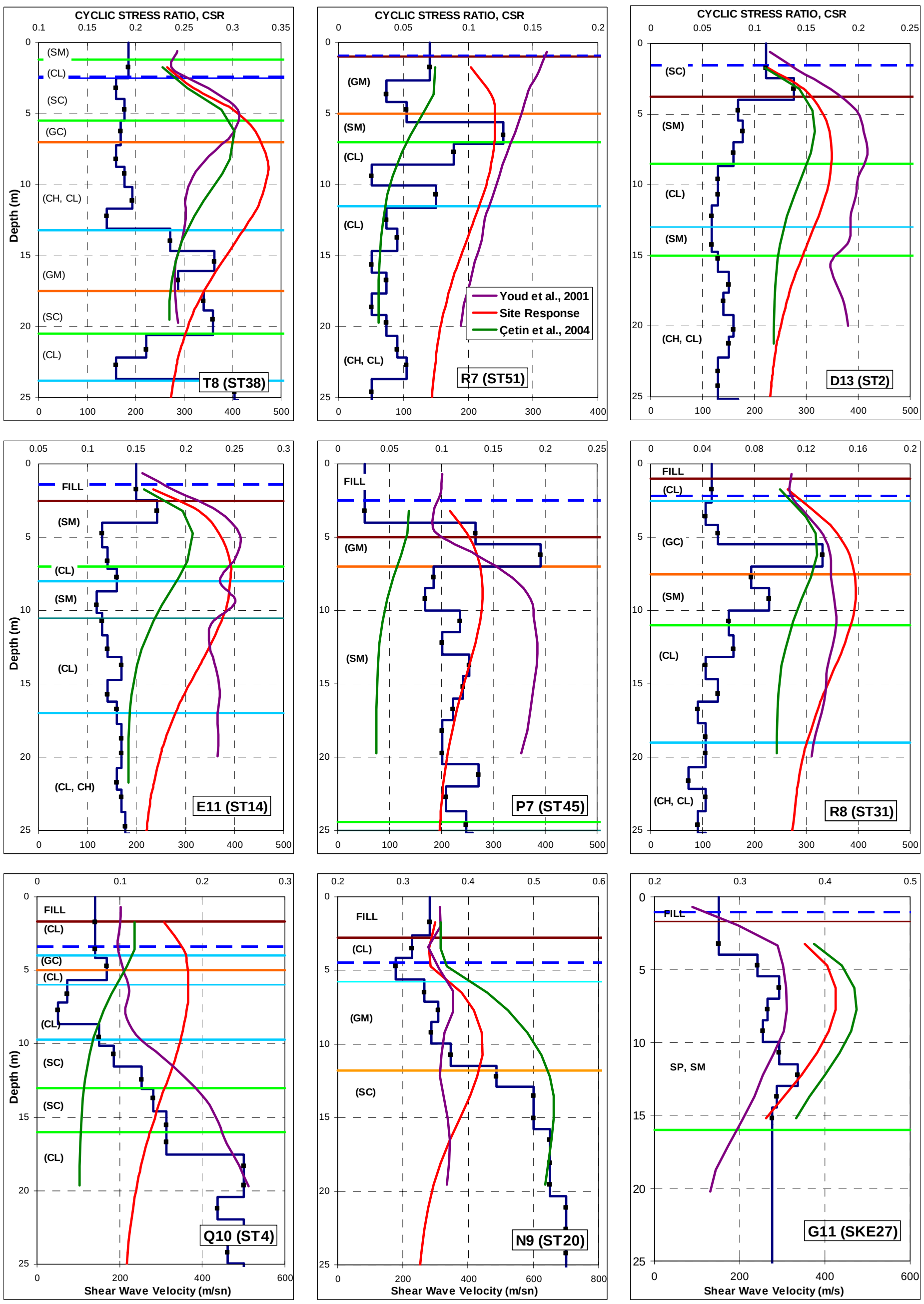

Figure 2. Comparisons of CSR by site response analysis and r_d simplified procedure recommended by Youd et al., 2001 and Cetin et al., 2004.

Microzonation with respect to Liquefaction Susceptibility

Due to the damage distributions observed during past earthquakes, it became evident that zonation maps prepared at small scales may 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 feasible to conduct seismic 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.

As a tool to improve the state of land use management in Turkey and better mitigate earthquake risk, a major microzonation project was initiated after the 1999 Marmara earthquakes. One of the components of this project was to conduct microzonation studies in the selected six municipalities.

The first phase involved the compilation of geological and geotechnical data. The second phase was the evaluation of the earthquake hazard for the microzonation study. The study areas were divided into 500m x 500m cells to evaluate earthquake hazard parameters in terms of spectral accelerations for each cell (Erdik et al., 2004).

The third phase was the evaluation and analysis of the available geotechnical data to determine the necessary parameters for conducting microzonation base maps with respect to different parameters. Representative soil profiles and site conditions for each cell were determined. Site response analyses were conducted for each cell using earthquake hazard and acceleration spectra compatible three PGA scaled acceleration time histories. The fourth phase involved the evaluation of the liquefaction susceptibility and landslide hazard based on the results obtained in the third 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 (Ansal et al., 2004).

The approach adopted to perform microzonation maps in terms of liquefaction susceptibility was based on the method summarised by Youd et al., 2001 and Iwasaki et al., 1982. The variation of the safety factors with depth were determined for each representative borehole for all regions based on the method proposed by Youd et al., 2001. 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 based on (a) CSR using peak ground accelerations calculated from site response analysis and r_d procedure suggested by Youd et al., 2001 and (b) CSR calculated by site response analyses (Figure 3).

The liquefaction potential for each borehole was calculated according to the procedure proposed by Iwasaki et al., 1982 using the variation of the safety factors with depth. The severity of possible liquefaction at any site was quantified by introducing a factor called the liquefaction potential index, PL defined as

$$P_L = \int F(z)w(z)dz \qquad (4)$$

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. Eq.(4) gives values of PL ranging from 0 to 100.

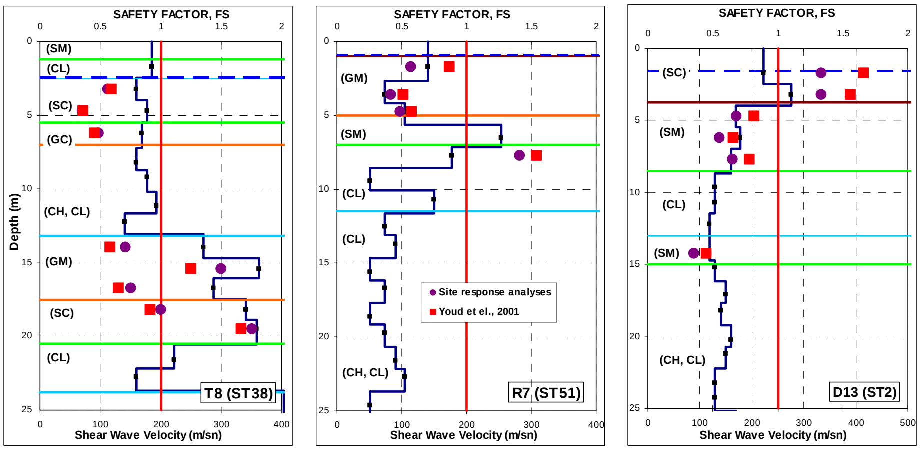

Figure 3. Variation of liquefaction safety factor with depth based on r_d procedure proposed by Youd et al., 2001 and site response analyses

Based on the results reported by Iwasaki et al., 1982, 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 using the safety factors computed based on CSR using r_d simplified procedure and using the values obtained by site response analyses. The differences between the two approaches were not very significant for Gemlik city as can be observed in Figures 4.

Conclusions

In general terms seismic microzonation can be considered as the process of establishing suitable and applicable hazard parameters that could be utilized for urban planning and thus for earthquake risk mitigation. Microzonation maps with respect to liquefaction susceptibility are one output set within this framework. The approach adopted to perform microzonation maps for liquefaction susceptibility was based on the procedure proposed by Youd et al., 2001. A suitable microzonation parameter to identify the surface manifestation of liquefaction was taken as the liquefaction potential index suggested by Iwasaki et al., 1982 to produce liquefaction microzonation maps for the six municipalities during the pilot microzonation study conducted in Turkey.

The evaluation of liquefaction susceptibility of soil layers in nature for engineering purposes is performed based on empirical procedures developed using Standard Penetration Test results obtained by in-situ testing. One of the most popular procedures was originally developed by Seed and Idriss, 1971 and later summarised by Youd et al., 2001. Two variables are required for the assessment of liquefaction resistance of sandy soil layers; the seismic demand expressed in terms of cyclic stress ratio, CSR; and the capacity of the soil layers to resist liquefaction, expressed in terms of cyclic resistance ratio, CRR. The variation of the safety factors with depth were determined for each representative borehole where CSR is calculated using stress reduction factor and CRR based on SPT blow counts. In addition CSR was calculated based on site response analyses and using the stress reduction formulation suggested by Cetin et al., 2004. As expected all three procedures gave different results depending on the CSRs. Assuming that site response analyses would yield more reliable results, the two procedures suggested by Youd et al., 2001 and Cetin et al., 2004 yielded results on the unsafe side. Thus even though r_d procedures to estimate the variation of CSR with depth are simpler and could be applied much faster, the calculated safety factors may not always be on the safe side.

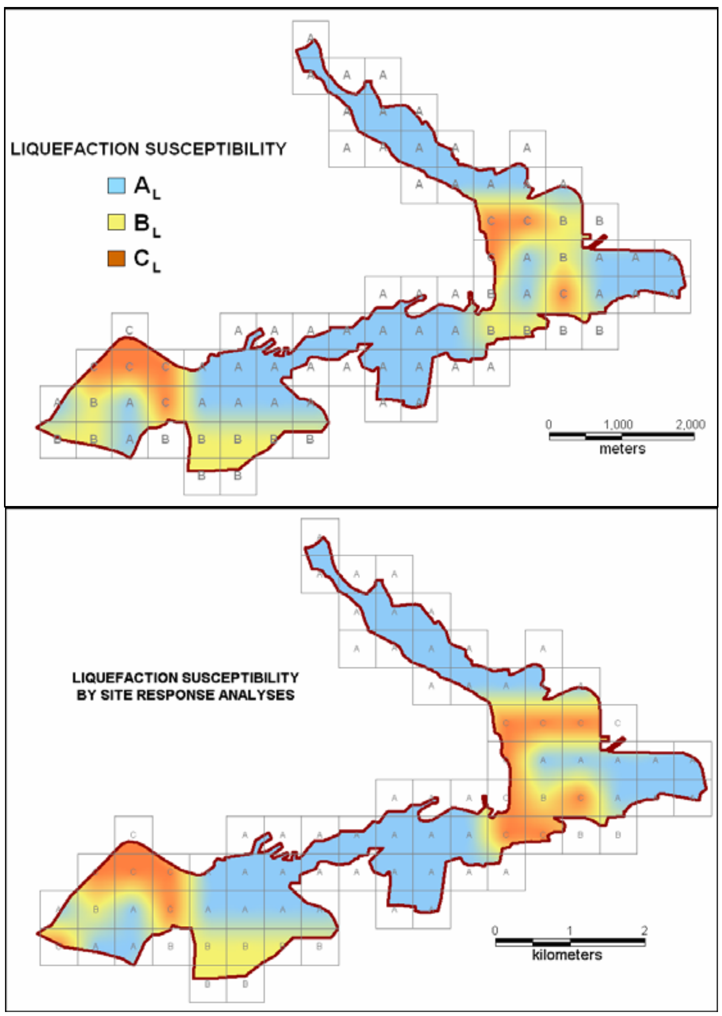

Figure 4. Variation of liquefaction susceptibility based on CSR determined by stress reduction factor and site response analyses

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