Preparation of Liquefaction Potential Risk Maps Using Ordinary Kriging Method in Eskisehir

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Abstract: - In this study, liquefaction potential risk is investigated according to the 0.4 g ground acceleration, which may be caused by a proposed earthquake magnitude of 6.4 on Richter scale in Eskisehir City Center. Factors of safety against liquefaction are calculated from Standard Penetration Test (SPT) values for 64 bore-hole locations. Calculated factors of safety are processed by ordinary kriging, which is one of the well known methodologies of geostatistical methods, for estimation of the liquefaction values of locations that have no data. Estimated values are classified depending on liquefaction potential as risky, potential, and no risk, therefore preparing liquefaction potential risk maps. Due to liquefaction potential risk map, conglomerate and alluvial regions beside the Porsuk River, which passes through the city center, are the risky zones. Hilly sides in the south laid on schist lithology have no risk, and the contact zones between these lithologies are potential risk on liquefaction which may be caused by a proposed earthquake magnitude of 6.4. Also a comparison is done with the results, which were obtained from Eskisehir Preliminary Disaster Mitigation Plan.

Key-Words: - Geographic Information Systems (GIS), geostatistics, liquefaction, ordinary kriging

1 Introduction

On August 17, 1999 an earthquake measuring 7.4 on the Richter scale devastated the Marmara region of Turkey. According to the governmental records, over 17,000 lives were lost, and estimated 200,000 people were made homeless in the region, and Turkey's industrial heartland was extensively damaged. A major reconstruction effort and recovery plan was needed, in addition to a mechanism to reduce the costs of future natural disasters. For this purpose governmental institutions and municipalities, were focused on laws and regulations about building construction to improve and inspect them more attentive.

Eskisehir has a rapid growing rate with rich industrial raw material deposits, but important percentage of urban area of Eskisehir City located on alluvial region, besides close ground water level to the surface. In the past on February 20, 1956 an earthquake measuring 6.4 on the Richter scale devastated Eskisehir City Center, which is dropped within second degree risk region according to the map of Earthquake Risk Map which was prepared in 1998 by Turkish Republic Ministry of Public Works and Settlement. After this quake thousands of houses were discharged, and hundreds of buildings were demolished or became useless.

Eskisehir is located on potential earthquake risk region. In such regions like Eskisehir City Center which is laid on water saturated slack alluvial lithology, ground deformations may occur such as ground sitting and lateral spreading, because of liquefaction [1]. Therefore, it is very important to estimate liquefaction potential risk regions truly and accurately.

Geostatistics has been popularly applied in investigating and mapping in GIS, in recent years, and proved useful in characterizing spatial variability. The objective of this paper is to investigate the liquefaction potential risk using GIS and geostatistics as an integrated tool, in order to map spatial variability, accurate estimation of the liquefaction values of locations that have no data. For this purpose, to prepare a potential liquefaction map using Ordinary Kriging (OK) with GIS support, the sub-section of Eskisehir downtown area has been chosen as study area.

In this study, liquefaction factor of safety was calculated basis on geotechnical data, according to the 0.4 g maximum ground acceleration for the region. Calculated liquefaction factors of safety values are processed by ordinary kriging, which is one of the well known methodologies of geostatistical methods, down to 30 m. depth.

2 Materials and Methods

2.1 Study Area

The study area is Eskisehir City Center. Eskisehir is located in the north-western part of Anatolia and it is located at equal distance from the Primary Metropolitan City Istanbul and the Capital Ankara. There is a railway and highway connection between these cities. Its area is 13,653 sq.km, with this area, city covers 1.8% of Turkey, and its approximate altitude is 792 m. above the sea level (Fig.1).

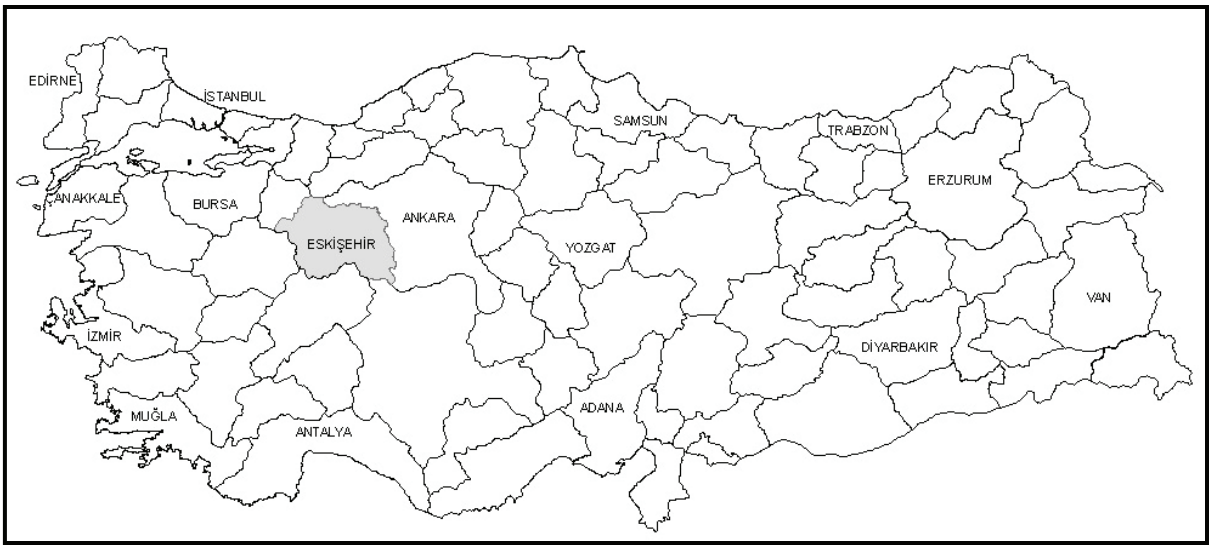

Fig.1 Location map

2.2 Data Sampling and Analysis

After the earthquake on August 17, 1999, the importance of building construction regulations were taken into consideration in construction facilities by Greater Eskisehir Municipality. For this purpose disaster mitigation plans and ground resistance investigations were made by different institutions for Greater Eskisehir Municipality. During these studies several drillings were made in the city center, and presented as reports.

In this study, different from the former studies such as disaster mitigation plans and ground resistance investigations, GIS tools and geostatistic methods with ordinary kriging were used to prepare liquefaction risk maps. Integration of these tools gives more accurate and reliable results. Data, which was collected in these former studies, was compiled. SPT values for 64 borehole locations are selected for calculation of factor of safety against liquefaction.

2.3 Liquefaction Analysis Method

In this method, the factors of safety against liquefaction (Fs) were computed with the simplified procedure proposed by *Seed and Idriss (1971)* [2] and *Seed et al. (1985)* [3]. The factor of safety against liquefaction based on the SPT is determined by the ratio of the cyclic resistance ratio (CRR) to the earthquake induced cyclic stress ratio (CSR) at that depth from a designated earthquake. Soil with Fs greater than 1.2, between 1.0 and 1.2, and less than 1.0 are defined as non-liquefied, marginally liquefiable, and liquefiable, respectively [4].

The CSR values were calculated using the equation proposed by *Seed and Idriss*:

$$CSR = 0.65 \cdot (a_{max} / g)(\sigma_{vo} / \sigma'_{vo}) \cdot r_d \qquad (1)$$

where,

CSR: the cyclic stress ratio induced by a given earthquake

a_{max}: the peak horizontal ground acceleration

σ_{vo}: the total vertical overburden stress

σ'_{vo}: the effective overburden stress

r_d: the stress reduction coefficient

For the evaluation of liquefaction potential in Eskisehir we employed an a_{max} value equal to 0.4 g and a magnitude of 6.4.

2.4 Geostatistical Methods
The main application of geostatistics to liquefaction risk map has been the estimation and mapping of factors of safety against liquefaction in unsampled areas.

Geostatistics is based on the concept of Random Functions (RF), whereby the set of attribute values $Z(x)$ at all locations x are considered as a particular realization of a set of spatially dependent Random Variables (RV) $Z(x)$. To make this approach acceptable, certain assumptions have to be made, which are introduced under the hypothesis of stationarity [5].

2.4.1 The hypothesis of stationarity
In the strictest sense, a RF is stationary when all the moments of its distribution are invariant under translation [6].

In geostatistics, often only the first two moments of the RF are considered, called second-order or weak stationarity. A RF is said to be weakly stationary when the mathematical expectation $E[Z(x)]$ exists and does not depend on the support point x:

$$E[Z(x)] = m \qquad \forall x \tag{2}$$

and when for each pair of RV $\{Z(x), Z(x+h)\}$, the autocovariance exists and depends on the separation distance h:

$$C(h) = E[Z(x+h)\cdot Z(x)] - m^2 \quad \forall x \tag{3}$$

This hypothesis can be reduced when assuming stationarity of the first two moments of the increments of the RF, termed intrinsic stationarity. This assumes that the mean and variance of the increments $\{Z(x+h)-Z(x)\}$ exist and are independent of x:

$$E\left[\{Z(x+h)-Z(x)\}^2\right] = 0 \qquad \forall x \tag{4}$$

$$Var\left[Z(x+h)-Z(x)\}\right] = E\left[\{Z(x+h)-Z(x)\}^2\right] = 2\gamma(h) \ \forall x \tag{5}$$

where $\gamma(h)$ is the semivariance.

2.4.2 Ordinary kriging
Ordinary kriging (OK) is one of the most basic kriging methods. At an unsampled location x_0, Z is estimated by:

$$Z^*(x_0) = \sum_{i=1}^{n} \lambda_i Z(x_i) \tag{6}$$

where $Z^*(x_0)$ is the estimated value of the RV Z at the unsampled location x_0 and λ_i are the n weights assigned to the observation points $Z(x_i)$. The weights λ_i sum to one to assure unbiased conditions and they are found by minimizing the estimation variance.

The RV $Z(x)$ can be decomposed into a trend component $m(x)$ and a residual component $R(x)$:

$$Z(x) = m(x) + R(x) \tag{7}$$

OK assumes stationarity of the mean and considers $m(x)$ to be a constant, but unknown, value. Nonstationary conditions are taken into account by restricting the domain of stationarity to a local neighborhood and moving it across the study area. The residual component $R(x)$ is modeled as a stationary RV with zero mean and under the assumption of intrinsic stationarity, its spatial dependence is given by the semivariance $\gamma_R(h)$:

$$\gamma_R(h) = \frac{1}{2} E\left[\{R(x+h) - R(x)\}^2\right] \tag{8}$$

3 Mapping and GIS Studies
In GIS environment continuous surfaces or maps can easily be created from measured sample points stored in a point-feature layer. The sample points may be measurements such as elevations, depth to the water table, or levels of pollution [7].

In this study, 64 borehole locations were transferred to a database table with x,y,z coordinates. Using the coordinate columns, point features were created in a GIS environment related with their calculated attributes, such as CRR, CSR and Fs.

To make better decisions when creating a surface or a map, dataset should be explored for obvious errors in the input sample data that may drastically affect the output prediction map.

Interpolation methods in geostatistics that are used to generate a map give the best results if the data is normally distributed. If the dataset is skewed it must be transformed to make it normal. First of all, Fs values at 64 locations at different depths were averaged in order to get unique value for each location. Afterwards, the dataset of Fs explored if the data is normally distributed or not.

Semivariograms were developed to establish the degree of spatial continuity of Fs values and to establish the range of spatial dependence for Fs variable. For parameter estimation, data distribution should be normal. Real data often violate this assumption, so the data that were not normally distributed should be logarithmically transformed. In this study, the histogram in Fig.2 shows that, data distribution is normal and do not need to be transformed.

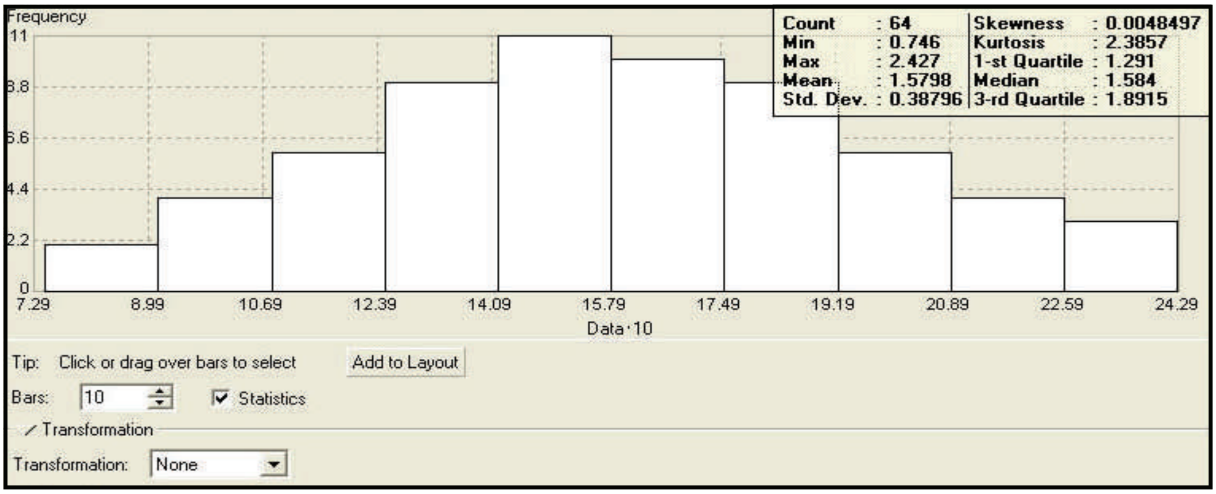

Fig.2 Histogram summary statistics of 64 observation points

Kriging, like most interpolation techniques, is built on the assumption that things that are close one to another are more alike than those farther away. The empirical semivariogram is a means to explore this relationship. Pairs that are close in a distance should have a smaller measurement difference than those farther away from one another. The extent that this assumption is true can be examined in the empirical semivariogram [7].

There must be a similarity between the empirical semivariogram and a function line that provides the best fit through the points in the semivariogram cloud. This function line such that the squared difference between each point and the line is as small as possible, which is referred to as the least-squares fit. This function line is considered a model that quantifies the spatial autocorrelation of the data. Several standard models are available to fit the empirical semivariogram, e.g., spherical, exponential, Gaussian, linear and power models. For this purpose empirical variogram is fitted on a standard exponential model shown in Fig.3 with yellow line. As the parameters of semivariogram

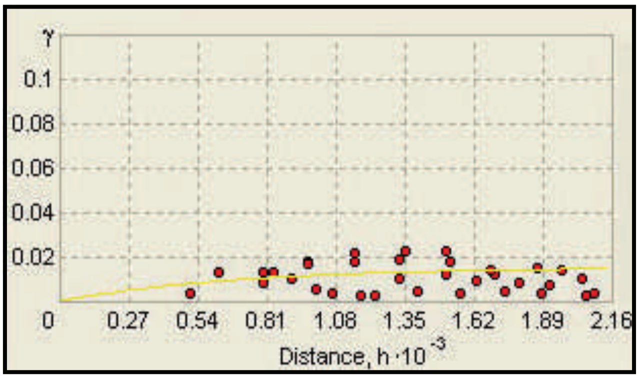

Fig.3 Fitted exponential semivariogram model

model, lag size is taken approximately 180 meters, and the number of lags is set to 12. In the exponential semivariogram model, which is fitted to, nugget and sill values are calculated as $0.46{\cdot}10^{-2}$ and $0.15{\cdot}10^{-1}$, respectively.

The equations for ordinary kriging are contained in matrices and vectors that depend on the spatial autocorrelation among the measured sample locations and prediction location. The autocorrelation values come from the semivariogram model described above. The matrices and vectors determine the kriging weights that are assigned to each measured value. Finally, predictions can be calculated for the locations with the unknown values from these kriging weights [7].

In this study, ordinary kriging prediction map was generated to determine Fs values for the locations with unknown values, which depend on the spatial autocorrelation among the measured sample locations. Three classes were chosen to assign a thematic meaning to the prediction map, which denotes liquefaction potential risk. Also for quick look check and an easy interpretation, 50% transparent hillshade map, which is created from dem (digital elevation model), was added as a layer, whether liquefiable zones were not laid on hilly rocks.

Maps are the most commonly used tools for understanding and interpreting spatial relationships among features. To support the interpretation, different features were added as layers, such as Porsuk River, district boundaries, and so on (Fig.4).

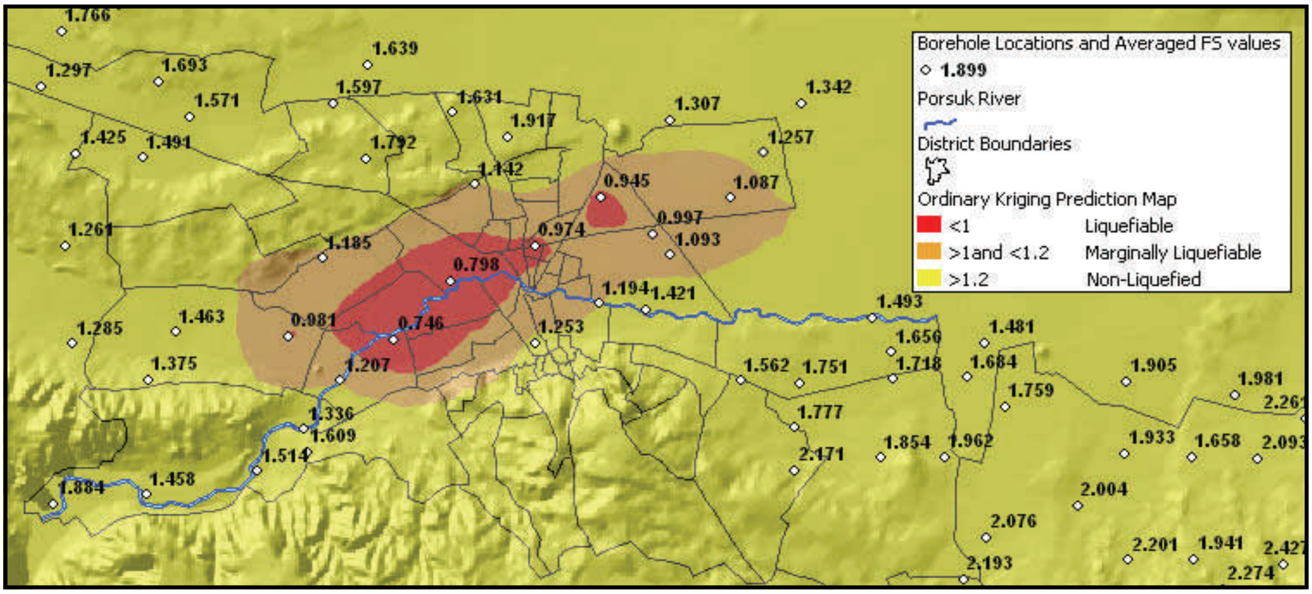

Fig.4 Ordinary kriging prediction map

4 Comparison with Former Studies

In the former study, named Microzonation and Hazard Vulnerability Studies for Disaster Mitigation covered by Eskisehir Preliminary Disaster Mitigation Plan, which was prepared by ABS Consulting in April-2006, liquefaction susceptibility was based on the method developed by *Youd et al. (2001)* [8] and *Iwasaki et al (1982)* [9]. The safety factors were determined for each representative borehole containing liquefiable sand or silt layers for the region. Based on the results reported by *Iwasaki et al. (1982)*, three zones (A_L, B_L, and C_L) were identified with respect to liquefaction potential index. Zone C_L indicating high liquefaction susceptibility, zone B_L is the intermediate zone, and zone A_L is the safest zone indicating very low liquefaction susceptibility. The map for liquefaction susceptibility determined by this approach is shown for Eskisehir region laid on lithological units in Fig.5 [10].

As it shown in Fig.5, high liquefaction susceptibility zones were laid on schist lithology, on hilly regions, which is a thought-provoking situation. The calculation methodology used in this

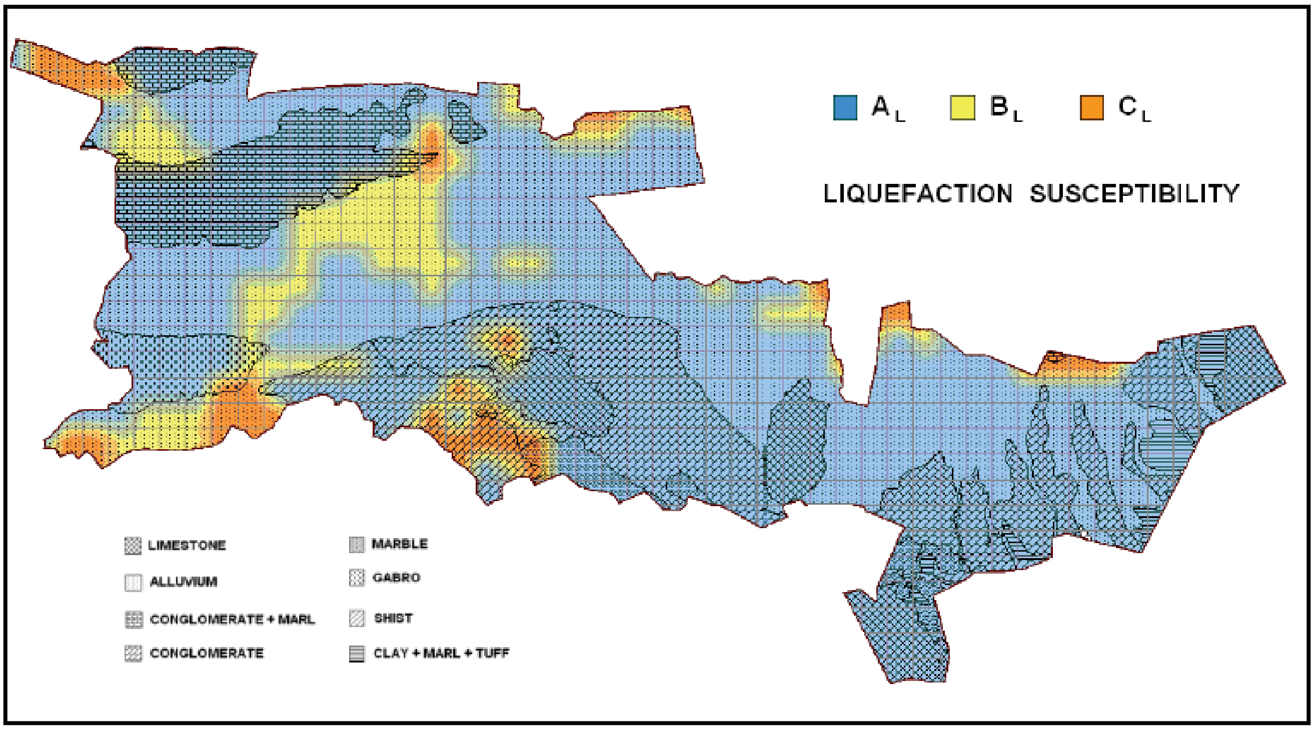

Fig.5 Liquefaction susceptibility map prepared by ABS Consulting

former study based on the method developed by *Youd et al. (2001)* is a revised version of the method suggested *by Seed et al. (1985)*, which is used in this study. Hence, the factor of safety against liquefaction values, which are calculated with different methods, should be considered similar for the same region, but the interpolation method, which is unknown for the former study, used for prediction for the locations with unknown values, is caused these thought-provoking different results.

5 Results and Discussions

In this study, Fs values for 64 borehole locations were calculated with the simplified procedure proposed by *Seed and Idriss (1971)* and *Seed et al (1985)*. Calculated values were averaged and transferred as unique value point features in a GIS environment. Afterwards, a liquefaction potential risk map was prepared using ordinary kriging which is a well known method of geostatistics. To verify the results of the study, a comparison is made with the former study results named, Eskisehir Preliminary Disaster Mitigation Plan, prepared by ABS Consulting.

In addition, to perform accuracy assessment of the results, cross-validation is done to get an idea of "*how well*" the model predicts the unknown values. The objective of cross-validation is to choose best model that provides the most accurate predictions. In the prediction errors in cross-validation results of this study, the mean error value is $-0.89 \cdot 10^{-2}$, which should be close to 0, the root mean square value is 0.178, and the average standard error is 0.12, those should be as small as possible, and the root-mean-square standardized error is 1.456 should be close to 1, for an accurate prediction.

Finally, in the comparison with the former study and the prediction errors in the cross-validation results shows that, ordinary kriging estimation, which is used in this study, is better than the unknown interpolation method used in the former study, and may be considered as a good interpolation method that can be used in spatial analysis.

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