



An IDW-based GIS application for assessment of geotechnical characterization in Erzincan, Turkey

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Abstract

Preparing maps for geotechnical characterization in earthquake-prone areas is significantly important for decision-makers and local-planners in order to reduce loss of lives. This study presents a series of maps for Erzincan city, which is mostly located in a deep alluvial basin in nearby area of North Anatolian Fault Zone (NAFZ). The maps for addressing certain physical properties of soils Atterberg's limits, classification, standard penetration test (SPT), shear wave velocity (V_s), and primary wave velocity (V_p) findings in the region have been prepared using field-based methods and geotechnical data of 92 available boreholes in Erzincan. The geological units underlying the city is consisted of various amounts of silt, clay, gravel, and sand, while it is predominantly classified as either low plastic clay (CL) or medium plastic silt (SM). Liquid limit (LL) and plastic limit (PL) values varied between 28–45% and 5–24%, respectively. The lowest SPT blow counts were found to be in southern part of the Erzincan city. The northern parts with the highest V_s values (higher than 1000 m/s) have been determined as very dense cohesionless soils. Furthermore, a correlation performed via NN between the unconfined compression testing results and dynamic elastic modulus from field studies yielded a very high correlation coefficient ($R^2=0.97$). Evidently, the GIS maps produced by inverse distance weighting (IDW) method could be efficiently used by engineers as well as researchers for the purpose of land-use planning and urban development in earthquake-prone regions.

Keywords GIS · Erzincan · Geotechnical characterization

Introduction

Assessment of sub-surface soil features in an earthquake-prone area is one of the vitally important issues in geotechnical engineering, because significant damage in engineering structures and loss of life in residential areas primarily depends on the local site

conditions. Erzincan city is mostly located in a deep alluvial basin in nearby area of North Anatolian Fault Zone (NAFZ), along which Turkey has a long history of destructive earthquakes. Anatolian Block, which moves westward because of north-south convergence between African-Arabian and Eurasian Plates, is reason of deformations along the NAFZ causing seismic activities in Erzincan and its vicinity area (Ambraseys 1970; Sengor 1979; Westaway 1994; Bozkurt 2001; Ozturk 2020). Erzincan city, where numerous earthquakes in different magnitudes have taken place, has recently experienced a rapid transformation because of rapid urbanization, population growth, technological, social, and cultural changes. However, a proper assessment of sub-surface soil characterization required for selecting appropriate sites for residential areas and planning for engineering structures in the area has been got behind in recently created residential areas. Lack of understanding the properties of the sub-surface soil in the field can lead to the catastrophic engineering failures caused by problems in design. The fact is that potential

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geotechnical risks with engineering structures attributed to sub-surface soil characterization present for many infrastructure designs (Ground Board 1991). Many of such risks are affected by quality, quantity (Hoek and Palmeiri 1998; Clayton 2001), and cleansing of sub-surface investigation data. Thus, a proper assessment of sub-surface soil

characterization including Atterberg’s limits, classification, standard penetration test (SPT), and shear wave velocity (v_s) values is one of the most challenging tasks in geotechnical engineering.

Geographic information system (GIS) is a data processing system used in order to create maps for various civil

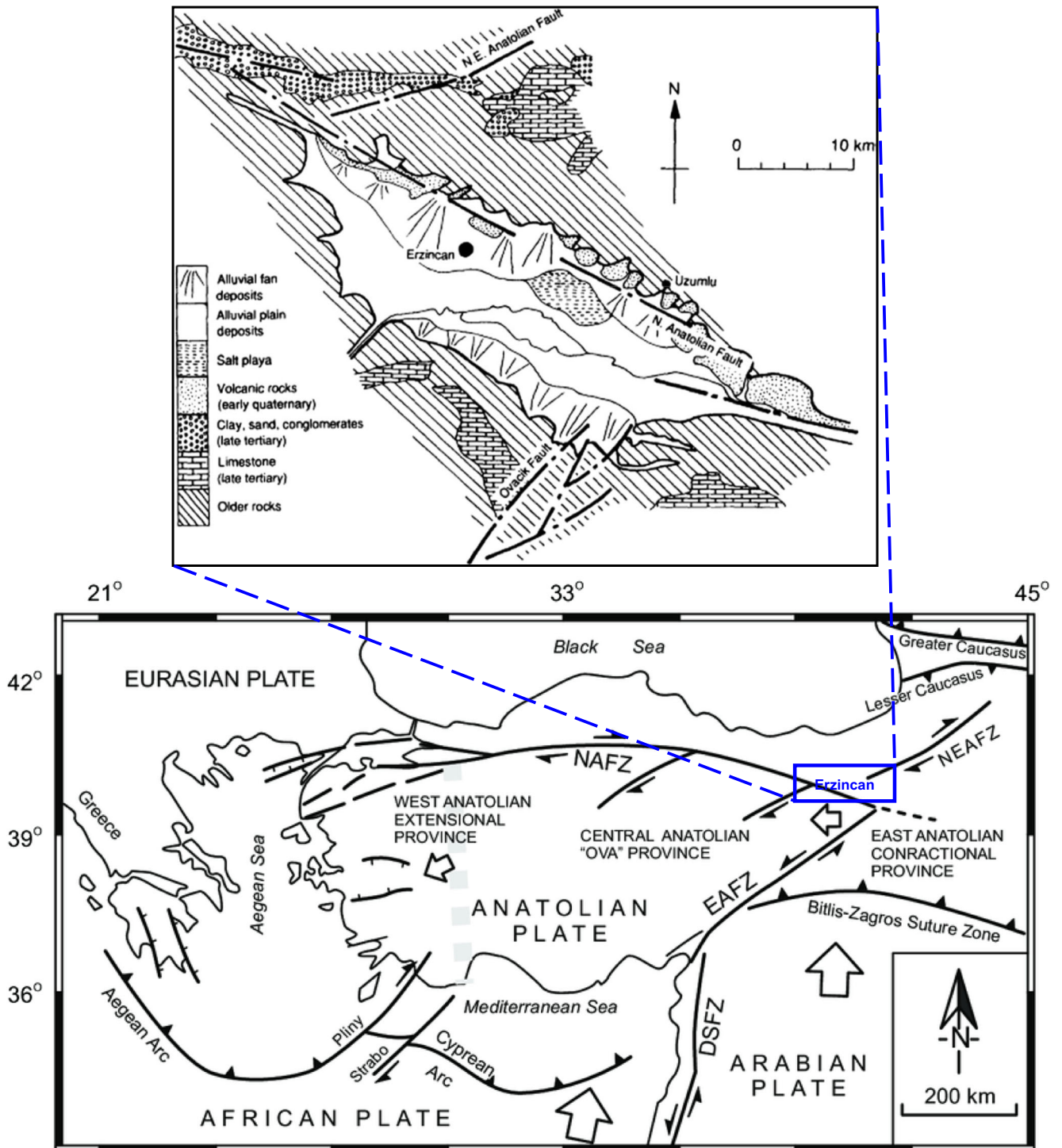


Fig. 1 Simplified tectonic map of Turkey showing major neotectonic structures, neotectonic provinces, and fault segments and geology in the study area (Sengor et al. 1985; Barka and Gulen 1989; Barka and Reilenger 1997; Kiratzi and Louvari 2001; Bozkurt and Sozbilir 2004)

engineering applications including surveying, construction, land analysis, waste management, transportation system, groundwater vulnerability evaluation, and disaster management (Dai et al. 2001; Hellowell et al. 2001; Mancini et al. 2009; Orhan and Tosun 2010; Venkatraman and Anitha 2017). There are different types of interpolation techniques being used in GIS applications, including inverse distance weighting (IDW). The IDW estimates the grid values being mapped by averaging the values of sample data points in the neighborhood of each processing grid (Gunnink and Burrough 1996). The authors considered that a systematic assessment of sub-surface soil characterization is necessarily required for Erzinan city by employing a GIS-based computer software. The city with a population of about 175,000 is located in eastern Turkey within $39^{\circ}.15'–39^{\circ}.50'$ E and $39^{\circ}.32'–39^{\circ}.52'$ N. It lies on the Erzinan plain at an elevation of about 1200 m from the sea level surrounded by 3500 m height Mountain Kesis in north, Mountain Munzur in south, and Karadag in the west. Karasu, a river reach of Euphrates, and other streams create large planes on this plain (Duman and Ikizler 2014; Duman et al. 2015) (Fig. 1). Actually, the Erzinan Basin has recently attracted considerable attention in the literature because of its complex incompletely understood geologic, tectonic, and morphologic features.

The present study adds to the recent researches by mapping numerous geotechnical characteristics in the study area. The maps addressing many properties of sub-surface soils including natural water content, Atterberg's limits, classification, SPT, V_s , and V_p values have been prepared using field-based methods and geotechnical data of 92 available boreholes in the study area (Fig. 2). Also, high-resolution maps have been generated by employing the nearest neighbor value interpolation method. Furthermore, this study contributes to the current understanding of how static laboratory testing findings can be effectively used for seismic wave estimates in the field. The fact is that the seismic wave estimates carried out during the fields studies are commonly employed to investigate how the soils response under dynamic loads due to the earthquakes. However, as characterizing the response of soils under dynamic loads by using seismic wave measurements becomes much more complicated and expensive than assessing the response of soils subjected to monotonic loads, a limited number of researchers have studied on correlating response of soils under dynamic test with those under static loads yet (Consoli et al. 2009; Flores et al. 2010; Cabalar et al. 2018). Therefore, there is

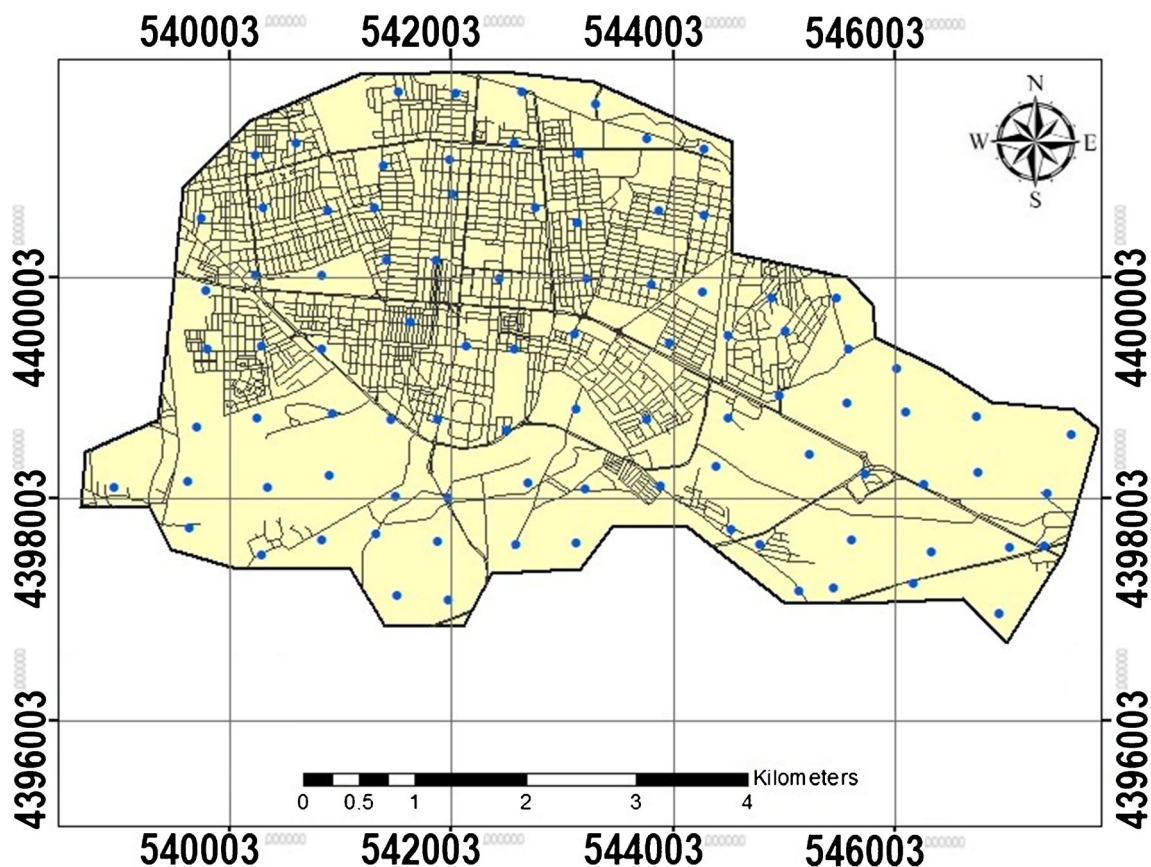


Fig. 2 Locations of boreholes in the city of Erzinan

Table 1 Some of the historical earthquakes in Erzincan Basin (Tan et al. 2008)

| Date | N (longitude) | E (latitude) | Magnitude (Mw) |
|-------------------|---------------|--------------|----------------|
| 15 September 1929 | 40.3 | 38.1 | 5.0 |
| 10 December 1930 | 39.7 | 39.2 | 5.6 |
| 13 October 1935 | 39.4 | 40.5 | 5.0 |
| 26 December 1939 | 39.8 | 39.5 | 7.9 |
| 22 April 1940 | 39.6 | 39.9 | 5.2 |
| 12 November 1941 | 39.7 | 39.4 | 5.9 |
| 17 August 1949 | 39.6 | 40.6 | 5.3 |
| 7 July 1957 | 39.4 | 40.4 | 5.1 |
| 14 January 1958 | 39.5 | 40.4 | 5.1 |
| 26 January 1960 | 40.2 | 38.8 | 5.9 |
| 31 August 1965 | 39.4 | 40.8 | 5.6 |
| 26 July 1967 | 39.5 | 40.4 | 5.9 |
| 3 September 1970 | 39.6 | 38.8 | 5.3 |
| 18 November 1983 | 39.8 | 39.4 | 5.0 |
| 13 March 1992 | 39.7 | 39.5 | 6.8 |

an urgent requirement for an in-depth investigation of a comparison between seismic wave estimates and static testing findings. Actually, the studies by Consoli et al.

(2009), Flores et al. (2010), and Cabalar et al. (2018) suggest that the unconfined compressive strength (q_u) values and G_{max} identified by a pair of bender element, a non-destructive laboratory test, are able to be correlated for various types of soils. However, no relationship has yet been found between the shear wave velocity values (V_s, V_p) values measured in the field and the q_u values obtained in the laboratory. Thus, predicting the E_d values from q_u by employing the neural networks (NN) model has emerged as one of the aims of the study. Hence, for the first time in the literature, the unconfined compression testing results (q_u) have been correlated with the dynamic elastic modulus (E_d) values obtained from field studies by using NN prediction model for further use by the researchers.

Study area

The study area is located in Erzincan basin with 50 km east-west and 15 km north-south, surrounded on all sides by mountainous terrain with more than 3000 m height (Fig. 1). Therefore, geological structure of the study area is affected by the basin, which was initiated by pull-apart motion between two divergent segments of the North Anatolian Fault.

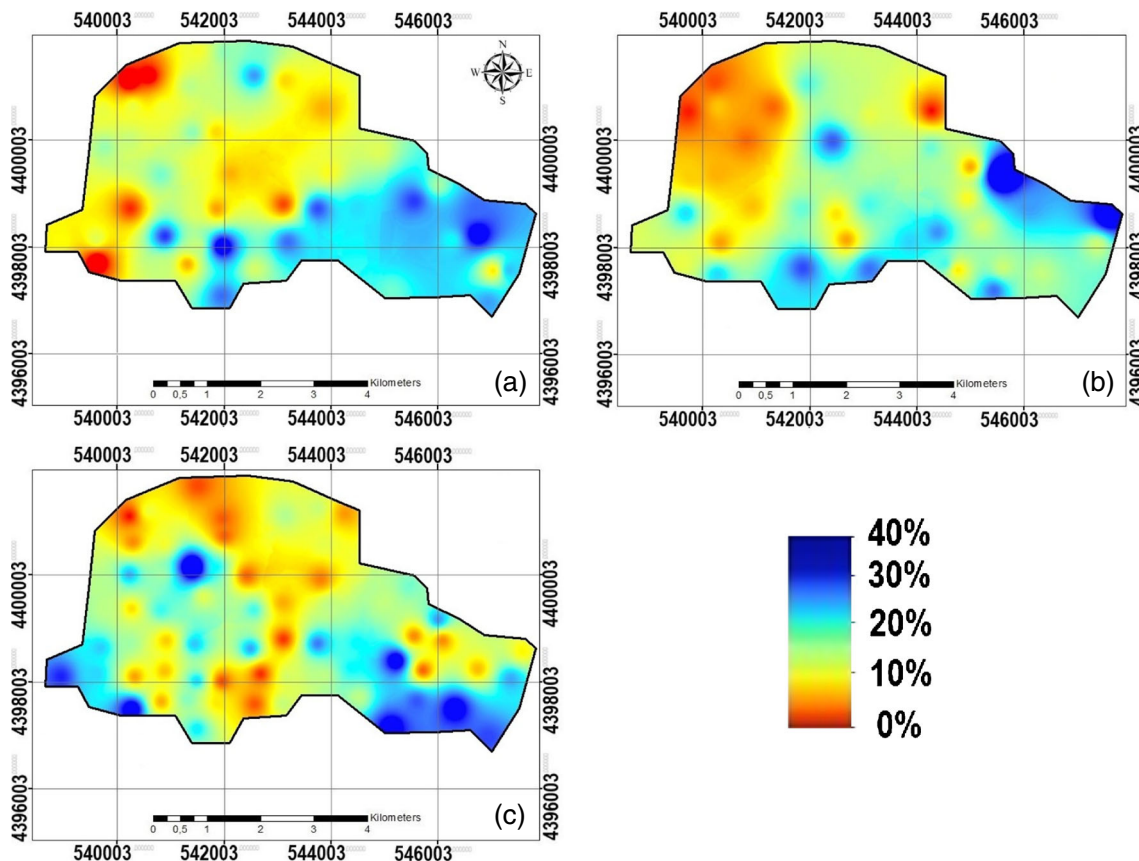


Fig. 3 Natural water contents of the soils at **a** 1.5–3.0m, **b** 6.0–7.5m, **c** 10.5–12.5m depths in the study area

Actually, the basin was initially formed because of a 4-km wide releasing step-over and a 15° divergence between two segments of the NAF, along which the westward tectonic escape of the Anatolian Block has been taking place. Center of the basin, where Erzinca city is located, is filled with thick alluvial deposits with silts, sands, and gravels. These comprise much looser geomaterial than the alluvial fan deposits available around the edges of the basin (Aydin and Nur 1982; Barka and Gulen 1989; Duman et al. 2015).

Erzinca city is in first-degree seismic zone in the seismic hazard map of Turkey. Numerous earthquakes in various magnitudes, the largest of which was 7.9 in December 26, 1939, have occurred throughout the history, leading to loss of many lives (Ministry of Reconstruction and Settlement 1996; Kaypak 2002; Tan et al. 2008; Fraser et al. 2012)(Table 1). The 1939 earthquake resulted in an about 360 km length surface rupture taken place up to Erbaa/Tokat, and then towards Amasya Province. This earthquake triggered seismic activities, which moved towards west in the faulting system from 1939 to 1967 (Emre et al. 2010). The earthquake occurred in 1992 with the magnitude of 6.8 was the second largest devastating one, and took place between the east end of 360 km section of NAF which was torn in 1939 and the east of Erzinca city. It took place along the fractures spread over an area about in a 50-km length and 3-km width,

and exposed an about 4-cm right lateral movements and 30-cm drifts in those fractures (Akyildirim 1993; Barka and Eyidogan 1993; Fuenzalida et al. 1997).

Data and method

The paper primarily studies results from laboratory tests. Laboratory testing results provide sub-surface soil features needed to accurately estimate the behavior of soil and rock materials. Samples obtained from 92 boreholes in the study area were used to determine geotechnical parameters that are not affected by disturbance, including natural water content, grain size distribution, Atterberg's limits, and soil classification. The ASTM standards defining the tests were employed throughout the works. The study then focuses on field investigations which identify the earth materials by drilling and sampling the areas and layers of them to address any site-specific issues or to satisfy design requirements. SPT counts and V_{s30} measurements were recorded for mapping variations over the study area. The field investigations were conducted in the specific locations, where 92 boreholes had been opened (Fig. 2). Also, prediction models via soft computing techniques have been applied to various problems in geotechnical engineering in order to obtain a flexible ability and adapted to

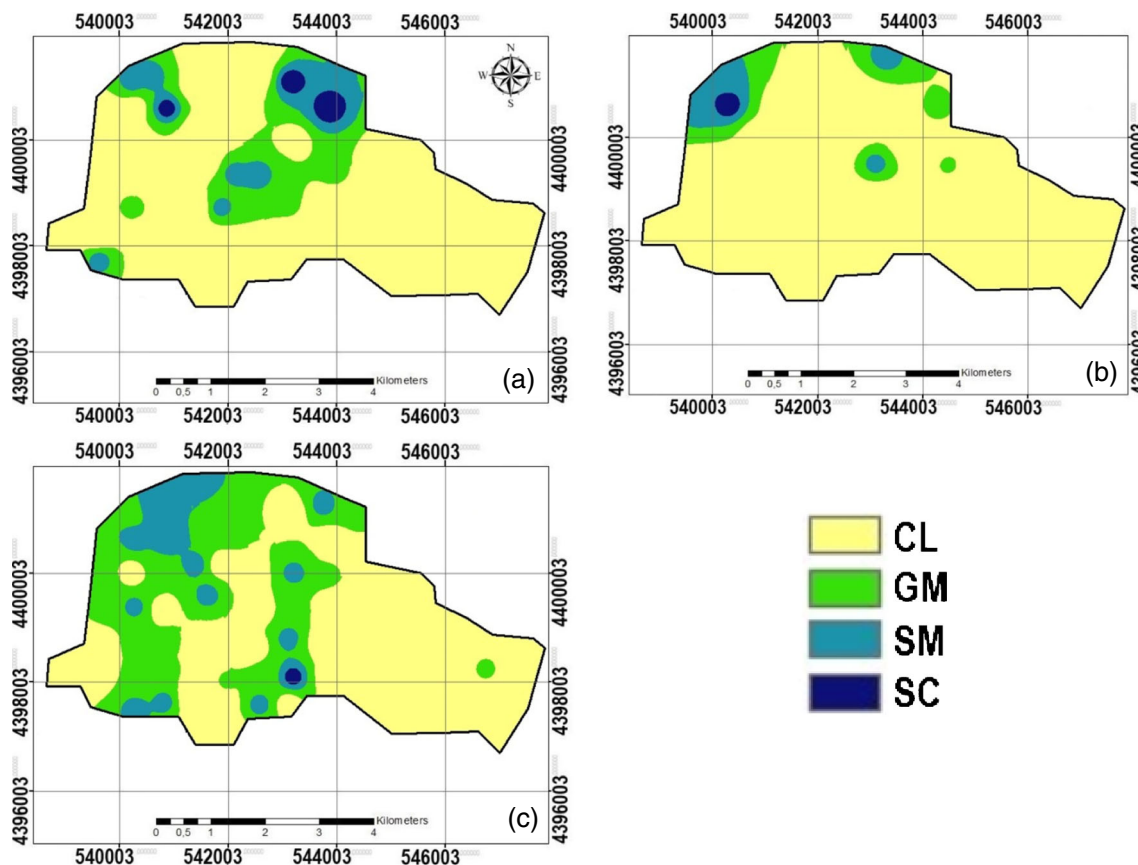


Fig. 4 Types of the soils at a 1.5–3.0m, b 6.0–7.5m, c 10.5–12.5m depths in the study area

cases of the real world (Zadeh 1994; Cabalar et al. 2012). The foundations of the first computational model using NNs are based on research carried by McCulloch and Pitts (1943). At the beginning of the 1950s, the first simple neural network model was successfully modeled and run (Farely and Clark 1954).

Results

Laboratory tests

Figure 3 presents the natural water content at various depths (depth1=1.5–3.0 m, depth2=6.0–7.5 m, depth3=10.5–12.5 m) of the study area in order to have a greater understanding of the soil behavior in field. While the water content values in the south and south east of the study area reached 40%, the water content values determined in the northwest of the study area remained at much lower levels. It was also realized that, in most of the places, the liquid limit values changed between 28 and 50%, while the plastic limit values changed between 5 and 24%. Figure 4 presents the classification of soils in the study area determined in accordance with the Unified Soil Classification System (USCS), one of the most commonly

used systems to describe grain size distribution of a soil for geotechnical engineering purposes. It is observed that particularly the south and south east of the study area are predominantly composed of clay and/or silt soils. The response of the specimens tested in accordance with the ASTM D2166-16 2016 is presented in the Fig. 5. The unconfined compressive strength (q_u) values of the soils obtained from the depth of 4 m changed from 0.4 to 2.5 MPa, while those of the soils obtained from the depth of 10m and 14 m were found to be between 0.4 and 12 MPa, and between 2 and 24 MPa, respectively.

Field investigations

Figure 6a, 6b, and 6c present the SPT values (ASTM D1586-11 2011) recorded at the depths of 1.5–3.0m, 6.0–7.5m, and 10.5–12.5m, respectively. The lowest SPT blow counts were found to be in southern part of the Erzincan city. The depths from 10.5 to 12.5 m, it was observed that the SPT values recorded in the north of the city are approximately 40 and above, while the values in the south are around 20 and below. The V_{s30} measurements in the Erzincan city carried out using the multichannel analysis surface wave (MASW) technique are presented in Fig. 7. It is seen that the distribution of V_{s30} in the study area changes between 390 and 1050 m/s. Hence, from NEHRP (1994), the V_{s30} maps

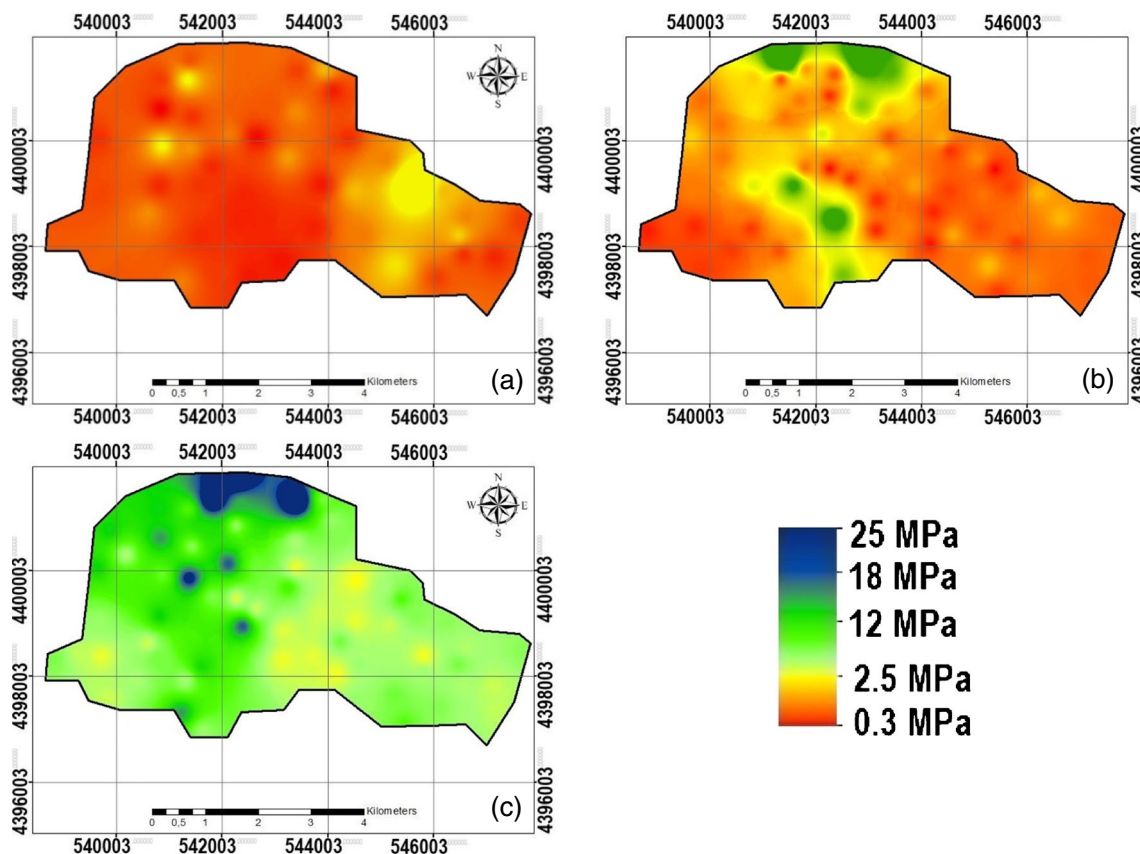


Fig. 5 The q_u values of the soils at a 4.0m, b 10.0m, c 14.0m depths in the study area

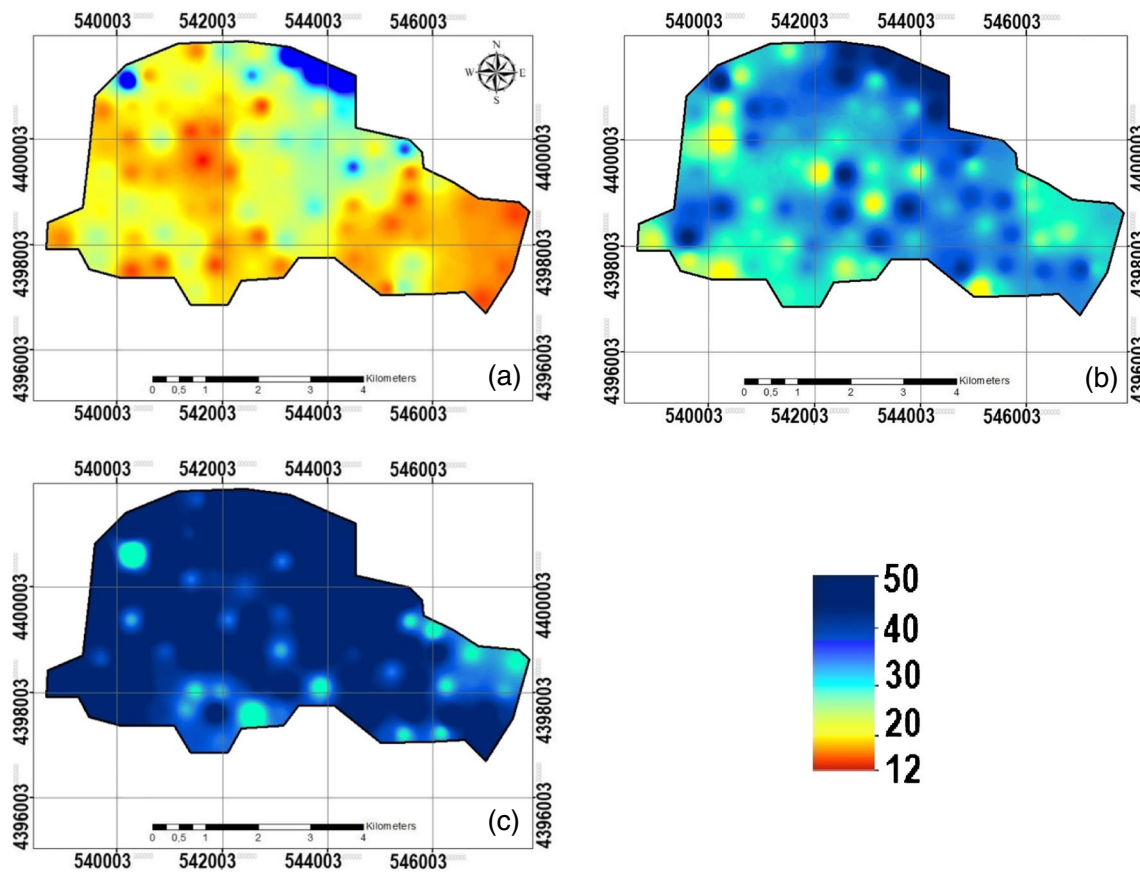


Fig. 6 The SPT values of the soils at **a** 1.5–3.0m, **b** 6.0–7.5m, **c** 10.5–12.5m depths in the study area

categorize the study area mainly under class B (rock) and C (very dense soil and soft rock).

Prediction model

In the present study, a multilayer perception NN model was developed to estimate the q_u , compressive strength of specimens. An input layer with five input parameters namely;

dynamic modulus of elasticity (E_d); the seismic velocity ratio (V_p/V_s); the density of specimen; Poisson’s ratio, depth of the specimen were defined. A hidden layer with 20 neurons displayed the best prediction performance by a series of trial-and-error process with different numbers of neurons. The output layer consists of one neuron, namely; the q_u . The architecture of the proposed ANN model is given in Fig. 8. The data was obtained by experimental studies and randomly divided into three subsets: 60% for the training phase, 20% for the validation phase, and 20% for the testing phase. A high number of training dataset was used to supervise the model with introduced data. The validating dataset has a particular function to verify the prediction capability of the model. The test dataset was the data sample used to provide an unbiased assessment of the model that fits the training dataset. The most commonly preferred iterative algorithm, Levenberg-Marquardt was used in the training stage due to its fast and stable convergence to nonlinear functions. A continuously differentiable function, tangent sigmoid, was used as an activation function. The highest performance of the model was determined on the basis of mean squared error (MSE) and the coefficient of determination (R) values. The performance of the trained, validated and tested network with the presented data was evaluated according to MSE and R values. If the desired performance would not achieved, the network’s

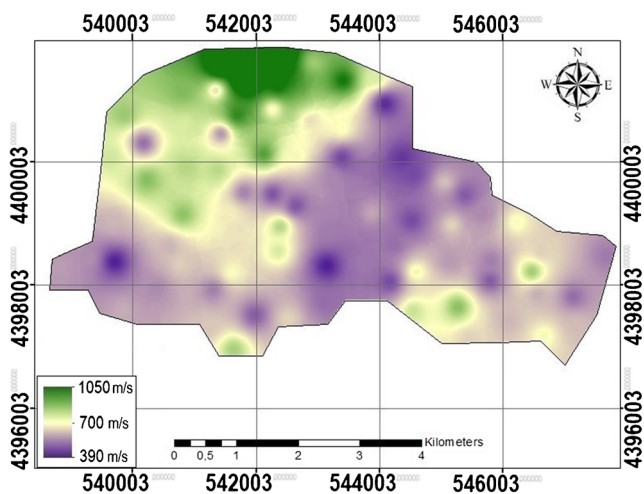


Fig. 7 The V_{s30} values of soils in the study area

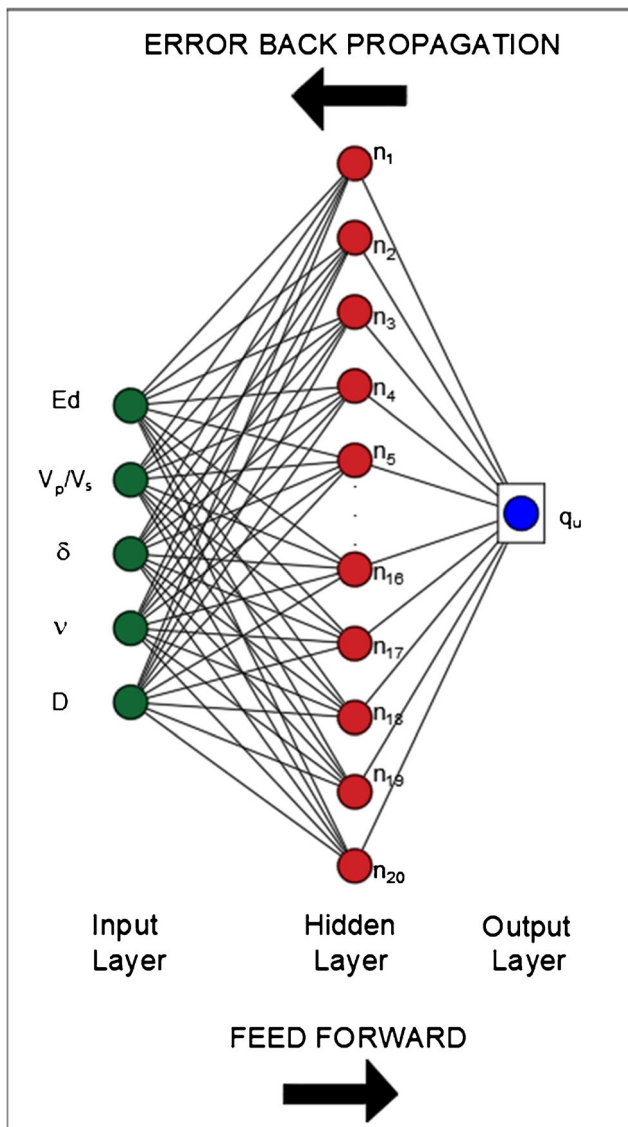


Fig. 8 The architecture of the proposed network

features would be revised and simulation was repeated by following the same steps. The developed model approximated the function by flowing information in the forward direction. The calculated gradient of the error function was propagated backward through the network. The methodological flow chart of this research is presented in Fig. 9.

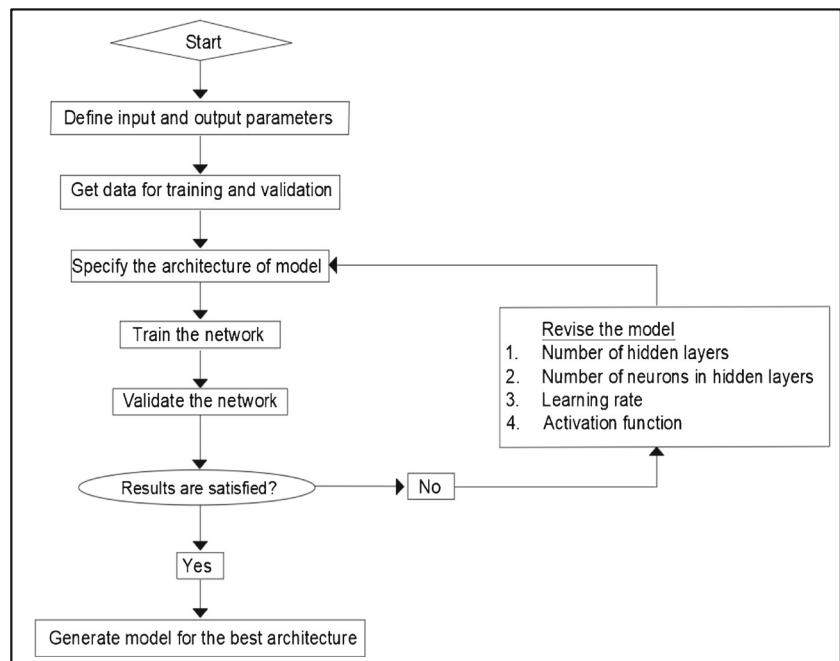
Discussion

Laboratory tests

The water content (w , %) is defined as the mass of the water to the mass of the dry soil grains. It is one of the most important features used in establishing a correlation between soil response and its index properties, as well as in expressing the phase relationships of water,

air, and soil grains for a specific volume (O'Kelly 2005). The water content will give an insight of the state of soil in the field by estimating the bearing capacity and settlement. Testing method ASTM D2216-19 2019 provides the standard procedures for determining water content of rock as well as soil by mass. The reason for the case presented in Fig. 3 is thought to be that the Degirmenpinar creek, one of the branches of the Euphrates River, passes about 3 km south of the city, affects the hydrogeological structure in this area. The water contents at which the soil properties change significantly are the Atterberg limits, the most useful practical indices of the behavior of fine-grained soils (Atterberg 1911; Casagrande 1932; Iwasaki 1986; Bowles 2012). The Atterberg limits give an idea on the assessment of some properties including bulk density, moisture, hardness, and resistance. Thus, the Atterberg limits of soils at various parts indicate surface resistance and its sensitivity to catastrophic mass movements (Ramezani et al. 2010; Lalitha et al. 2021). The water contents corresponding to transition from one state to the next, which are known as the liquid limit and the plastic limit (ASTM D4318-00 2000), were found to be quite variable. It was observed that both values reached relatively higher values at all depths in the south and south east of the study area. The fact is that it has been long understood that the water content is much more dominant in the behavior of fine-grained soils (Sridharan and Prakash 1998). Therefore, it is necessarily required to define the soil classification in order to understand the water-soil interaction well. Grain size is another significant criterion in order to have an understanding of certain physical and mechanical response of soils to be employed in many applications, including piping, swelling, liquefaction potential, consolidation characteristics, and strength (Lee and Fitton 1969; Chen, 1988; Budhu 2000; Cabalar and Hasan 2013; Puppala et al. 2014; Cabalar 2018; Cabalar et al. 2021). It is observed that particularly the south and south east of the study area are predominantly composed of clay and/or silt soils (Fig. 4). The unconfined compression test is a simple laboratory method of fine-grained soil shear testing as it is a quick and cheap method of measuring shear strength. The response of the specimens tested in accordance with the ASTM D2166-16 2016 is presented in the Fig. 5. As can be seen from the Fig. 5, the q_u values of the deeper samples are higher, likely because of the changes in the overburden pressure. As expected, the q_u values of the soils obtained from the south and south east regions of the city were found to be 85% to 95% lower than in other regions. Laboratory studies, geology, and seismotectonic investigations reveal that there is a

Fig. 9 Flowchart of the neural network model



high-risk potential that can trigger various soil mechanics problems including earthquake-induced bearing capacity loss, landslides, and liquefaction in the study area, particularly in the south and south east regions.

There are a limited number of studies supporting this in the literature (Barka and Eyidogan 1993; Duman and Ikizler 2014). It is clear that field tests need to be examined in detail and transferred to user-friendly GIS

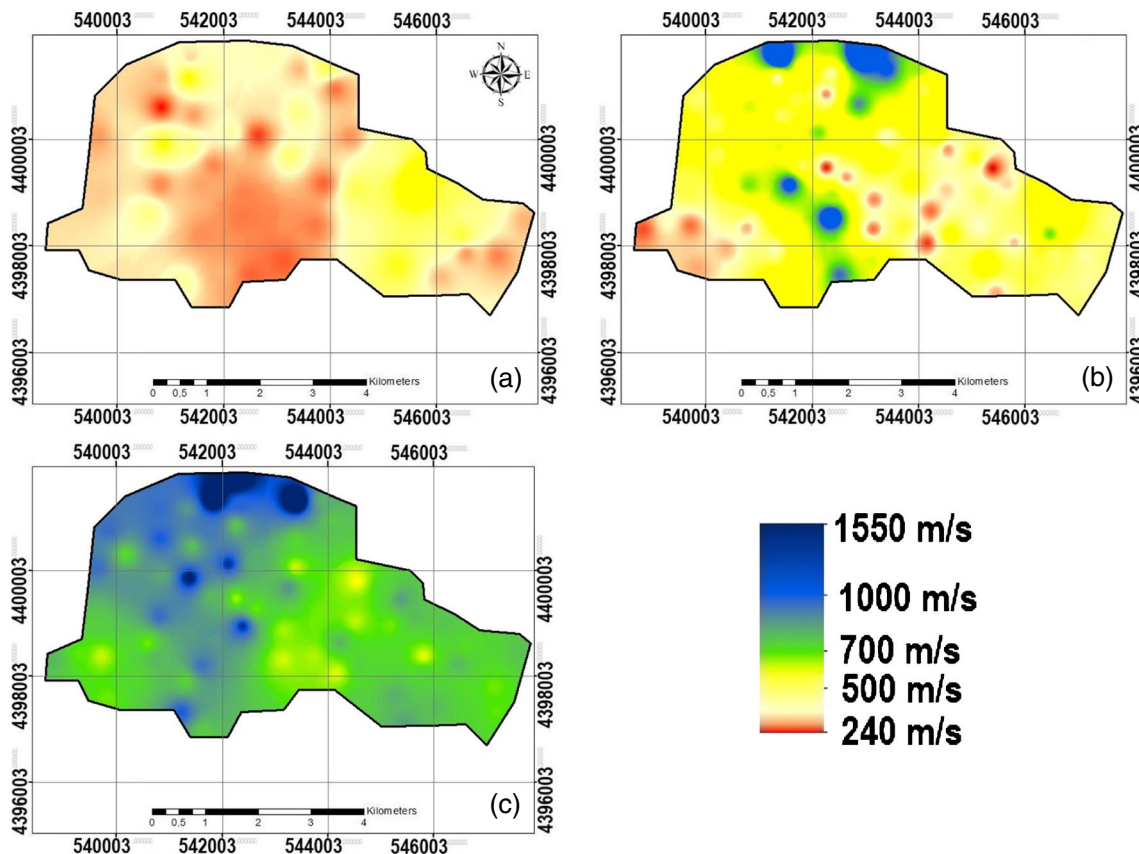


Fig. 10 The V_s values of soils at a 4.0m, b 10.0m, c 14.0m depths in the study area

maps in order to be used by local authorities and residents to minimize the loss of life and property in the city due to a possible earthquake in the study area. For this purpose, the field tests in the next section have been examined.

Field investigations

As can be seen from the Fig. 6, although the SPT values in the whole study area show a more homogeneous distribution at shallower depths, it has been seen that the SPT counts obtained at greater depths were found to be relatively heterogeneous by giving out different values at every location. In a mathematical expression, the SPT values recorded at less depths were found to be more spread out thus has a higher standard deviation ($\sigma_{1.5-3.0m}=6.53$, $\sigma_{6.0-9.5m}=6.41$), while those recorded at lower depths are more clustered around the mean therefore has a lower standard deviation ($\sigma_{10.5-12.5m}=3.04$) through the whole SPT counts recorded. The SPT testing still remains one of the most reliable field tests on granular soils, although clayey soils could have various driving resistance while dry or moist. Duman et al. (2015) pointed out the liquefaction potential in a large part of the city, particularly the southern regions, in their analysis using the SPT values. The SPT values are usually used in conjunction with other field tests including

shear wave velocity measuring (V_s), a parameter to evaluate the dynamic properties of soils. The average shear wave velocity in the top 30 m of a soil profile is called as V_{s30} , which is employed in order to characterize the seismic coefficients for designing buildings against the earthquakes (BSSC 1994). Actually, the V_{s30} had been initially introduced for mapping regional variations in ground response, and later as a parameter for seismic site classification due to its correlation with amplification and physical properties of geologic units in the field (Borcherdt 1991, 1992, 1994; Borcherdt et al. 1991; Borcherdt and Glassmoyer 1992; Boore et al. 2011). Interestingly, it was realized that the SPT maps presented in Fig. 8 and the V_{s30} maps presented in Fig. 7 have revealed that the soil classes in the study area are different to a high extent. The differences among the maps prepared by two different approaches could be explained by the accuracy of both MASW tests and SPT drops (Naji et al. 2020). Looking at Fig. 10 for more details, it was seen that the layer at 4.0 m depth identified with V_s in the range 240–550 m/s is under class C, the layer at 10.0 m depth identified with V_s in the range 240–1115 m/s is under class B and C, and the layer at 14.0 m depth with V_s in the range 500–1550 m/s is mostly under class C. Furthermore, Fig. 11 shows that compression wave velocity (V_p) changes in the study area. As can be seen, the layer at 4.0 m depth varied from 305 to 950 m/s, the layer

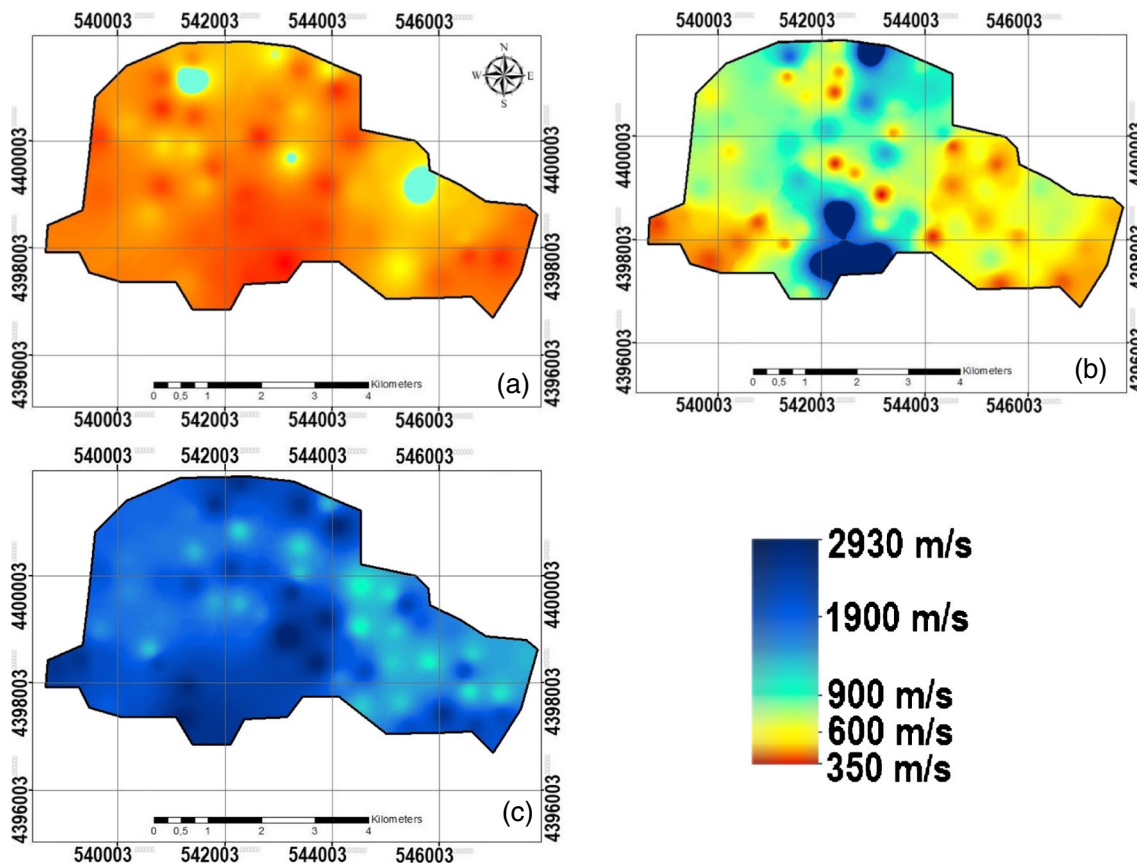


Fig. 11 The V_p values of soils at a 4.0m, b 10.0m, c 14.0m depths in the study area

at 10.0 m depth varied from 380 to 2650 m/s, and the layer at 14.0 m depth varied from 875 to 2930 m/s.

Dynamic elastic modulus (E_d) estimated based on the V_s and V_p values shows elasticity performance of soils under dynamic loads (Conte et al. 2009; Brotons et al. 2016; Huang et al. 2020). The E_d values calculated for depths of 4.0 m, 10.0 m, and 14.0 m in the study area are presented in Fig. 12. As can be seen, the E_d values estimated at 4.0 m depth varied from 170 to 965 MPa, while those estimated at 10.0 m varied from 13 to 6950 MPa, and those at 14.0 m varied from 1100 to 11750 MPa, respectively.

Prediction model

As is widely known, soft computing techniques, particularly neural network (NN) is the information processing structure, which inspired by the human brain. Due to the learning and generalization features, such studies find wide application opportunities in many fields of science including geotechnical engineering (Cevik et al. 2011; Alemdag et al. 2016; Jena and Pradhan 2020; Jena et al. 2020a, b; Gokceoglu et al. 2021; Jena et al. 2021). The accuracy of the predicted values by the NN model was determined by comparing the experiment results. Figure 13 shows the regression curves obtained by the model. The laboratory test results are given on the x-axis as

target values, whereas the numerical analysis results are shown on the y-axis. The performance evaluation of the model has been done using MSE and the squared correlation coefficient (R^2) values. The linear output demonstrates the success of the prediction model. The R^2 between the measured and predicted compressive strength was obtained as 0.977, 0.988, and 0.972 for training, validation, and testing stages, respectively. The correlation coefficient representing the overall performance of the developed model was obtained as 0.980. The high coefficient of correlation between measured and predicted values shows that the adopted model is performing successfully. The highest percentage of the estimated data is gathered around the minimum error value of -0.293 . As it is evident, the proposed prediction model presented reasonable compressive strength values.

Conclusions

A GIS-based geotechnical investigation in Erzincan city, mostly located in a deep alluvial basin in nearby area of seismically active NAFZ in eastern Turkey, was carried out by producing an intensive series of maps for both laboratory and field testing results. The natural water content values in the south and south east of the study

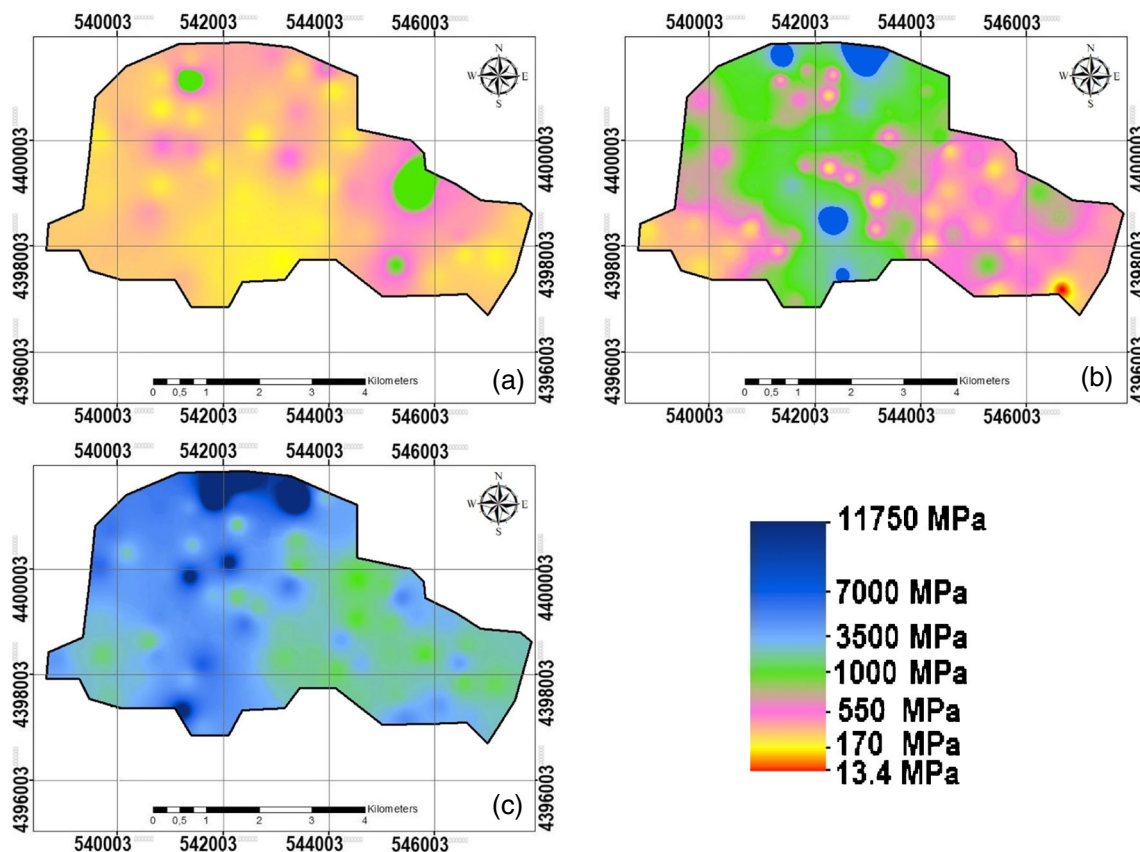
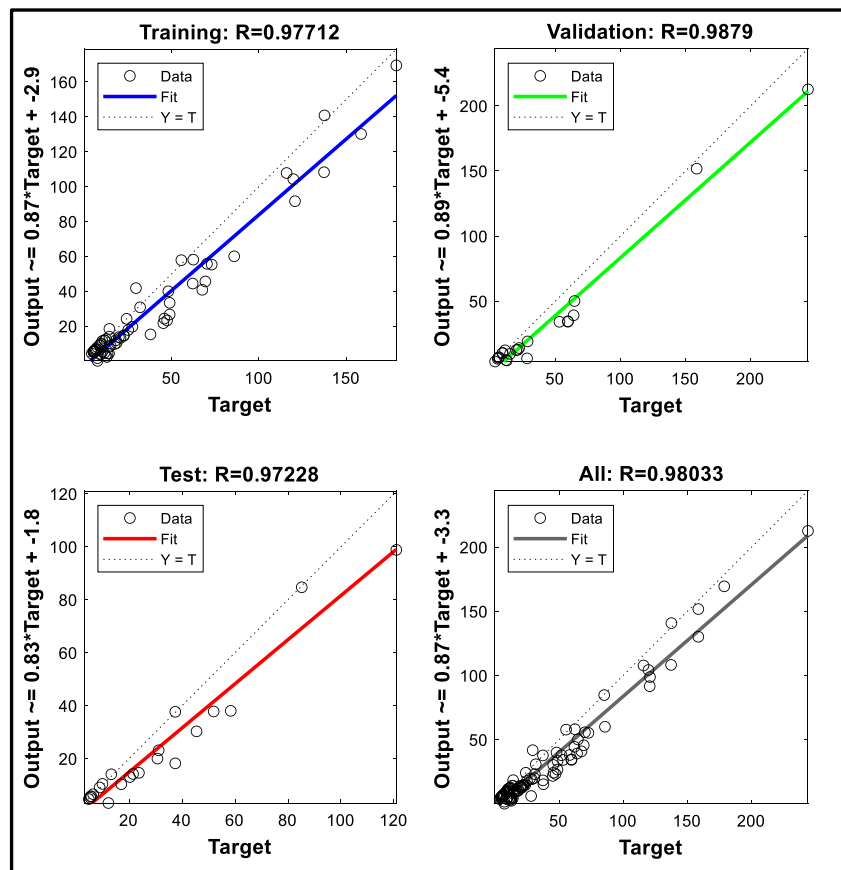


Fig. 12 The E_d values of the soils at a 4.0m, b 10.0m, c 14.0m depths in the study area

Fig. 13 Scatter plots of output versus target values of q_u by developed NN prediction model for (i) training stage, (ii) validation stage, (iii) testing stage, (iv) overall performance



area, predominantly composed of clay and/or silt soils, were found to be much higher than those in the north-west of the study area, likely because of the Degirmenpinar creek. Liquid limit and plastic limit values, reached relatively higher values in the south and southeast, vary between 28 and 45%, and between 5 and 24%, respectively. The q_u values of the soils varying from 0.4 to 24 MPa were found to be 85% to 95% lower in the south and south east regions of the city than those in other regions. The SPT values recorded at less depths were found to be more spread out with a higher standard deviation ($\sigma_{1.5-3.0m}=6.53$, $\sigma_{6.0-7.5m}=6.41$), while those recorded at lower depths are more clustered around the mean with a less standard deviation ($\sigma_{10.5-12.5m}=3.04$). The correlation performed via NN between the q_u from laboratory studies and the E_d from field works yielded a very high correlation coefficient of $R^2=0.97$. Evidently, the study suggests that the GIS applications in geotechnical engineering could be effectively employed by the engineers for land-use planning and urban development.

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