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Liquefaction Potential Analysis and Mapping of Alluvium Soil: A Case Study in Nazilli-Aydın (West Turkey)

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Abstract

The importance of urban planning for sustainable cities is indispensable. For this, the preparation of geotechnical maps, especially, comes to the agenda. Liquefaction susceptibility mapping is important for towns located in first-degree earthquake regions. This study investigated the susceptibility to liquefaction in a possible earthquake in Nazilli (Aydın) county considering geologic and geotechnical studies. In line with this, firstly drilling was completed at 110 points, with experiments performed on location and geotechnical properties determined in soil samples taken during this process. Generally, the county is founded on alluvial soils with groundwater very close to the surface. This situation makes it important to determine the liquefaction status of the town during a possible earthquake. The liquefaction potential (FS) of the study area was determined with the simplified SPT based method and additionally the liquefaction potential index (LPI) was calculated. Using this data and an ArcGIS program, the FS and LPI maps of the study area were prepared. According to the results obtained, the majority of the study area has very high liquefaction potential index.

Keywords: Nazilli, Standard Penetration Test, liquefaction potential, liquefaction potential index.

1. Introduction

For sustainable cities, it is necessary to perform good urban planning and to prepare geotechnical maps. One of the most important geotechnical maps to be prepared for cities located in first-degree earthquake regions, especially, are liquefaction susceptibility maps. Liquefaction events due to earthquakes are recorded in many places around the world [1-10]. Damages during earthquakes and liquefaction also show the importance of structure-soil interaction [11-12].

A sand deposit saturated with loose water displays a tendency to compress and reduce in volume when exposed to ground shaking. If drainage of water is not possible, the reduction in volume causes an increase in cavity hydraulic pressure. If this increase in cavity hydraulic pressure reaches a point equal to vertical stress, effective stress becomes zero and the sand deposit completely loses shear strength. In this situation, liquefaction develops [2].

The first thing required for soil liquefaction analysis is to determine whether the soil profile contains layers that may liquefy. It is long known that clean sands have the potential to liquefy. With the aim of determining soil conditions that may lead to potential liquefaction, the soil conditions are investigated in the field and field and laboratory experiments are performed.

Liquefaction potential analyses and the detailed maps prepared using them have vital importance, especially for regions susceptible to liquefaction. Just as these types of studies may reduce the risks due to liquefaction in these areas, they may reduce or prevent damage that will occur during a possible earthquake. A range of field and laboratory experiments may be performed to determine liquefaction potential. Experiments in the filed include standard penetration test (SPT), seismic refraction, multi analysis surface wave (MASW), (Vs) and conic penetration test (CPT). Laboratory experiments include dynamic simple shear, dynamic three-axis and shaking table. Various liquefaction analyses methods were applied to determine the liquefaction potential of different areas by various researchers [5, 13-17].

Seed and Idriss [1] proposed an analysis method based on SPT data, called as he simplified method, with the aim of determining the liquefaction potential after the

Alaska and Niigata earthquakes in 1964. Additionally, Tokimatsu and Yoshimi [18] recommended a method based on SPT data again. The method of Seed and Idriss [1] was modified several times in the following years [19, 4, 20, 21]. The method was debated for the last time at international earthquake geotechnical engineering symposia and was updated by Youd et al. [8] to reach its final form.

The study area of Nazilli is a county linked to the province of Aydın located in southwest Turkey. Nazilli is located in a first-degree earthquake region. Significant earthquakes have occurred in Nazilli in the historical and instrumental periods.

The main aim of this study is to contribute to organized and sustainable urban planning in light of geologic and geotechnical data. The liquefaction case forms a danger especially for cities located in first-degree earthquake zones. In line with this, within the scope of the study, the liquefaction susceptibility of Nazilli county due to probable earthquakes was investigated.

This study firstly prepared the geological map of the study area based on previous studies. The engineering characteristics of soils in the study area were determined with field and laboratory studies. With the data obtained, the liquefaction potential and liquefaction potential index for Nazilli county were determined and maps were prepared using GIS. The liquefaction susceptibility of Nazilli, located in a first-degree earthquake zone, was not previously determined with these methods. Within the scope of the study, the safety factor against liquefaction (FS) was determined using the simplified approach proposed by Youd et al. [8] using corrected SPT data. Within this framework, the SPT data obtained from drilling in different locations were used. Additionally, with the aim of determining the physical and mechanical features of samples obtained during drilling, laboratory experiments were completed. Groundwater levels were measured in the drilled wells.

2. Materials and Methods

2.1. Liquefaction assessment

The liquefaction assessment for an area can be performed using laboratory tests or in situ tests and empirical methods. The method depending on SPT N value developed by Seed and Idriss [1, 2] and Seed et al. [19, 4] was used in this study to evaluate the liquefaction susceptibility of the Nazilli settlement area. This method developed by Seed and Idriss [1] is based on the relationship between cyclic stress ratio (CSR), necessary for liquefaction to form, and standard penetration test (SPT). CSR is defined as the effective confining pressure ratio of mean earthquake-linked shear stress affecting soil in an earthquake (Equation 1) [1].

$$CSR = 0.65 \frac{a_{max}\sigma_v}{g\sigma'_v} r_d \quad \textbf{(2.1)}$$

Here, r_d is the stress reduction factor calculated in Equation 2 and 3 according to Liao and Whitman [22] and a_{max} is the peak ground acceleration. In first-degree earthquake regions, it is recommended to be taken as 0.4 g by the Disaster and Emergency Management Presidency (AFAD). Within the scope of this study, the a_{max} value was accepted as 0.4 g during liquefaction analyses.

$$r_d = 1\text{-}0{,}00765z\ (z \leq 9.15m) \quad \textbf{(2.2)}$$

$$r_d = 1.174 - 0{,}0267z\ (9.15 \leq z \leq 23\ m) \quad \textbf{(2.3)}$$

Another component of cycle resistance ratio (CRR) is defined as the capacity to resist liquefaction [8]. CRR used in liquefaction potential analyses represents the resistance of a soil to liquefaction (Equation 4). CRR is generally associated with the modified SPT impact number. The CRR of soil also affects the oscillation time and is associated with the magnitude scaling factor (MSF). As a result, for an earthquake with magnitude Mw=7.5, CRR was expressed as follows by Youd et al. [8].

$$\mathrm{CRR}_{7.5} = \frac{1}{34-(\mathrm{N}_1)_{60}} + \frac{(\mathrm{N}_1)_{60}}{135} + \frac{50}{[10(\mathrm{N}_1)_{60}+45]^2} - \frac{1}{200} \quad \textbf{(2.4)}$$

Here, σ'_v is effective vertical stress. The $(N_1)_{60}$ expression used in this formula is the SPT-N value obtained in the field and corrected according to some standard systems. These corrections were performed according to Robertson and Wride [5] and are calculated with Equation 2.5.

$$(N_1)_{60} = N_{field} C_N C_R C_B C_E C_S \quad \textbf{(2.5)}$$

N_{field} in the Equation (2.5) is the number of SPT impacts measured in the field. CE, CR and CS are correction coefficients within the scope of the study of the energy correction factor for reliable hammer types CE=0.75 (Donut type of hammer and 2 turns of rope release mechanism was used in this study.), the rod length correction factor (CR) of 0.75, 0.85, 0.95 and 1.00 according to length and the linear correction factor taken as CS =1.0 for standard sampling. The bore-hole diameter correction factor was taken as CB =1.0.

CN, correction factor based on the effective stress is calculated according to Equation 2.6 developed by Liao and Whitman [22].

$$C_N = \sqrt{\frac{P_a}{\sigma'_v}} \tag{2.6}$$

If $(N1)_{60}$ values of silty and sandy soils were greater than 30, they were accepted as non-liquefiable soil by Youd et al. [8] and Seed et al. [9].

Hence, the liquefaction factor of safety (FS) is found by comparing the earthquake loading with the liquefaction resistance (Equation 2.7). If the factor of safety is larger than 1, liquefaction resistance is larger than earthquake loading and liquefaction is not expected in this situation.

$$FS = (CRR_{7.5}/CSR)MSF \tag{2.7}$$

CRR curves state whether liquefaction will occur only in situations with magnitude 7.5, so it is necessary to mention the magnitude scaling factor (MSF). MSF was calculated according to Youd et al. [8] using Equation 2.8. For this study a possible earthquake scenario was considered at a magnitude (Mw) of 6.9.

$$MSF = \frac{10^{2.24}}{M_w^{2.56}} \tag{2.8}$$

If the FS value is larger than 1 at the end of calculations, soil is accepted as not being liquefiable. In situations where FS is smaller than 1, soil is expected to liquefy. However, value of “1” in the limit-balance situation is not a good marker. As a result, in situations with FS between 1 and 1.2, soils are classified as marginally liquefiable and values of FS>1.2 are accepted as not liquefy [1, 25]. However, Seed and Idriss [2] (1982) stated that the acceptable safety factor ranged from 1.25 to 1.5. Considering these types of uncertainties in the safety factor, it can be said this remains a theoretical value. In reality, liquefaction potential is linked to the thickness of the liquefiable soil layers and the depth from the surface. As a result, the liquefaction potential of a region may be determined by finding the liquefaction risk index (Ls) of a soil profile using the factor of safety and soil layer thicknesses. Iwasaki et al. [3] proposed the liquefaction potential index (LPI) to remove this type of limitation from FS. LPI is evaluated in four categories of very low, low, high and very high. However, there are some limitations to this classification. These include the lack of determination of “non-liquefiable” and “moderate” categories in the liquefaction potential index (LPI). As a result, Sonmez [26] made a new proposal by adding these two categories to the classification (Equation 2.9). Here, the FS=1.2 threshold value is determined to be the lowest limit where liquefaction will not occur [2].

$$LPI = \int_0^{20} FS(z)w(z)dz \tag{2.9}$$

Here, FS is the liquefaction factor of safety, z is the depth of the central point of the soil layer investigated and w is the liquefaction potential reduction factor linked to depth from the surface. W is taken from Equation 10-11.

$$z < 20\ m \quad w(z)=10-0.5z \tag{2.10}$$

$$z \geq 20\ m \quad w(z)=0 \tag{2.11}$$

$$F_S < 1.0;\ F(z)=1-F_S \tag{2.12}$$

$$F_S \geq 1.0;\ F(z)=0 \tag{2.13}$$

The liquefaction potential index (LPI) with boundary value of LPI modified from Sonmez [26] is tabulated in Table 1 with liquefaction susceptibility descriptions. In this LPI calculation, Sonmez [26] modified F(z) (Equation 14-16).

$$F(z) = 0 \qquad \text{for } F_S \geq 1.2 \tag{2.14}$$

$$F(z) = 2\times10^6 e^{-18.427F_S} \qquad \text{for } 1.2 > F_S < 0.95 \tag{2.15}$$

$$F(z) = 1 - F_S \qquad \text{for } F_S < 0.95 \tag{2.16}$$

Table 1. Modified liquefaction potential index classification [26]

Liquefaction potential index (LPI)	Description
0	Non-liquefiable (based on FS ≥ 1.2)
0<LPI≤2	Low
2< LPI ≤5	Moderate
5≤ LPI ≤15	High
15< LPI	Very high

3. Results and Discussion

3.1. Study area and geological setting

The study area is Nazilli county settlement area in Aydın province, located in southwest Turkey. The study site covers an area of about 644 km^2. The population of Nazilli was 156,748 in 2019.

The basement in the study area is the Plio-Quaternary Asartepe Formation (Tpa) comprising poorly consolidated and low strength conglomerate, sandstone, siltstone, claystone and marl alternations. The formation has fine-medium bedding and occasionally massive appearance. The clasts in the conglomerate have block and coarse clast size and appear to be a debris flow.

Clasts were derived from rocks from the Menderes metamorphics. The Asartepe formation was first mapped by Ercan et al. [27] in the Uşak region. Later it was reported from the north side of the Büyük Menderes Graben by Sözbilir and Emre [28].

Above the Asartepe formation there are Quaternary terrace sediments comprising coarse pebbles, sand and clay units (Qt); Quaternary alluvial fan sediments comprising loose coarse pebbles, sand, silt and clay units (Qaly); and Holocene floodplain-swamp sediments from the Menderes River comprising loose, water-saturated fine sand, silt and clay units (Qtb) (Figure 1) [29].

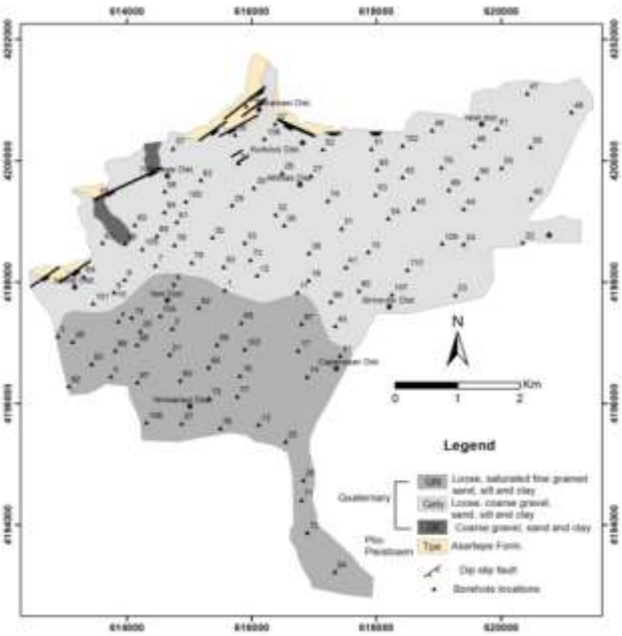

Figure 1. Geological and borehole location map of Nazilli settlement area

3.2. Seismotectonics of the study area

Turkey is located in one of the most seismically active regions on the earth. The study area of Nazilli is located in a first-degree earthquake region according to Turkey's earthquake hazard map.

The Aegean Graben System, encompassing the study area of Nazilli and surroundings, is generally formed by many blocks bounded by E-W striking normal faults [30]. Nazilli is located on the Great Menderes River in Western Anatolia within the Büyük Menderes Graben, an E-W striking depression area between Denizli in the east and Ortaklar in the west [31]. The Büyük Menderes Graben is one of the main active neotectonic structures found in Western Anatolia [32]. In the Büyük Menderes graben, two fault sets with N-S and E-W strike have developed since the Miocene (Figure 2) [33]. The N-S striking faults are found between Nazilli in the north, Kuyucak in the west and Atça-Kılavuzlar. The lengths of these faults observed at the surface vary from 3-5 km. These faults probably continue under alluvium from Nazilli. The second fault set with E-W strike forms steps within the Büyük Menderes graben and are south-dipping normal faults [33] (Figure 2).

According to Ergin et al. [34], the 20 September 1899 earthquake developed between Aydın-Nazilli and was felt throughout the whole of Western Anatolia. The estimated magnitude of the earthquake is IX [34-38]. The 20 September 1899 Menderes earthquake was one of the most destructive events to occur in the Büyük Menderes graben in the last 100 years [32]. Ambraseys and Finkel [37] stated that a 70 km long surface rupture developed between Aydın and Nazilli with a 3-meter offset. Figure 4 shows some photographs taken in Nazilli after the earthquake.

The Aydın-Nazilli fault begins 1 km west of Yılmaz village in the east of Aydın province and continues to 2.5 km west of İmamköy. The fault zone separates alluvium from the Asartepe formation and has 3-5 m fault scarps [33].

Active main fault segments well-defined in Nazilli and surroundings are the Nazilli, Arslanlı, Kuyucak, Yöre, Kurtuluş, Gencelli, Feslek, Çavdardüzü and Ortakçı segments, from west to east. The activity of these faults is not just based on morphotectonic criteria, earthquakes have occurred historically (25 or 26 B·C., 23 February 1653 A.D., and 20 September 1899 A.D. Menderes valley earthquakes with intensity IX) [32, 37, 39, 40, 41] and in recent periods (4 May 1966 Incirliova, 11 October 1986 Çubukdağ earthquakes) due to the main fault segments in the Kuyucak fault zone [41]. Some photos from the 1899 Aydın-Denizli earthquake were shown in Figure 3.

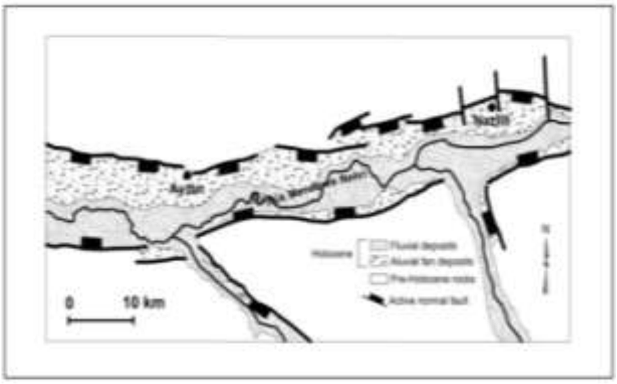

Figure 2. Map showing variation in active fault-controlled facies of sedimentary fill developing in the Holocene in the Büyük Menderes graben [42, 43, 33]

Celal Bayar University Journal of Science
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Figure 3. Some images from the 1899 Aydın-Denizli earthquake; a) Nazilli Yahyaoğlu street, b) Nazilli Factory Forbes [44]

3.3. Field studies and geotechnical evaluation

This study chose Nazilli town centre as the research area. Three important parameters are required for liquefaction research. These are soil conditions, water in the environment and seismic characteristics. SPT data have an important place in liquefaction analyses. With the aim of determining changes in the units in the study area in horizontal and vertical directions, engineering properties and geotechnical parameters, 110 boreholes were drilled with depths from 11 m to 25 m. As seen in Figure 2, drillings have very equal distribution within the study area. The horizontal distances of the drillings change from 200 mto 500 m. Bore holes were drilled by Erdem Earth Sciences (Fethiye) with the aim of preparing a geotechnical report for Nazilli town centre. During drilling, groundwater measurements were made. The groundwater level in the study area varied from 1 m to 18 m below the surface (Figure 4). Considering the depth from the surface of groundwater on this map, it is expected that a probable earthquake will cause liquefaction in the majority of Nazilli settlement area.

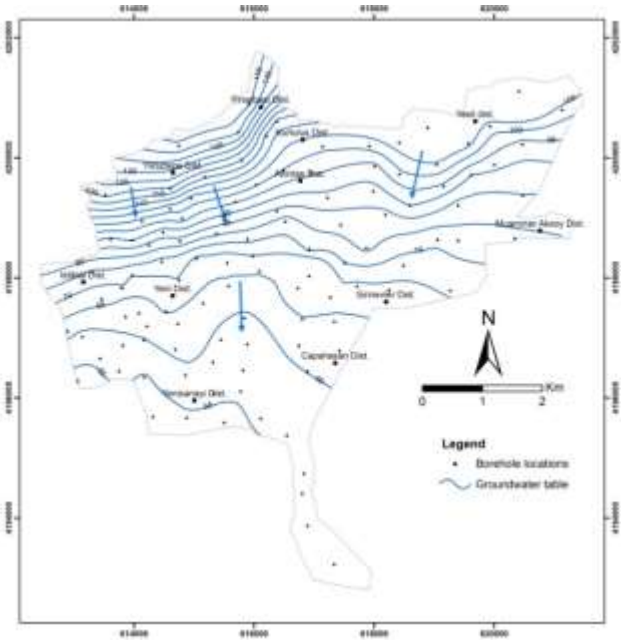

Figure 4. Groundwater table map of the study area

During drilling standard penetration test (SPT) were performed every 1.5 m (ASTM D1586-99). The main rock in the study area is the Asartepe formation comprising dark brown-light yellow mudstone, conglomerate and sandstone intercalations covering small areas in northern sections. In other sections, Quaternary deposits (Qt, Qaly, Qtb) are present (Figure 1). SPTs were performed in all units in the study area (Figure 1). Quaternary alluvial fan sediments and Holocene floodplain-swamp sediments covering large sections of the study area had SPT-N values varying from 2 to 12. The Plio-Quaternary Asartepe Formation found in very limited areas in the north and the Quaternary terrace sediments found along Hamalı stream have values from 12 to 50+. SPT-based zoning map for 9 m were given in Figure 5. Based on this map most part of the city has low SPT-N value (<10) and this supports the results of the liquefaction analysis.
With the aim of determining index properties of the soil samples, disturbed and undisturbed samples were taken from 110 boreholes and laboratory experiments were completed. These were natural moisture content, unit weight, grain size distribution (sieve and hydrometer analysis), and Atterberg limits.

The water content of soils in the study area vary from 11%-28% while unit weight values vary from 18.0-20.0 kN/m^3 but general distribution is 18.0 kN/m^3. The soils taken from boreholes were classified based on "The Unified Soil Classification System (USCS)". The Quaternary alluvial terrace and fan sediments in the study area were ML, GW, SC-SM, SW and CL group soils, while Holocene flood-swamp sediments were CL, ML and SW group soils. General distribution of the fine contents of the soils in the study area ranges between

13-15%. In Figure 6, depth to groundwater table was given with soil types for 9 m. Therefore, it is easier to see the liquefiable areas for the city. But liquefaction potential (FS) and liquefaction potential index (LPI) maps were prepared considering the depths during 20 m for each boreholes.

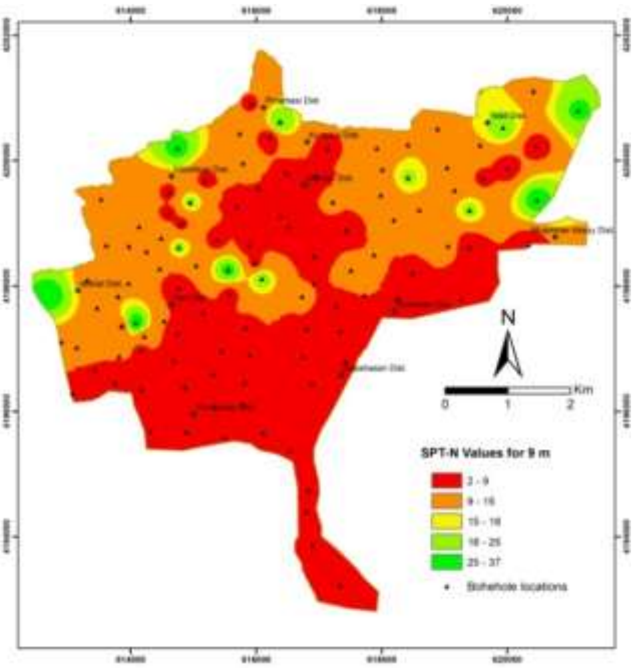

Figure 5. SPT-N zoning map for 9 m

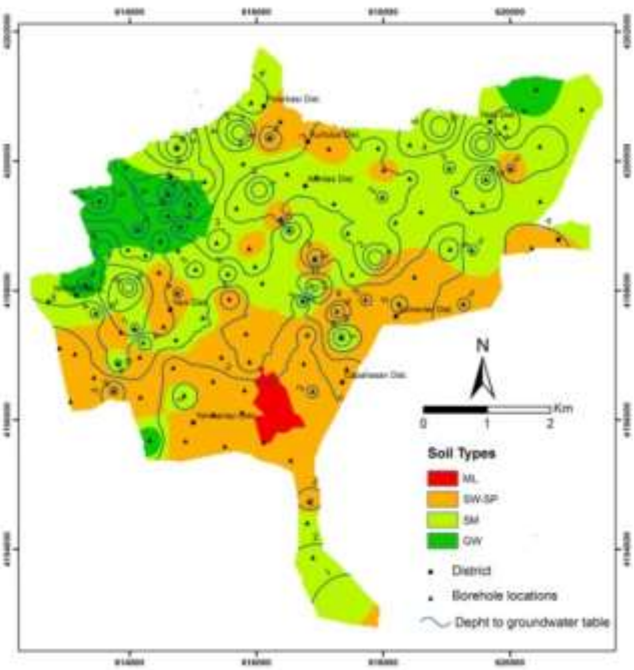

Figure 6. Depth to groundwater and soil type zoning map for 9 m

3.4. Liquefaction potential map of Nazilli settlement area

Assessment of liquefaction potential is one of the critical topics in geotechnical earthquake engineering. At the same time, liquefaction resistance maps are important geotechnical maps and have a very important place in our ability to make good urban planning for sustainable cities. The most susceptible sediments for liquefaction are sediments deposited as a result of Holocene delta, fluvial, floodplain, terrace and coastal sedimentation processes. These types of soils are present in the whole of the study area. Considering the groundwater status in the study area, liquefaction analysis is indispensable in this region.

This study calculated the liquefaction potential of Nazilli settlement area according to Seed and Idriss [1], according to the simplified SPT based method proposed by Seed et al. [4] and based on the liquefaction potential index (LPI) modified by Sönmez [26].

The liquefaction potential indices were calculated for 110 drillholes and liquefaction hazard maps based on LPI were prepared using ArcGIS version 10. Maps prepared according to FS and LPI values are given in Figures 7 and 8, respectively. As seen in both figures, nearly all of Nazilli settlement area has liquefaction potential in a possible earthquake. If the LPI categories in the city are examined, very high liquefaction potential is present for a large area of Nazilli in a probable earthquake. Yesil neighbourhood in the NE of the county has high liquefaction potential index.

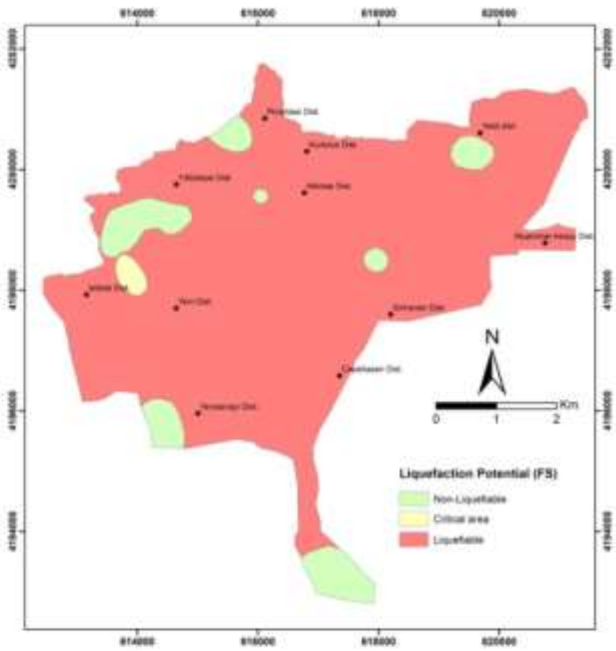

Figure 7. Liquefaction potential (FS) map

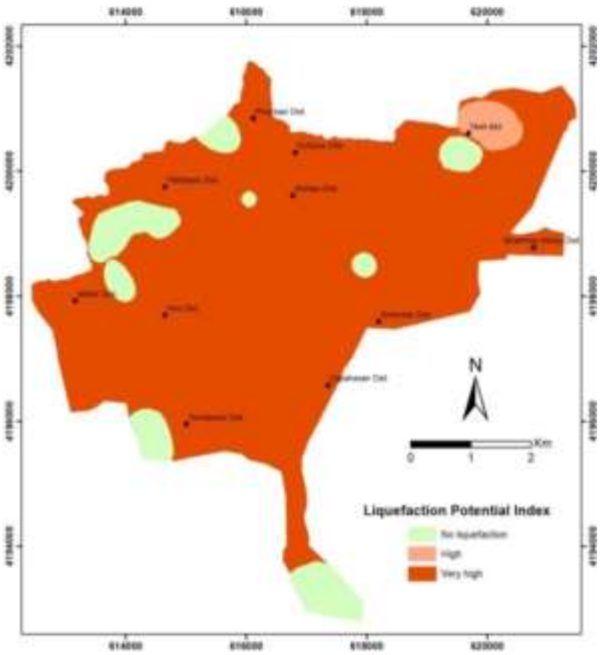

Figure 8. Liquefaction potential index (LPI) map

4. Conclusion

In towns founded on alluvium, especially, the earthquake-soil-building interaction comes to the agenda and these types of areas should be carefully investigated for liquefaction cases. Considering these facts, urban planning should be made carefully and geotechnical maps need to be noted during the planning process.

Nazilli settlement area is located on two different soil types. Both of these are loose and water-saturated soils included in the liquefaction susceptible soil class. The groundwater depth in the study area varied from 1 m to 18 m. As a result, due to the geological, hydrogeological and tectonic properties of Nazilli county, it is at risk of liquefaction during probable strong ground movements. Liquefaction susceptibility maps were prepared for Nazilli settlement area with the scenario magnitude 6.9 (Mw) for subsurface geological materials and horizontal peak ground acceleration of 0.4 g. These were the “liquefaction potential” maps based on results from analyses with the method recommended by Youd et al. [8] and the “liquefaction potential index” map modified by Sonmez [26]. Both maps provide very similar results and it was identified that a large section of Nazilli had conditions susceptible to liquefaction in a possible earthquake.

The results obtained in this study and the liquefaction susceptibility maps comprise very beneficial base maps for urban and regional planning in Nazilli. In this situation, care should be taken of the geotechnical features of liquefiable soils during appropriate foundation design for buildings planned in the study area to prevent loss of life and property during a possible earthquake.

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Author’s Contributions

Hayrullah Yürekli: Performed the field studies and experiments, prepared the maps.

Öznur Karaca: Drafted and wrote the manuscript, supervised the experiment’s progress and preparing the maps, result interpretation and analysis.

Ethics

There are no ethical issues after the publication of this manuscript.

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