Mugla Journal of Science and Technology

SOIL LIQUEFACTION HAZARD ASSESSMENT OF DALAMAN RESIDENTIAL AREA

Orkun TÜRE*, Department of Geological Engineering/Engineering Faculty, Mugla Sitki Kocman University/Türkiye, orkunture@mu.edu.tr
(https://orcid.org/0000-0002-7708-3903)
Ergun KARACAN, Department of Geological Engineering/Engineering Faculty, Mugla Sitki Kocman University/Türkiye, ekaracan@mu.edu.tr
(https://orcid.org/0000-0002-6583-4861)

Received: 13.03.2024, Accepted: 17.05.2024 Research Article
*Corresponding author DOI: 10.22531/muglajsci.1452122

Abstract

The Phenomenon of Liquefaction gained importance after the 1964 Alaska and Niigata Earthquakes, and it has started to be studied worldwide. Türkiye, located in a very tectonically active zone, has been exposed to many devastating earthquakes. Dalaman is located in SW Anatolia which is under the control of active extensional tectonic regime that may generate such devastating earthquakes in the future. Moreover, because the Dalaman residential area is located on sedimentary deposits, determination of the liquefaction susceptibilities of the soils in the region is an important task to take essential precautions. Analyses have been performed according to two earthquake scenarios with magnitudes Mw=5.5 and Mw=7.5. Standard Penetration Test blow number-based simplified procedure has been used in the analyses and it has been seen that Dalaman residential area is highly susceptible to liquefaction. Most of the liquefiable soils are sands and they make the central part of the area. The northern part of the basin is formed of gravels and safer compared to the southern part, which is formed mostly of sands, silts and clays. Considering the population of the residential area approximately 40.000 people are under danger in case of a M=7.5 earthquake scenario.

Keywords: Earthquake, Liquefaction, Simplified Procedure, Dalaman

DALAMAN YERLEŞİM ALANININ SIVILAŞMA TEHLİKESİNİN DEĞERLENDİRİLMESİ

Özet

Sıvılaşma olgusu 1964 Alaska ve Niigata Depremlerinden sonra önem kazanmış ve dünya çapında çalışılmaya başlanmıştır. Tektonik açıdan son derece aktif bir kuşakta yer alan Türkiye bir çok yıkıcı depreme maruz kalmıştır. Dalaman, gelecekte bu tür yıkıcı depremlere yol açabilecek aktif genişlemeli tektonik rejimin kontrolü altındaki GB Anadolu'da yer almaktadır. Ayrıca, Dalaman yerleşim alanını sedimanter çökellerin üzerinde bulunduğu için Dalaman yerleşim alanındaki toprak zeminlerin sıvılaşma yatkınlıklarının belirlenmesi, gerekli önlemlerin alınması açısından önemli bir çalışmadır. Sıvılaşma analizleri Mw=5.5 ve Mw=7.5 olmak üzere iki deprem senaryosuna göre gerçekleştirilmiştir. Çalışmada yöntem olarak Standart Penetrasyon Deneyi darbe sayıları bazlı basitleştirilmiş metod kullanılmış ve de sonuçlara göre Dalaman yerleşim alanının sıvılaşma açısından büyük tehlike altında olduğu gözlenmiştir. Sıvılaşabilir zeminlerin çoğu kumdur ve alanın orta kısmını oluşturur. Havzanın kuzey kısmı çakıllardan oluşmakta olup, çoğunlukla kum ve siltlerden oluşan güney kısmına göre daha güvenlidir. M=7,5 deprem senaryosunda yerleşim bölgesinin nüfusu dikkate alındığında yaklaşık 40.000 kişi tehlike altındadır.

Anahtar Kelimeler: Deprem, Sıvılaşma, Basitleştirilmiş Yöntem, Dalaman

Cite

Türe, O., Karacan, E., (2024). "Seismic Soil Liquefaction Hazard of Dalaman Residential Area", Mugla Journal of Science and Technology, 10(1), 72-81.

1. Introduction

Naturally occurring events such as landslides, rockfalls, floods, and earthquakes that harm humanity are defined as natural hazards [1]. The rate of occurrence of these natural hazards and their effects are different in each country. Even if the rate of occurrence of earthquakes as a natural hazard is not significant, they are the most important in terms of their severe effects in Türkiye [2, 3].

Earthquakes from these natural hazards have several secondary effects such as tsunamis, mass movements, liquefaction, etc. [4]. Deformations occur not only because of inappropriate material on the structures but also misunderstanding of the geo-engineering properties of the soils beneath them. Liquefaction is one of the soil-related problems caused by earthquakes. During earthquakes, pore water pressure of loose and saturated soils increases rapidly and effective stress decreases to zero. Strength and stiffness of the soil decrease. Solid-state soil changes its phase and behaves like fluid. Finally, structures over the problematic soils fail. This phenomenon is defined as liquefaction [5-8].

Liquefaction caused severe effects in Türkiye [9]. Even if the best example of the liquefaction case history in Türkiye is 1999 Kocaeli Earthquake, the first recorded event is 1992 Erzincan Earthquake [9-11] and the most recent examples are 2023 Kahramanmaraş Earthquake sequence [12].

The depositional environment is one of the factors controlling liquefaction [6]. There are various depositional environments including fluvial, coastal, marine, lacustrine, glacial, aeolian, alluvial, and delta environments according to type of modifying geological processes [13]. Fluvial, alluvial, delta and beach environments are highly susceptible to liquefaction, which may co-exist together and, they cover wide range of liquefiable, complex soil types in terms of liquefaction.

Dalaman is an important tourist attraction with its crowded population. Because Dalaman residential area is located within one of the most actively extending regions (Figure 1) in which high magnitude earthquakes occurred in the history including 1957 (M=7.1 and Mw=7.3) Fethiye Earthquakes (Figure 2) [14]; is such a mixed depositional environment as mentioned above and groundwater level in the area is close to the surface (Appendix A), it is highly susceptible to liquefaction.

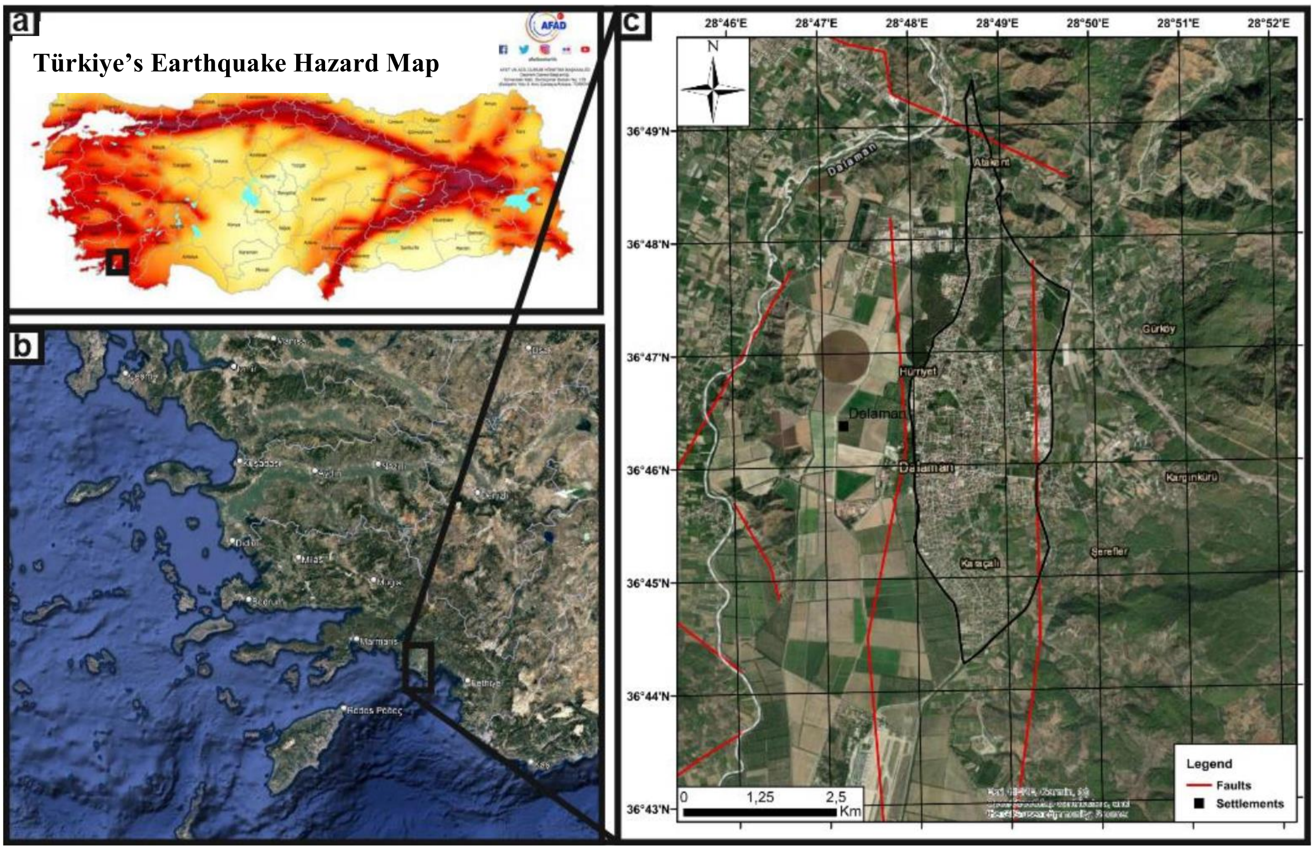


Figure 1. Location map of the study area [15] a) Türkiye's earthquake hazard map showing the importance of the study area (Modified from [16]). b) Location of the study area in SW Anatolia. c) Location of Dalaman residential area. Faults have been compiled and modified from [17, 18].

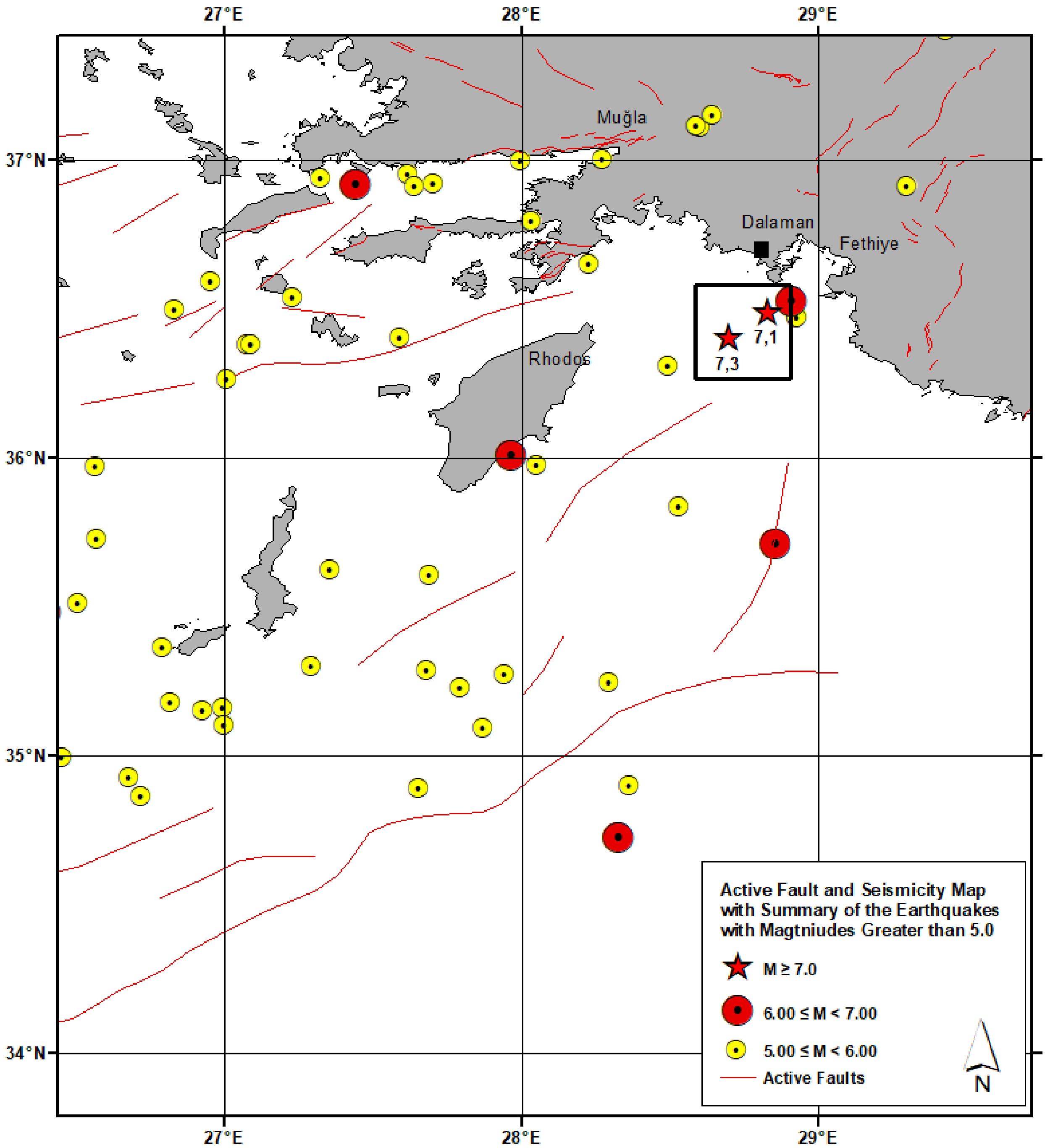


Figure 2. Seismicity Map of the SW Anatolia showing the locations of Fethiye Earthquakes. Earthquake data have been obtained from the earthquake catalogues of Ministry of Interior: Disaster and Emergency Management Presidency (AFAD), Kandilli Observatory and Earthquake Research Institute (KOERI) and U.S. Geological Survey (USGS). Active faults have been compiled and modified from [19,20]

That is why determination of the liquefaction potentials is significant for safe city planning which is significant for the population and economy of the country. Standard Penetration Test (SPT) blow number-based Simplified procedure which has been proposed by Seed and Idriss in 1971 has been used to determine the liquefaction potentials of the granular soils; and liquefaction potentials of the cohesive soils have been determined according to the researches of Seed et al. and Bray and Sancio [21-23].

2. Geological and Morphological Background

Dalaman Basin, a sedimentary depositional environment, is located on the coast of the Mediterranean Sea. Köyceğiz borders the basin in the West and Fethiye borders the basin in the East. Basin, which is located in the South of 2500m high E-W trending Sandras Mountain, is surrounded by relatively smaller hills that border the basin from East and West. These smaller hills are formed of various rock types with different ages and types comprising clastic and carbonate rocks of Marmaris Ophiolite Nappe, Lower Cretaceous peridotites of Marmaris Ophiolite Nappe, Rhaetian-Lower Liassic Continental clastic rocks of Gülbahar Nappe, Jurassic-Cretaceous Pelagic Limestones of Gülbahar Nappe, Middle-Upper Triassic basalt of Gülbahar Nappe, Middle Eocene-Lower Miocene clastic and carbonate rocks of Tavas Nappe, Lower Jurassic neritic limestones of Tavas Nappe and Lower Miocene clastic and carbonate rocks of Tavas Nappe [15, 17]. Geological map of the region is given in Figure 3.

Quaternary evolution of Dalaman Basin is associated with the combination of geological and tectonic processes. Deposition of the sediments through the basin has been initiated by the activity of Northeast to Southwest flowing ~185km long Dalaman Stream which initially flowed through the Köyceğiz Lake along the narrow and deep Pleistocene valleys that follow pre-Quaternary tectonic lineations [24, 25].

The region has experienced sea level changes and climatic variations. Flandrien transgression during climatic optimum between 3000-4000 B.C and Wurm regression during the end of the Pleistocene were two important sea level changes. The evolution of the delta environment over the Mediterranean Sea continued during this period. Dalaman Stream changed its flow direction before 700 B.C and started to flow southward. The shallow western part of the Dalaman basin, which subsides along the basin margin active faults along the hills on three sides of the basin, has begun to form as the Dalaman Stream crosses the hills during its southward movement. However, even if it was slow, the previous branch of the basin was still active in this period. Continuous sediment inflow by Dalaman stream following the changes in the flow direction of the stream has filled the rest of the Dalaman Basin [24, 25].

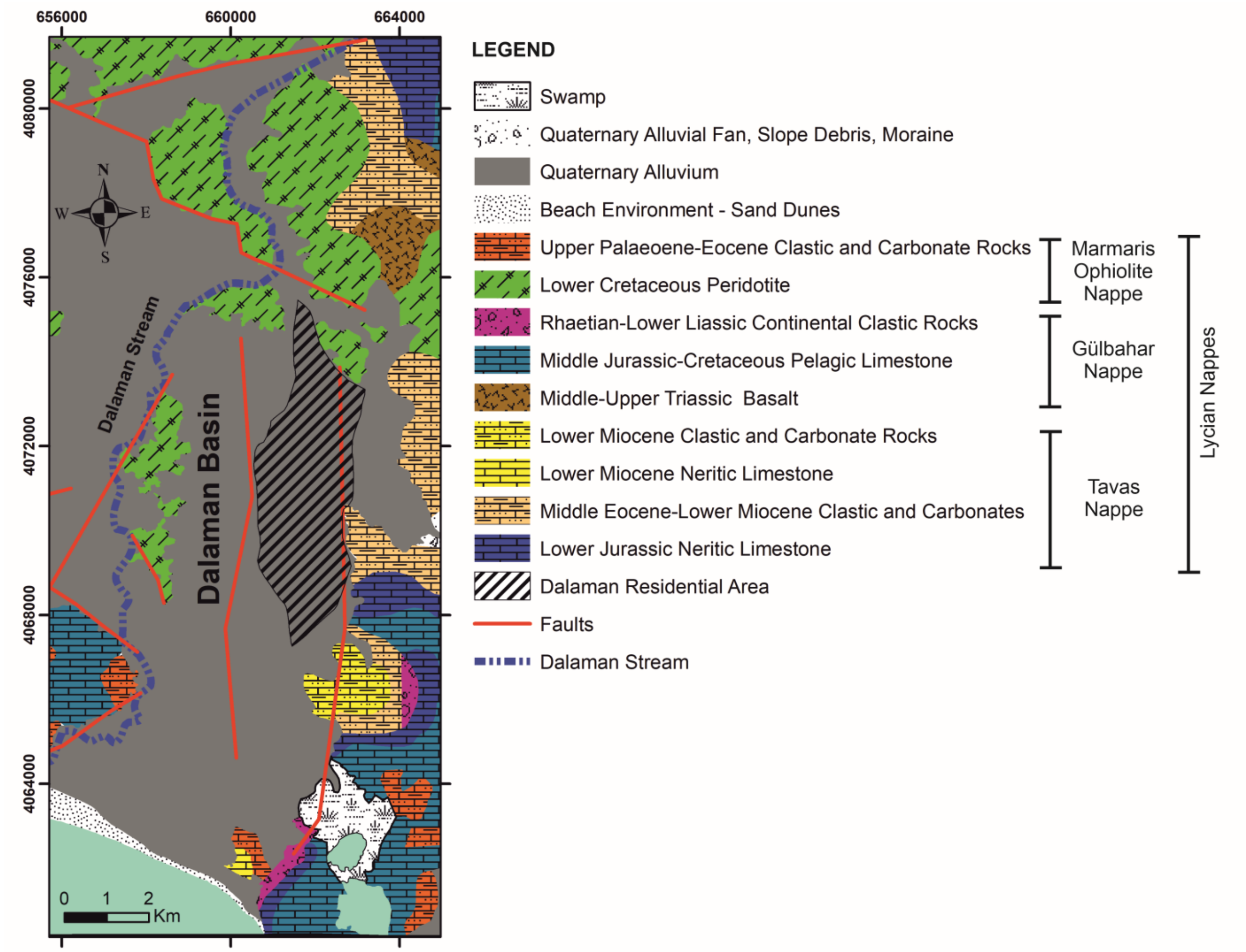


Figure 3. Geological Map of the Dalaman Basin [15]. Faults have been compiled and modified from [17, 18].

Deltaic system of the basin shifted Southward throughout the continuous sedimentation in the basin. As the deltaic system evolved to the South, the former portion of the deltaic deposits have been overlain by the fluvial deposits. Deposition in the basin due to sediment transportation to the basin from the mountains has been discussed so far. However, tsunami-related soil layers have also been observed in the basin [26, 27] (Figure 4).

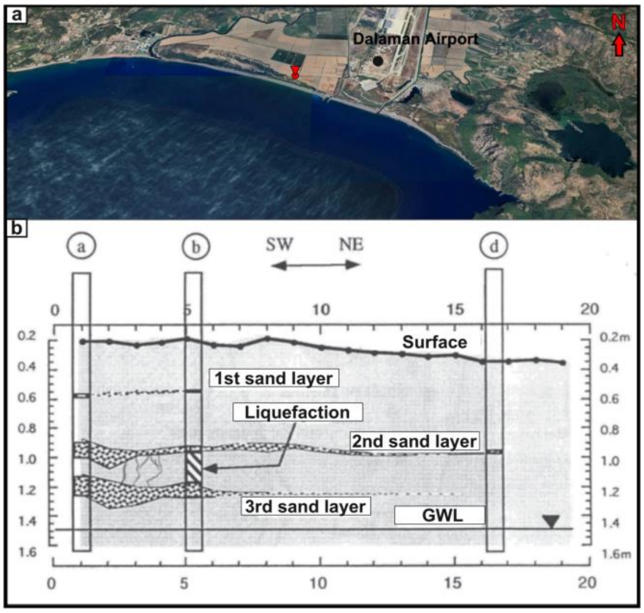


Figure 4. Tsunami deposits in the Dalaman Basin and liquefaction on tsunami deposits [15]. Modified from [26, 27].

3. Calculation of the Liquefaction Potentials

There are lots of site investigation techniques used to determine the geo-engineering properties of the soils like standard penetration test (SPT), cone penetration test (CPT), Becker Penetration Test (BPT), and Seismic Velocities. Totally 66 boreholes were drilled in the Dalaman Residential area and Dalaman airport (64 Dalaman Residential Area and 2 Dalaman Airport zone) (Appendix B) and investigated for soil liquefaction potentials. Because the minimum earthquake magnitude that may trigger liquefaction is 5.5 [28] and the probable highest earthquake magnitude is 7.5 according to the historical earthquakes, the liquefaction potentials of the soils have been evaluated for these two different earthquake scenarios. In this study, liquefaction potentials of the Quaternary deposits of the Dalaman residential area have been explained in terms of Factor of safety value (FS) which has been calculated based on the SPT-based simplified method [21]. This method has also been compatible with the Turkish Earthquake Code (2018) [29]. FS value is defined as the ratio of Cyclic Resistance Ratio (CRR) to the Cyclic Stress Ratio (CSR) which are resisting forces that resist liquefaction and driving forces that initiate liquefaction respectively (Equation 1).

$$FS = CRR/CSR \tag{1}$$

CRR is the representation of the strength of the soil. SPT blow numbers control the CRR and are originally based on the shear strength of the soil. CSR is the measure of the driving forces which represents the load applied to the soil and is based on the earthquake magnitude [21, 30]. So, the greater the resisting forces, the lower the liquefaction susceptibilities of the soils. The threshold value of the FS for liquefaction occurrence has been accepted to be 1.1 by Turkish Earthquake Code (2018). Calculations of the CRR and CSR are given in Equations 2-6 below [21, 29-32].

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

$$CSR = \left(\frac{M-1}{10}\right)\left(\frac{\sigma}{\sigma'}\right)(a_{max})r_d \tag{3}$$

$$a_{max} = (0.4)S_{DS} \tag{4}$$

$$r_d = 1.0 - 0.00765z \ if \ z \leq 9.15m \tag{5}$$

$$r_d = 1.174 - 0.0267z \ if \ 9.15m < z \leq 9.15m \tag{6}$$

S_{DS} value is available online and is obtained from the interactive web application of Turkish Earthquake Hazard Maps prepared by the Ministry of Interior-Disaster and Emergency Management Presidency [31]. It must be noted that the CRR equation has been prepared for an earthquake with a magnitude of 7.5. So, in order to calculate the FS value, the CRR value must be multiplied by a magnitude scaling factor (MSF). MSF which has been accepted by Turkish earthquake code 2018 is given in Equation 7 and calculation of corrected CRR is given in Equation 8 below [29].

$$MSFS = 10^{2.24}/\mathrm{M_w}^{2.56} \tag{7}$$

$$CRR = \mathrm{CRR_{7.5}\,.\,MSFS} \tag{8}$$

Liquefaction potentials of cohesive soils are controlled by their plasticity index, liquid limit, and water content values [22, 23].

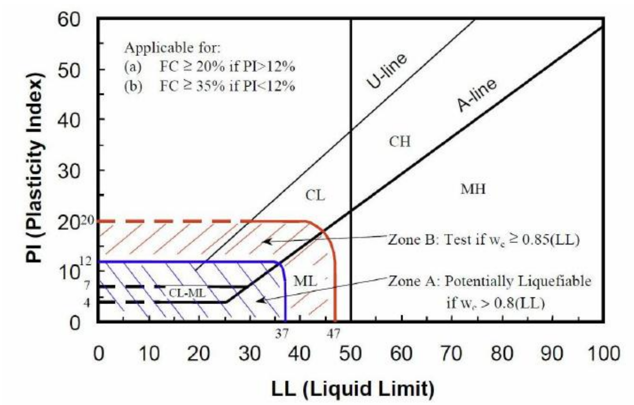


Figure 5. Liquefaction susceptibility criteria [22].

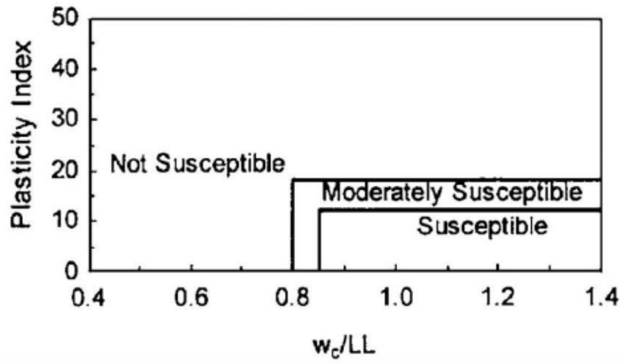


Figure 6. Liquefaction susceptibility criteria [23].

FS values were converted to liquefaction potential index [34] and liquefaction severity index [35].

$$LPI = \int_0^{20} F(z).W(z).dz \quad (9)$$

$$FS_L < 1.0; (Fz) = 1 - FS_L \quad (10)$$

$$FS_L > 1.0; (Fz) = 0 \quad (11)$$

$$LSI = \int_0^{20} PL(z).W(z).dz \quad (12)$$

$$z < 20m \quad W(z) = 10 - 0.5z \quad (13)$$

$$z > 20m \quad W(z) = 0 \quad (14)$$

$$FL < 1.411 \quad PL(z) = \frac{1}{1 + (\frac{FL}{0.96})^{4.5}} \quad (15)$$

$$FL > 1.411 \quad PL(z) = 0 \quad (16)$$

LPI is the liquefaction potential index, F(z) is the liquefaction degree in terms of function of FS which is calculated for each liquefiable soil layer, W(z) is weighted function that varies according to depth, d(z) is depth increment, P_L is liquefaction potential. Classification of the liquefaction potentials according to the LPI and LSI are given in Table 1-2 [32-35].

Table 1. Classification of liquefaction potentials of soils in terms of liquefaction potential index values [34]

Liquefaction Potential Index	Liquefaction Potential
0	Very Low
0 < LPI ≤ 5	Low
05 < LPI ≤ 15	High
15 ≤ LPI	Very High

Table 2. Classification of liquefaction potentials of soils in terms of liquefaction severity index values [35]

Liquefaction Severity Index	Liquefaction Potential
85 ≤ LSI < 100	Very High
65 ≤ LSI < 85	High
35 ≤ LSI < 65	Moderate
15 ≤ LSI < 35	Low
0 ≤ LSI< 15	Very Low
LSI = 0	Safe

Liquefaction potentials of the soils have been calculated with the help of chart proposed by the Turkish Chamber of Geological Engineers [32, 33].

4. Liquefaction Susceptibility Mapping

Geographic information Systems (GIS) are the most commonly used tools for mapping and liquefaction susceptibilities of the soils in the Dalaman Residential Area have been mapped by using GIS software. Liquefaction susceptibilities of the soils in the Dalaman residential area have been mapped according to the LPI and LSI values for earthquakes with magnitudes 5.5 and 7.5. Liquefaction susceptibility maps have not been prepared for different depths because LPI and LSI values represent the whole 20m of the locations of the borehole. Maps have been plotted over the satellite images from 2 different years to see the city's growth direction. Liquefaction susceptibility maps are given in Figure 7-10 with the city's growth direction which are indicated by white line and arrows. Also, there are still old buildings in the region which were constructed based on the previous Turkish Earthquake Codes or may be constructed without considering liquefaction phenomena. Moreover, because Dalaman Airport is one of the most important international zone within the Dalaman Basin which serves the economy and tourism of the country, liquefaction potentials of the soils beneath the airport have been evaluated separately even if it is located out of the residential area. Table 3 depicts the soil groups and liquefaction potentials of the soils beneath the airport area.

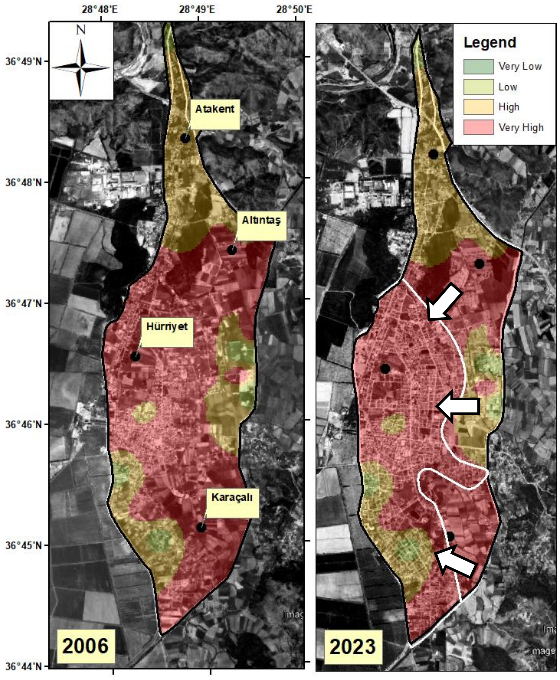


Figure 7. Liquefaction potential index-based susceptibility map for an earthquake with magnitude 7.5

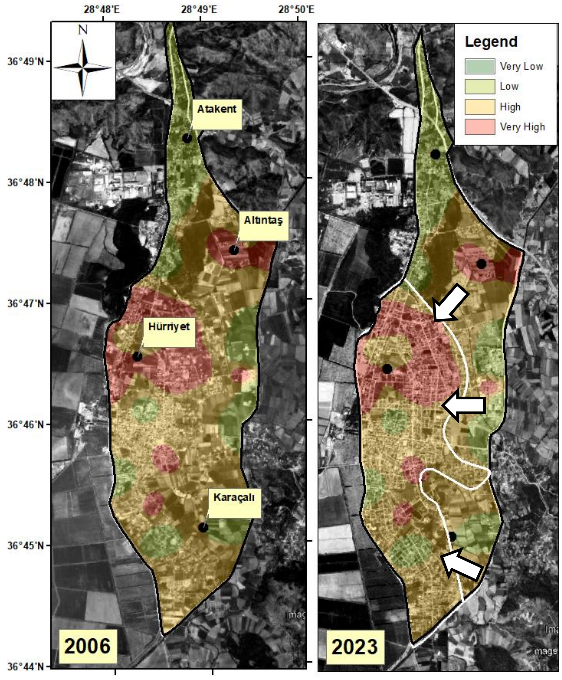


Figure 9. Liquefaction potential index-based susceptibility map for an earthquake with magnitude 5.5

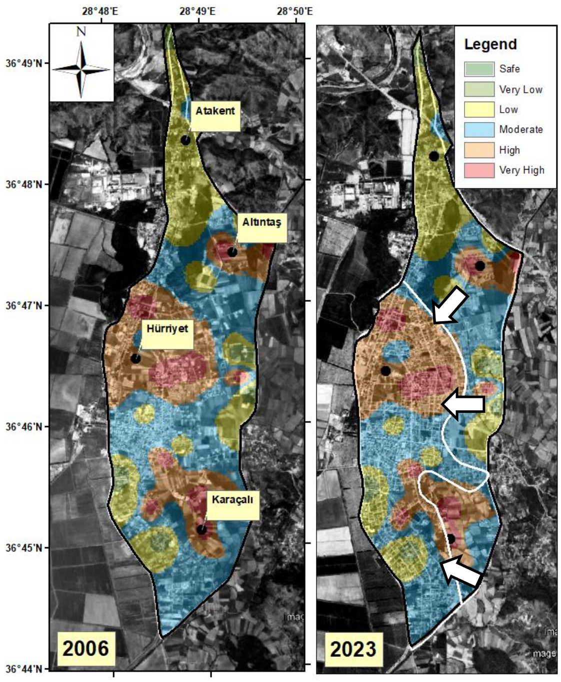


Figure 8. Liquefaction severity index-based susceptibility map for an earthquake with magnitude 7.5

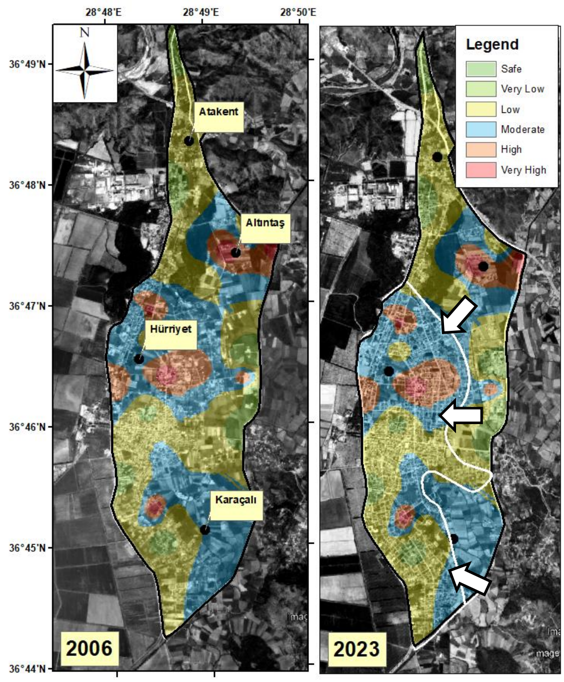


Figure 10. Liquefaction severity index-based susceptibility map for an earthquake with magnitude 5.5.

Table 3. Liquefaction susceptibilities of the soils beneath the Dalaman Airport.

BH-19 soil	Depth	BH-19	FS	BH-20	FS	BH-20 soil
SM	1.50	SAFE	-	SAFE	-	ML
ML	3.00	LIQUEFY	0.55	LIQUEFY	0.67	ML
ML	4.50	SAFE	-	SAFE	-	ML
ML	6.00	LIQUEFY	0.80	LIQUEFY	0.43	ML
ML	7.50	LIQUEFY	0.48	LIQUEFY	0.41	ML
ML	9.00	LIQUEFY	0.53	LIQUEFY	0.54	ML
SM	10.50	SAFE	-	SAFE	-	ML
SM	12.00			SAFE	-	ML
SM	13.50	SAFE	-	SAFE	-	ML
SM	15.00	LIQUEFY	0.70	SAFE	1.26	ML
SM	16.50	LIQUEFY	0.57	SAFE	1.30	ML
SM	18.00			SAFE	-	ML
SM	19.50	SAFE	-	SAFE	-	ML

GWL = 2.5m

	BH-19	BH-20
LPI	21 very high	21 very high
LS	46 moderate	41 moderate

5. Results and Discussions

Dalaman basin is a mixed depositional environment that hosts significant settlements. Each sub-environment of this mixed depositional environment (delta, fluvial, and beach depositional environments) is individually prone to soil liquefaction risk. Therefore, the liquefaction susceptibility of the Dalaman residential area has been evaluated in this paper.

Liquefaction potential calculations show that Dalaman residential area is highly susceptible to liquefaction for an earthquake with a magnitude Mw=7.5. Moreover, even if the Dalaman residential area is not as prone to liquefaction as in a 7.5 magnitude earthquake, it also carries the risk of liquefaction for a 5.5 magnitude earthquake.

It is observed that (Figure 7-10) Dalaman district has developed mostly between Hürriyet and Karaçalı region. It is also seen that the buildings in the western part of Dalaman district are old and those old constructions make the most of the basin. Because old structures are constructed based on the previous regulations or some of them are constructed without assessing the liquefaction potentials of the soils beneath them, they are in great danger. Population of the Dalaman residential area has been recorded as 47.482 in 2022 and during an earthquake with magnitude M=7.5 approximately 40.000 of this population is under risk according to the liquefaction susceptibility map based on LI values and approximately 30.000 of this population is under risk according to the liquefaction susceptibility map based on LS values.

Moreover, 2023 Kahramanmaraş earthquakes have resulted in the occurrences of liquefaction manifestations around the Hatay Airport [36, 37]. Even if the Dalaman airport is not a very large zone it is one of the most important locations of the SW Anatolia because of its socio-economic significance. Only 2 Boreholes could be obtained for the airport area (BH-19 and BH-20). Analyses show that liquefaction potentials of the soils beneath the airport are also highly great and an earthquake may result in the deformation of the roads and structures around the Dalaman Airport as happened in the Hatay airport zone after the Kahramanmaraş earthquakes.

It must be noted that liquefaction potential calculations are much more meaningful with liquefaction-induced surface and subsurface deformation information. Liquefaction-induced deformations have also been studied. However, they are not discussed in this paper.

6. Acknowledgment

This article has been produced as a part of Orkun TÜRE's PhD thesis with the topic "Determination of the Geo-Engineering Properties and Liquefaction Potential of the Quaternary Deposits of Dalaman-Muğla/SW Anatolia". The authors would like to thank Muğla Metropolitan Municipality, Dalaman Municipality and site investigation companies (Ufuk Mühendislik, Alfa Mühendislik, Erdem Yerbilimleri, Şahin Mühendislik, Durak Mühendislik and Etüt Mühendislik) who shared any kind of documents including borehole logs, laboratory testing results, in-situ test results with us and/or their knowledges.

7. References

[1] Burton, I., Robert W. K. and Gilbert F. W., *The Environment as Hazard*, Oxford University Press, 1978.

[2] Ertek, M. K. *"Sıvılaşma potansiyelinin belirlenmesi ve oturmalara etkisinin incelenmesi: Atakum örneği".* Dissertation. Ondokuz Mayıs University Graduate School of Natural and Applied Sciences, Samsun, 2015.

[3] Gökçe, O., Özden, Ş. and Demir, A. *"Türkiye'de afetlerin mekansal ve istatistiksel dağılımı afet bilgileri envanteri".* Bayındırlık ve İskan Bakanlığı Afet İşleri Genel Müdürlüğü. 2008.

[4] Slemmons, D. B. and Depolo, C. M. "*Evaluation of active faulting and associated hazards*." Active Tectonics, 45-62, 1986.

[5] Xiu, Z. et al. "Experimental investigation on liquefaction and post-liquefaction deformation of stratified saturated sand under cyclic loading." *Bulletin of Engineering Geology and the Environment* 79: 2313-2324, 2020.

[6] Silahtar, A, Karaaslan, H. and Kocaman, K. "Site Characterization and Liquefaction Hazard Assessment for the Erenler Settlement Area (Sakarya Province, Turkey) Based on Integrated SPT-Vs Data." *Sustainability,* 2023.

[7] Rahman, M. Z. and Siddiqua, S. "Evaluation of liquefaction-resistance of soils using standard penetration test, cone penetration test, and shear-wave velocity data for Dhaka, Chittagong, and Sylhet cities in Bangladesh." Environmental Earth Sciences 76: 1-14, 2017.

[8] Silahtar, A et al. "Assessment of the liquefaction potential of the Arifiye (Sakarya) region with multidisciplinary geoscience approaches in the GIS environment." *Journal of Applied Geophysics* 212: 104983, 2023.
[9] Babacan, A. E., Ceylan, S.. "Evaluation of soil liquefaction potential with a holistic approach: a case study from Araklı (Trabzon, Turkey)" *Bollettino di Geofisica Teorica ed Applicata* 62(1):173-198, 2021.
[10] Ansal, A., Bardet J. P., Bray, J., Cetin, O., Durgunoglu, T., Erdik, M., Kaya, A., Ural, D., Yilmaz, T. and Youd, T. L. "*Initial geotechnical observations of the August 17, 1999, Izmit earthquake"* Middle East Technical University, Earthquake Engineering Research Center, Ankara, Turkey, 68 pp. 1999.
[11] Kayabasi, A. and Gokceoglu, C. "Liquefaction potential assessment of a region using different techniques (Tepebasi, Eskişehir, Turkey)" *Engineering Geology,* 2018*.*
[12] Cetin, K. O., et al. "Soil liquefaction sites following the February 6, 2023, Kahramanmaraş-Türkiye earthquake sequence." *Bulletin of Earthquake Engineering* 1-24,2024.
[13] Wicander, R and Monroe, J. S. "*Historical Geology: Evolution of Earth and Life Through Time*" 5th Edition. Thomson Brooks/Cole Publishing, 2007.
[14] AFAD "Earthquake Catalogue", 2024. (https://deprem.afad.gov.tr/event-catalog).
[15] Türe, O. "Determination of the geo-engineering properties and liquefaction potential of the Quaternary deposits of Dalaman-Muğla/SW Anatolia", PhD Dissertation, Graduate School of Natural and Applied Sciences, Muğla Sıtkı Koçman Üniversitesi, 2023, 417p
[16] AFAD "Türkiye Deprem Tehlike Haritası", 2018.
[17] Gül, M., Salihoğlu, R., Dinçer, F., and Darbaş, G. "Coastal geology of Iztuzu Spit (Dalyan, Muğla, SW Türkiye)". *Journal of African Earth Sciences*. 151, 173-183, 2019.
[18] Tosun, L., Avşar, U., Avşar, Ö., Dondurur, D., and Kaymakcı, N. "Active tectonics and kinematics of Fethiye-Göcek Bay, SW Türkiye: Insight about the eastern edge of Pliny-Strabo Trenches" *Journal of Structural Geology,*145, 104287, 2021.
[19] Emre, Ö., Duman, T.Y., Özalp, S., Elmacı, H., Olgun, Ş. ve Şaroğlu, F., (2013) Açıklamalı Türkiye Diri Fay Haritası. Ölçek 1:1.250.000, Maden Tetkik ve Arama Genel Müdürlüğü, Özel Yayın Serisi-30, Ankara-Türkiye. ISBN: 978-605-5310-56-1.
[20] Pavlides, S., Chatzipetros, A., Valkaniotis (2008) Active faults of Greece and Surroundings. 33rd International Geological Congress, Oslo.
[21] Seed H.B. and Idriss I.M., "Simplified procedure for evaluating soil liquefaction potential". *J. Soil Mech. Found. Div*., ASCE 97**,** 1249-1273, 1971.
[22] Seed, R. B., Çetin, K. O., Moss, R. E. S., Kammerer, A. M., Wu, J., Pestana, J. M., Reimer, M. F., Sancio, R. B., Bray, J. D., Kayen, R. E. and Faris, A. "Recent advances in soil liquefaction engineering: A unified and consistent framework" Kenote presentation, *26th Annual ASCE Los Angeles Goetechnical Spring Seminar*, Long Beach, CA. 2003.
[23] Bray, J. D., and Sancio, R. B "Assessment of the liquefaction susceptibility of fine-grained soils" *Journal of Geotechnical and Geoenvironmental Engineering*. 32 (9): 1165–1177, 2006.
[24] Doğu, A. F. "Köyceğiz-Dalaman Çevresinde Tarihi Yerleşme Alanlarının Jeomorfolojik Birimlerle İlişkisi (Güneybatı Anadolu)". *A.Ü. DTCF Coğrafya Araştırmaları Dergisi.* 1988. cilt.32, ss.319-328.
[25] Doğu, A. F. "*Köyceğiz-Dalaman Ovaları ve Çevresinin Jeomorfolojisi*." Türkiye Bilimsel ve Teknik Araştırma Kurumu: Matematik, Fizik ve Biyolojik Bilimler Araştırma Grubu. Proje= TBAG-563. 1986.
[26] Yalçıner, A. C., Kuran, U., Minoura, K., Imamura, F., Takahashi, T., Papadopoulos, G., Ersoy, Ş. "Türkiye Kıyılarında Depreşim Dalgası (Tsunami) İzleri" *Türkiye Mühendislik Haberleri* (430), 50, 2005.
[27] Papadopoulos, G., Minoura, K., Imamura, F., Kuran, U., Yalçiner, A., Fokaefs, A., and Takahashi, T. "Geological evidence of tsunamis and earthquakes at the Eastern Hellenic Arc: correlation with historical seismicity in the eastern Mediterranean Sea" *Research in Geophysics*, 2(2), e12, 2012.
[28] Youd, T. Leslie, and Steven K. Noble. "Magnitude scaling factors." *Proc., NCEER Workshop on Evaluation of Liquefaction Resistance of Soils*. National Center for Earthquake Engineering, Research, Buffalo, NY, 1997.
[29] TBDY, "*Türkiye Bina Deprem Yönetmeliği: Deprem Etkisi Altında Binaların Tasarım için Esaslar*", Türkiye Cumhuriyeti, Ankara, 2018.
[30] Mase, L. Z., Tanapalungkorn, W., Likitlersuang, S., Ueda, K., and Tobita, T. "Liquefaction analysis of Izumio sands under variation of ground motions during strong earthquake in Osaka, Japan". *Soils and Foundations*, *62*(5), 101218, 2022.
[31] AFAD "Türkiye Deprem Tehlike Haritaları, İnteraktif Web Uygulamaları" (https://tdth.afad.gov.tr/TDTH/main.xhtml)
[32] Ozdemir, G., Işık, N. S., Koçkar, M. K. and Gültekin, N. "Türkiye Bina Deprem Yönetmeliği-2018 İle Uyumlu Basitleştirilmiş Zemin Sıvılaşma Potansiyeli Analizi Ve Sıvılaşma Sonrası Oturma, Yanal Deformasyon, Kayma Dayanımı Kaybı ve Kapak Tabakası Etkisi Hesap Cetveli Programı (V-2)", 2021.

[33] Ozdemir, G., Işık, N. S., Koçkar, M. K. and Gültekin, N. "Türkiye Bina Deprem Yönetmeliği-2018 İle Uyumlu Basitleştirilmiş Zemin Sıvılaşma Potansiyeli Analizi Ve Sıvılaşma Sonrası Oturma, Yanal Deformasyon, Kayma Dayanımı Kaybı ve Kapak Tabakası Etkisi Hesap Cetveli Programı kullanma kılavuzu (V-2)", 2021.

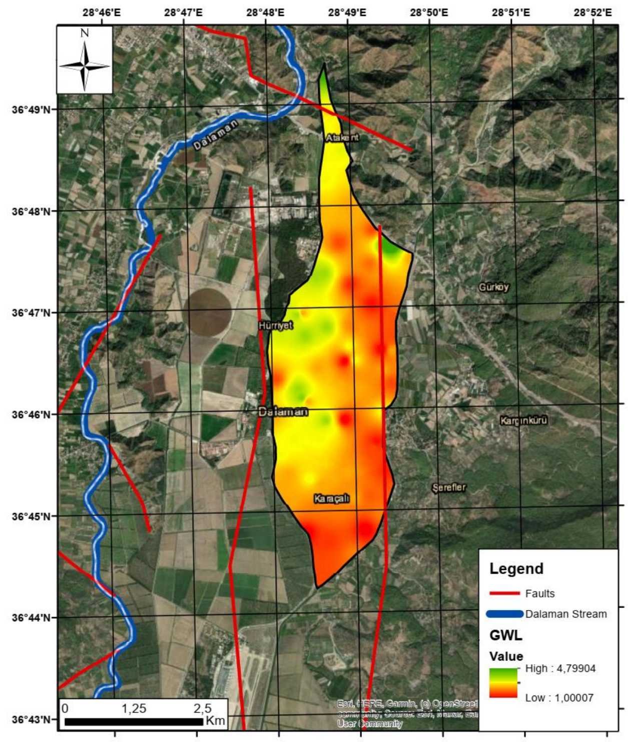
[34] Iwasaki, T., Arakawa, T., and Tokida, K. "Simplified procedures for assessing soil liquefaction during earthquakes." *Proceedings of the Conference on Soil Dynamics and Earthquake Engineering*, Southampton, UK, 925–939, 1982.

[35] Sönmez, H. and Gokçeoglu, C. "A liquefaction severity index suggested for engineering practice", *Environmental Geology*, 48(1), 81 – 91, 2005.

[36] Çakır, E., Çetin, K. Ö., Eyigün, Y. and Gökçeoğlu, C. "Soil liquefaction manifestations at Hatay Airport after the February 6 Kahramanmaraş Earthquake Sequence" *9th Geotechnical Symposium*. İstanbul, 2023.

[37] MSKÜ Department of Civil Engineering "6 Şubat 2023 Kahramanmaraş Depremleri: Pazarcık (Mw=7,7) and Elbistan (Mw=7,6) Ön Değerlendirme Raporu"

Appendix A. GWL Map of the study area



Appendix B. Locations of the boreholes used for mapping by IDW method and determination of the liquefaction potentials of the soils in airport area.