SAÜ Fen Bil Der 20. Cilt, 3. Sayı, s. 689-699, 2016

GIS – based evaluation of the effect of local soil properties on the earthquake damage patterns

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01.09.2016 Geliş/Received, 12.10.2016 Kabul/Accepted

doi: 10.16984/saufenbilder.01365

ABSTRACT

Moderate magnitude earthquakes hit the Sakarya region, Turkey, in the range of 10-30 years. The 1999 earthquakes, which occurred in the study area, gave different damage patterns due to the variation of soil properties. In-situ and laboratory investigations were performed by Sakarya University in the centres of two townships in the Sakarya region: Arifiye and Geyve, which are known to possess different soil properties. Borings and cone penetration soundings were performed around the selected towns and data were entered into a database, which is connected to a Geographical Information System (GIS) software. Some thematic maps have been prepared for depths up to 15 m and an evaluation of damage patterns has been performed from points of view including: geology, geomorphology and geotechnical engineering in the investigation area. By evaluating the maps prepared in GIS, local soil properties affected the earthquake destruction of buildings. The number of heavily damaged buildings decreased with increasing bearing capacity. It was also proven that the liquefaction phonomena has not occurred in clayey areas.

Keywords: GIS, earthquake, damage pattern, soil properties

Yerel zemin özelliklerinin deprem hasarı üzerindeki etkisinin CBS ile değerlendirilmesi

ÖZ

Orta büyüklükte depremler Sakarya bölgesini 10-30 yıl aralıklarla etkilemektedir. Bunların en sonuncusu olan 1999 depremleri bölgede zemin özelliklerine bağlı olarak farklı hasara neden olmuştur. Bu çalışmada, Sakarya Üniversitesi tarafından farklı zemin özellikleri gösterdiği bilinen Geyve ve Arifiye ilçe merkezlerinde yürütülen arazi ve laboratuvar çalışmalarından elde edilen sonuçlar CBS ortamında değerlendirilmiştir. Araştırma konusu iki ilçede yapılan sondajlar ve koni penetrasyon deneylerinden gelen bilgiler bir veri tabanına işlenmiş ve CBS tabanlı bir yazılımla değerlendirilmiştir. İncelenen 15 m derinlik boyunca tematik haritalar hazırlanarak, deprem sonrası oluşan hasar jeolojik, jeomorfolojik ve geoteknik açıdan değerlendirilmiştir. CBS ortamında hazırlanan haritalar yerel zemin özelliklerinin davranışı etkilediğini göstermekte, artan taşıma gücüyle ağır hasarlı bina sayısının azaldığı görülmektedir. Ayrıca, killi zeminlerin hakim olduğu bölgelerde sıvılaşma hasarının görülmediği teyit edilmektedir.

Anahtar Kelimeler: CBS, deprem, hasar dağılımı, zemin özellikleri

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1. INTRODUCTION

Besides the geological structure, local soil conditions are very important regarding earthquake damages. Because of soil heterogeneity and its chaotic structure, local earthquake damage patterns may differ from site - to - site in very close proximities. Mac Murdo (1824) is the first person to investigate the phenomena of damages to buildings founded on rock or soft soils [1]. Kramer (1996) emphasized that soil conditions affect the amplitude, frequency and duration of ground movements [2]. Some researchers indicated that damage on the alluvial soils are more significant than damage on the bedrock outcrops [3] [4]. This situation can be explained by amplification of the ground motion in an alluvial basin [5].

The Sakarya province is a busy agricultural and industrial city, approximately 150 km east of İstanbul, Turkey, with a population of approximately one million. Earthquakes with a magnitude of 6.5 - 7.5 occur approximately every 10 - 30 years in the Sakarya region, due to intense activity of the North Anatolian Fault (NAF), which is 900 km long and trending in the east - west direction on the northern part of Turkey. The center of the province, which sits on fluvial deposits, was devastated by the Kocaeli-Adapazarı earthquake, on August 17, 1999, with an unexpected death toll and building damage. After the earthquake, different damage patterns were observed by surveying different parts of the region in detail. Bol (2012) determined the relationship between soil properties and earthquake damage by using neural networks (NN) in Adapazarı [6]. The author evaluated the relationship between the physical, mechanical and dynamic properties of the soils and general distribution of the damage on the NN platform.

In this study, the two towns of Arifiye and Geyve, which suffered varying degrees of damage, were selected in the Sakarya Province and detailed in-situ and laboratory tests were performed. Data from these studies have been transferred to a database system called “Adapazarı Geotechnical Database”. After digitizing the borders of the selected districts, the database was connected to GIS and some thematic maps such as corrected standard penetration resistance, groundwater level and allowable bearing capacity were created for depths up to 15 m to show the relationship between soil properties and damage patterns.

2. MAJOR EARTHQUAKES IN THE REGION

The first known massive earthquake, to affect the Sakarya Province, was the 1894 İstanbul earthquake. After that time, the Sakarya Province has been considerably affected by 1943, 1957, 1967 and 1999 earthquakes in the last century. All of these earthquakes occurred in the western part of the North Anatolian Strike-Slip Fault zone. In these earthquakes, the number of deaths and damaged buildings increased gradually due to increasing population and building stock. These five major earthquakes are described below.

July 10, 1894 İstanbul Earthquake: The devastating earthquake which occurred in İzmit Bay caused widespread damage between İstanbul and Adapazarı. The epicenter was reported as 40.8 N latitude and 29.0 E longitude. According to Gündoğdu et al. (1991), the largest intensity of the earthquake was X [7]. However, Eginitis (1894) had stated that the highest intensity was VIII [8]. It has been reported that the greatest impacts were in Heybeliada, Yalova and Sapanca. The most affected area was bordered by zone 1 in Fig. 1a and intensities decreased gradually in the other zones represented by 2, 3 and 4. There was catastrophic damage in these regions with a larger proportion of casualties. According to Ambraseys (2001), 236 stone masonary buildings were destroyed in Adapazarı, the center of Sakarya [9].

June 20, 1943 Hendek Earthquake: The earthquake occurred at the coordinates of 40.43 N - 30.48 E. It caused 346 deaths, and countless injuries and economic loss. The intensity of the earthquake, which caused heavy damage in Adapazarı, Hendek, Akyazı and Arifiye was reported as I_0=VIII.

May 26, 1957 Abant Earthquake: The epicenter of the earthquake was 40.57 N - 31.00 E, and its magnitude was M_s = 7.0 - 7.1. This earthquake lasted 31 seconds. The length of the fractured segment was 40 km, with maximum and average strikes at 165 cm and 55 cm, respectively. The earthquake completely destroyed the region along the narrow valley between the Lake Abant and Dokurcun. Sixty-six people were reported dead and the intensity was observed as I_0 = X [12]. Although there were no deaths in Adapazarı, over 500 buildings were damaged or destroyed.

July 22, 1967 Mudurnu Earthquake: The earthquake occurred at 40.60 N - 30.80 E, at Mudurnu Valley, with a magnitude of M_s = 7.1, on the westward extension of the 1957 fault-break, and overlapped the whole zone that was ruptured in 1957. The fractured segment was 80 km long with maximum and average strikes of 260 cm and 90 cm, respectively. It killed 86 people, injured 332 and damaged more than 5000 houses in Mudurnu Valley. No damage or restricted damage was observed at the structures, which were well-designed by engineers. Fig. 1b shows the affected regions (maximum I_0 = X) [13] [10]. Ambraseys (1988) stated that widespread liquefaction was observed at the fluvial deposits, which were 25 km away from the fault [12].

August 17, 1999 Marmara Earthquake: The earthquake occured through the motion of the right lateral strike-slip fault, NAF, in the region and lasted 48 seconds with a moment magnitude of $M_w = 7.4$. The torn segment of the NAF consists of 4 segments, with a total length of 126 km [11]. Adapazarı is approximately 8 to 10 km north of this torn segment. Fig. 1c shows that Arifiye town was more affected than Geyve in this earthquake.

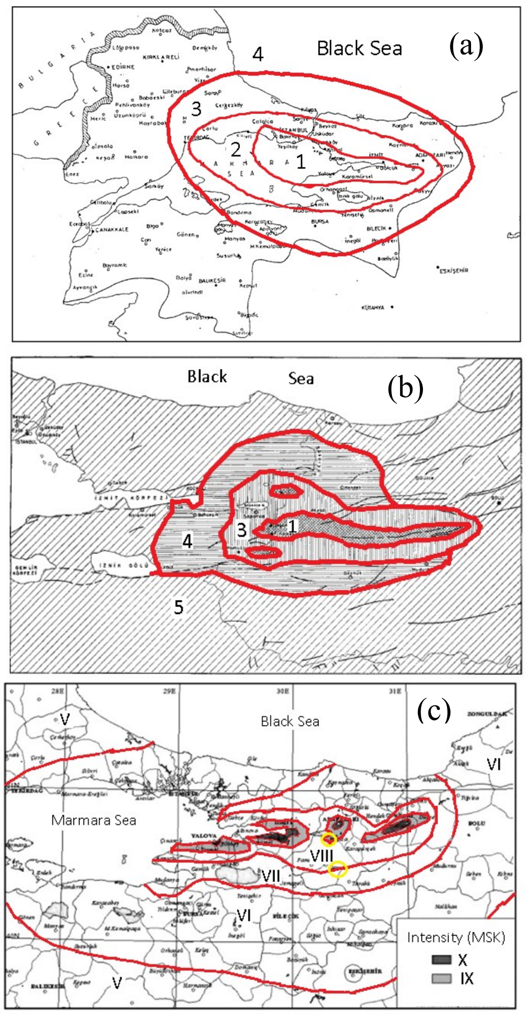


Figure 1. The isoseismal curves (a) 1894 (b) 1967 (c) 1999 earthquakes in the Marmara Region [8] [10-11]

3. LOCAL GEOLOGICAL AND GEOMORPHOLOGICAL SETTINGS

Fig. 2 shows the location of the selected towns, with reference to the active North Anatolian Fault (NAF). The outstanding feature of Fig. 2 is the widespread presence of quaternary alluvial deposits under the control of faults [14]. In this picture, fault ruptures resulting from the 1967 Mudurnu Valley ($M_w = 6.8$) and 1999 Kocaeli - Adapazarı ($M_w = 7.4$) earthquakes can be seen. The NAF passes through the middle of Arifiye, along the east - west direction, dividing the town into two different topographical parts, while Geyve is south of NAF. One common feature they share is the dominance of quaternary alluvial soils, which have been deposited by River Sakarya, which flows north.

The Arifiye town covers an area of 13.230.260 m^2. The northern part has a flat topography with 35 - 40 m in elevation and 0 - 3% of inclination, while the southern part shows higher altitudes and gradients. Soils from the northern part are composed of quaternary alluvial deposits (gravel, sand, silt, clay), which are sedimented by the Sakarya River, flowing along the east side towards the North (Fig. 3a). The Miocene - Pliocene bedrock Örencik formation (Tör) outcrops in the south part, consisting of middle - thick layered gravelstone, sandstone, mudstone, and claystone, where these units sometimes exhibit intact rock appearances [15].

Geyve is 20 km away from the NAF and covers an area of 700 km^2, 95% has a 0 - 3% inclination and only 5% of the northern side has a 10 - 15% inclination. There is a valley called the Geyve Strait, incised by the Sakarya River, between Arifiye and Geyve. The town center is divided by dominant soils into 6 different units, from borings and laboratory classification results, like: clays (Qkl), silty sands (Qsk), clayey sands (Qklk), sandy clays (Qkkl), sandy gravels (Qkç) and clayey gravels (Qklç) (Fig. 3b).

4. LABORATORY AND IN-SITU INVESTIGATIONS

The locations of borings and cone penetration tests (SPCPT), which were performed in the town centers, can be seen in Fig. 3. In this study, 38 borings (Total depth, TD: 640 m) and 4 SPCPT soundings (TD: 60 m) in Arifiye and 29 borings (TD: 590 m) and 1 SPCPT sounding (TD: 15 m) in Geyve were performed. Standard penetration tests (SPT) were performed at every 1.5 m depth in the boreholes (TD: 15 m) each yielding ten disturbed samples and corresponding standard penetration test numbers (SPTN), while

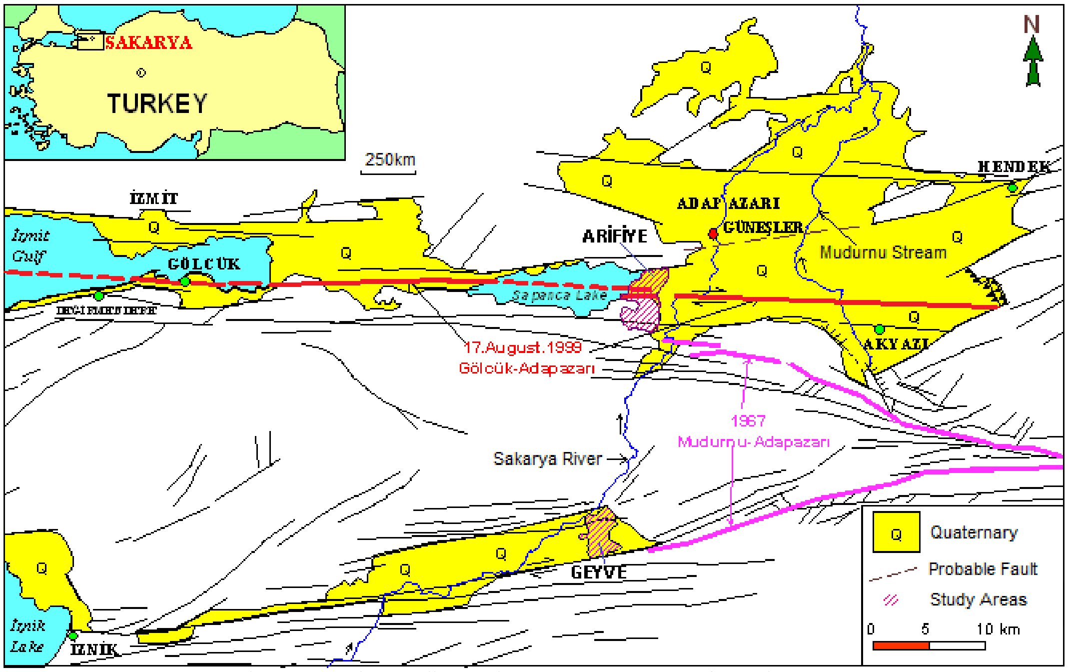


Figure 2. North Anatolian Fault (NAF) zone segments for study areas
(red 1999 earthquake, pink 1967 earthquake rupture and black other segments)

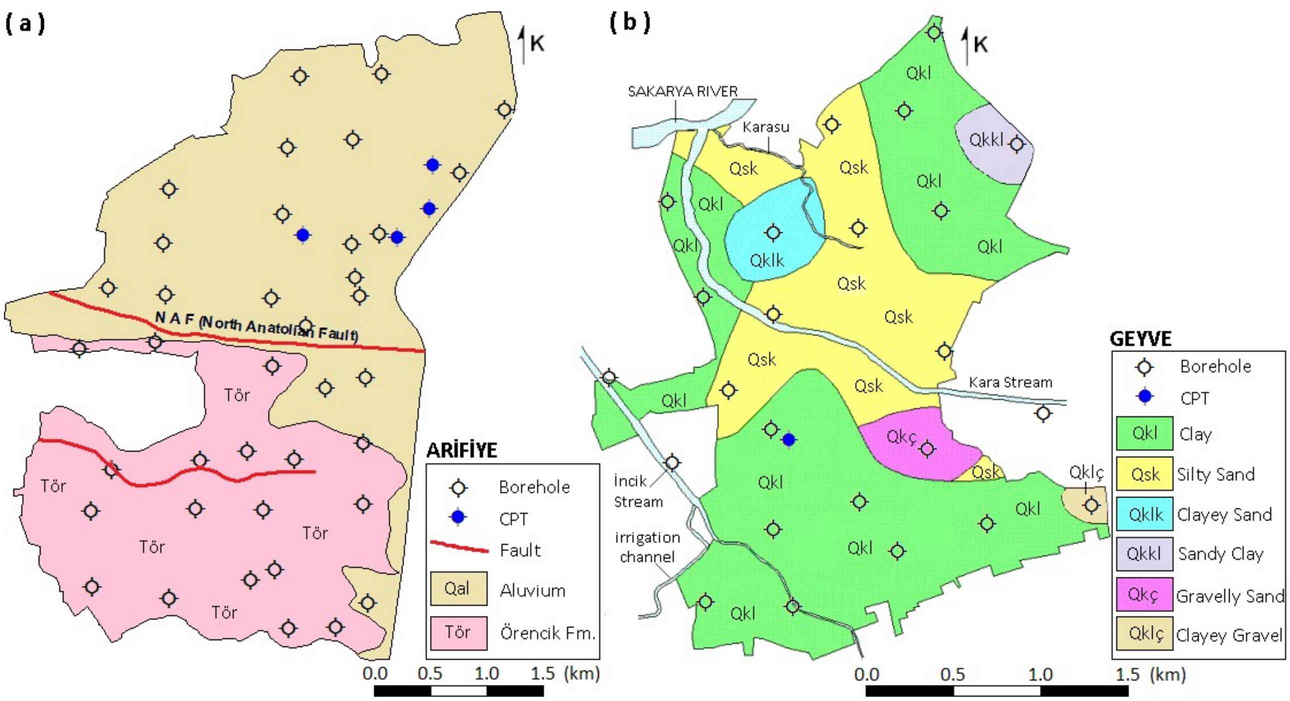


Figure 3. Geological maps and soil investigation locations (a) Arifiye (b) Geyve

SPCPT readings provided data at every 2 cm. Generally, one undisturbed sample was taken at depths of approximately 2 or 3 m depths. Both undisturbed and disturbed samples from the borings were tested according to TS1900 (TSE 1987) and classified with TS1500 (TSE 2000) at the Sakarya University Geotechnical Laboratory [16] [17]. Table 1 shows the numbers of classified samples for each town. In addition, shear wave velocity measurements, with the down hole seismic method, were taken at various depths when SPCPT soundings were being implemented.

Table 1. Number of tested samples for soil types

Soil Class	Arifiye	Geyve
High Plasticity Clay-CH	40	16
Intermediate Plasticity Clay-CI	25	39
Low Plasticity Clay-CL	10	22
High Plasticity Silt-MH	3	2
Intermediate Plasticity Silt-MI	6	1
Low Plasticity Silt-ML	10	3
Sands-S	22	13
Gravels-G	5	17
Total	121	113

The main soil groups, in the top 15 meters, and their distribution is presented in Fig. 4. It is observed that clays are dominant in both towns studied. According to Fig. 4, high plasticity clays are the dominant soil type in Arifiye. In Geyve, predominantly clays, but gravels and sands do occur [18] [19].

Results show that 75 of the 121 samples taken from the Arifiye region have a C - clay symbol and 40 of these have a CH - high plasticity clay symbol. All soil types can be encountered at the top of 9 meters. Gravels take part at 3 - 4 meters and 7 - 10 meters in many boreholes, while they were not met at 9 - 15 meters. Although sands sometimes appear, clays are certainly the dominant soil type [20] [21]. In addition, the boring logs indicated the organic lenses, identified with a gray/black color, can be encountered up to 15 meters. Except for a few gray and mixed colors, almost all of the samples are brown at the top and green at depth. It is known for this region that green indicates the effects of the metamorphic rocks in Holocene and brown represents the oxidation of the upper clay layers at the near geological past [22].

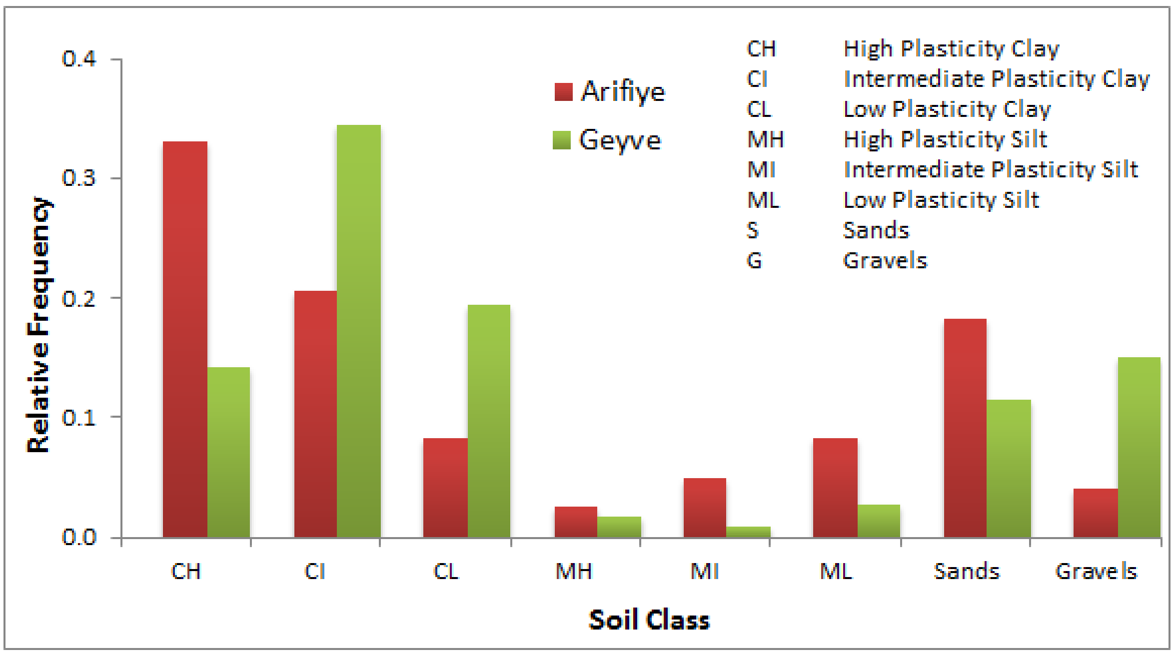
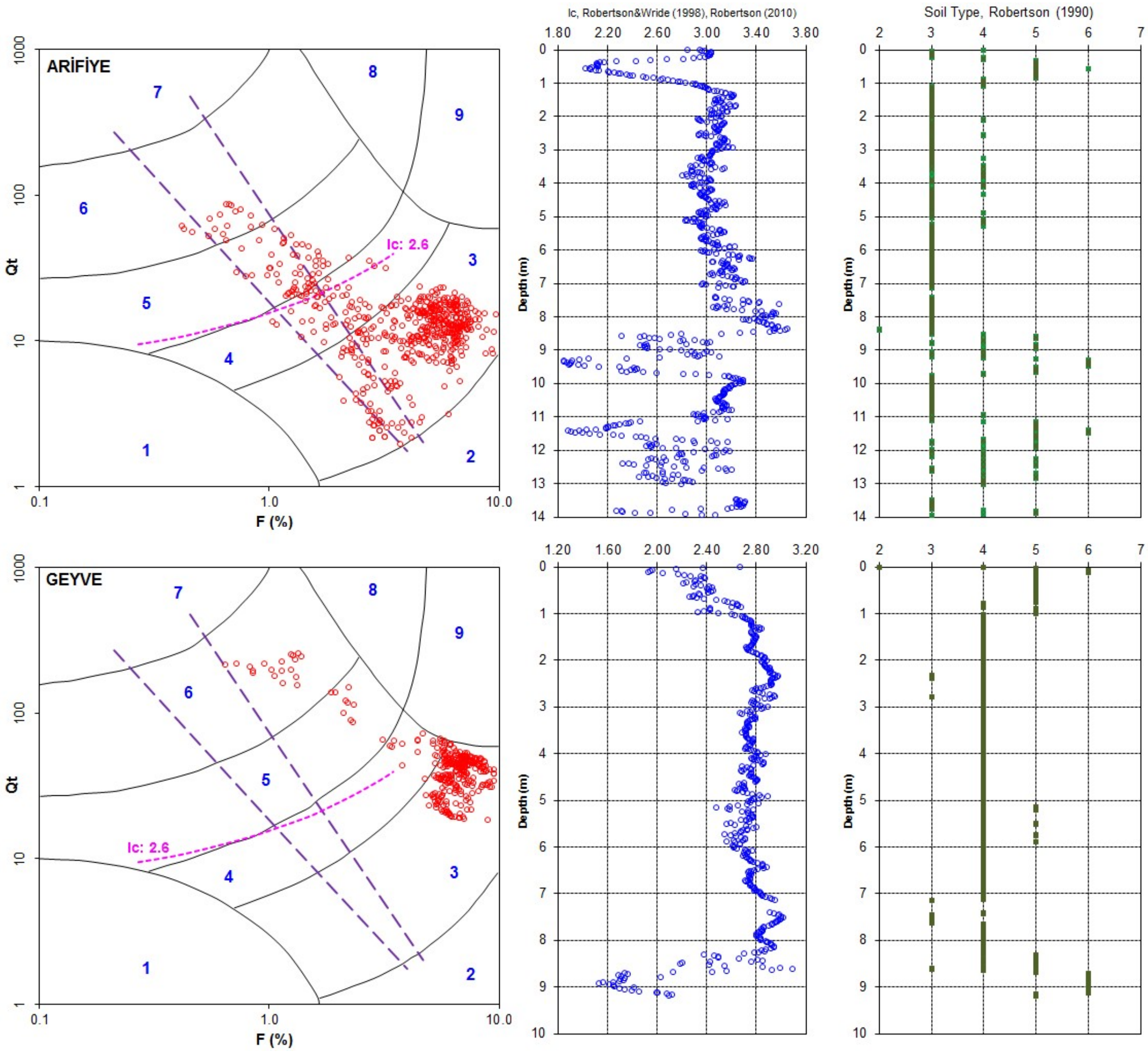


Figure 4. Main soil groups and their distribution in Arifiye and Geyve

Samples that came from Geyve do not show much variation. The gravel content sometimes rises and occasionally iron - oxide and caliche formation is observed. According to the classification test results, silts are minimal and nearly 3/4 of the samples assume clay symbols.

Data obtained from the SPCPT tests, for both districts, show the soil groups for the Robertson classification chart cluster in area 3 (clay - silty clay) confirm the laboratory findings (Fig. 5) [23] [24].

Normalized cone resistance and friction ratio (Q_t-F) relationship, at the same time, has given an idea about the stress history of the soils. Two parallel lines in the middle of the Q_t-F(%) diagram shows the limits of normal consolidated soils. The over consolidation ratio (OCR) value increases while going up from this band. It can be understood from Fig. 5 that OCR values of Geyve soils are higher than Arifiye soils.



1. Sensitive, fine-grained soils
2. Organic soils and peat
3. Clays [clay to silty clay]
4. Silt mixtures [clayey silt to silty clay]
5. Sand mixtures [silty sand to sandy silt]
6. Sands [clean sand to silty sand]
7. Gravelly sand to sand
8. Very stiff sand to clayey* sand
9. Very stiff, fine-grained*

(*) Heavily overconsolidated or cemented

Figure 5. SPCPT sample profiles for different soil classes [23] and depth - soil type behaviour index Ic relationship [24]

5. RESULTS

5.1. Standard Penetration Test

SPTN thematic maps, which represent the upper depths of the investigation areas are presented in Fig. 6. The SPTN values change between 2 and refusal in Arifiye town center (Fig. 6a). Intact rocks were encountered at only a few borings, however, some areas of the alluvial plain can be evaluated as swamp facies because of very low SPTN values. These findings are important to prove that soil has a complex structure in Arifiye town center, which is the nearest center of population to the NAF in the neighborhood.

It appears the high values of the SPTN measured in Geyve town center do not result from the superior qualities of the clays, but rather the resistance offered by the gravel content or cementation effect (Fig. 6b). When analyzing the SPTN readings taken from the upper 7.5 m, SPTN=35±12, average and standard deviation values were found. These high values draw attention to recent alluvial deposits. SPTN values are generally higher than 20 and maximum values are taken at the north and southeast regions. The blow counts are approximately 20 at the depths, where the formations are named as silty sand (Qsk) and clay (Qkl) around the city center. At the sandy gravel (Qkç) and clayey gravel (Qklç) formations, SPTN counts reach high values with an average of 70 southeast of the town. However, distribution of the SPTN values for the formation, defined as clay (Qkl), presents a difference from various directions. Taking into consideration this data, it is evident that clay (Qkl) formations, which are located in three different locations (south, north and west) have different characteristics. On the other hand, it is important to remember that the standard penetration test was developed especially for clean sands. Thus, using SPTN values in clays or coarse gravelly soils may be erroneous.

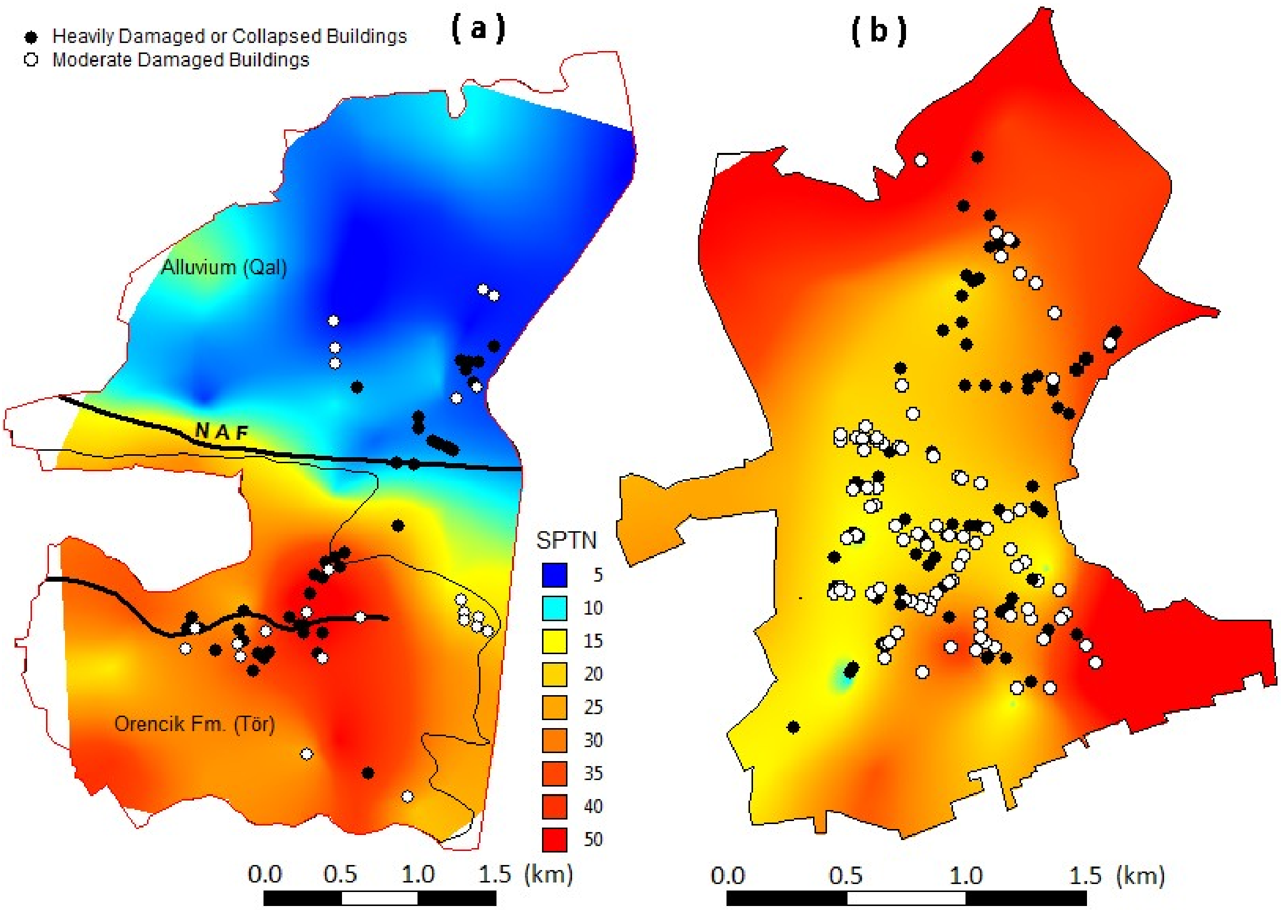


Figure 6. Standard penetration resistance maps and damage distribution (a) Arifiye (b) Geyve

5.2. Groundwater Condition and Liquefaction Potential

Since 1999, the phenomenon of ground failure and liquefaction have been extensively studied. Generally, in the town center of Adapazarı, the liquefaction was observed to have occurred in the low plasticity silts and fine sands at shallow depths [22]. To understand the process of liquefaction in these particular layers, the Adapazarı criterion has been developed [25]. According to this criterion, liquefied strata must have the following properties: soil group should be ML (NP), natural moisture content should be equal or higher than the liquid limit (in this conditon liquidity index is higher than unity: $I_L \geq 1$), liquid limit should be less than 30 and clay fraction ($D \leq 0.002$ mm) should be less than 15%. The CRR/CSR method has to be used to determine the liquefaction potential of silty and clean sands [26] [27]. According to the data obtained from the SPCPT test, the soil behaviour type index (I_c), which is the function of the normalized point strength (Q) regarding overburden pressure and the function of the friction ratio (F), should be between 1.7 and 2.6 [28].

Ground water level maps of Arifiye and Geyve are depicted in Fig. 7. While the ground water level determination is as high as -0.10 m in boreholes opened in alluvial deposits in Arifiye town center (Fig. 7a), ground water was not encountered in the limited amount of boreholes, which were opened in the Örencik Formation. Visual inspections and the physical properties of the soil show that there is no liquefaction potential in the Arifiye Region. Examination of the soil types there indicate that the number of clay layers is much higher than the silts and sands. Although the groundwater level is high in the region, due to this abundance of the clay layers, it is possible to present only restricted liquefied areas in the town. As a result, in the Arifiye region, the liquefaction rate is much less than the center of Adapazarı.

Ground water level is between -0.5 m and -7.0 m on the plain in Geyve town center (Fig. 7b). The groundwater level deepens in the Pliocene aged formations, where the topography starts to rise. During site investigations following the 1999 earthquake, no sign of liquefaction was encountered at Geyve. The main reason is the lack of silt and uniform sand layers.

The depth vs. I_c graphs derived from the SPCPT tests, carried out in both regions, are also given in Fig. 5. The I_c values, from the graphs, support the idea mentioned above. In both regions, dominance of clay layers, against the other layers, which are sensitive for the liquefaction like silts and uniform sands, have attracted attention.

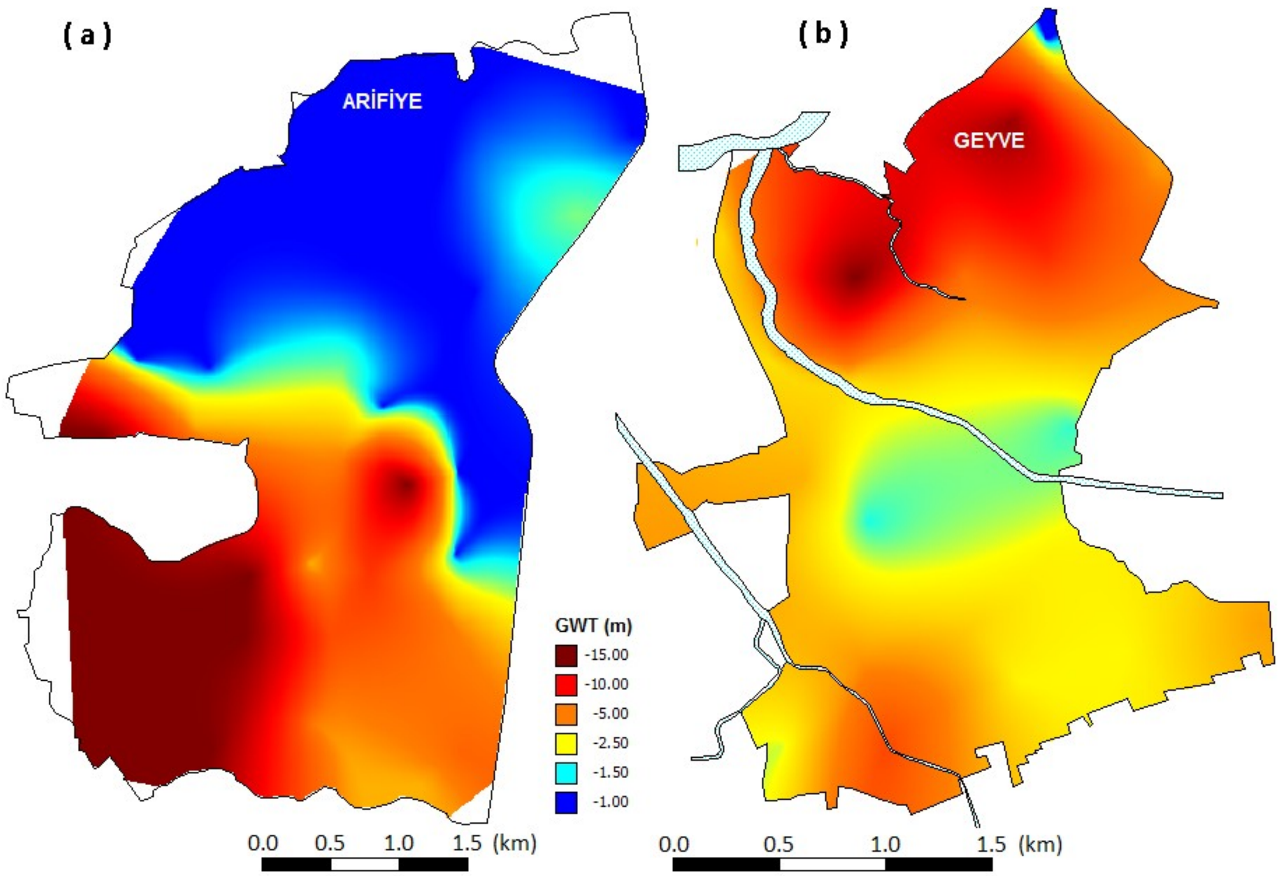


Figure 7. Ground water table depth maps (a) Arifiye (b) Geyve

5.3. Bearing Capacity

In both regions, all of the data, which comes from the borehole investigations and laboratory works, were ultimately evaluated and allowable bearing capacity values were calculated for each location. The Skempton (1951) formula was used to evaluate the short term bearing capacity of a strip foundation, by accepting the embedment depth of the foundation at 1-1.5 m and groundwater level is near the surface [29]. The corresponding bearing capacity maps in Fig. 8 were produced afterwards.

Due to its low population, tall buildings are not common in Arifiye. As a result, intensive destruction was not observed after the earthquake of 1999. According to the laboratory test results, undrained shear strength (c_u) of the alluvial deposits is higher than 30 kPa, while it is above 200 kPa in Örencik Formation. For shallow foundations, which have a minimum depth of embedment at 1.5 m, allowable bearing capacity is between 60 - 100 kPa in alluvial deposits and between 90 - 200 kPa in Örencik Formation (Fig. 8a). Therefore, in respect to the bearing capacity, the southern part of Arifiye has harder and more dense soils in comparison to the northern part.

When the test results on the undisturbed soil samples of Geyve town center were evaluated, undrained shear strength of the samples for the top 5 m were found to be c_u=112.3 ± 61 kPa. In clays with OCR=2-7, while compression indices have high values, low values of recompression indices varying from 0.02 to 0.05, result in very small settlement because most of the buildings apply a bearing pressure of smaller than 100 kPa. Internal friction angles of the dense sand and gravel layers, which appear sometimes in the city center, have a value of $\phi \geq 35°$. At the same time, the undrained shear strength value of clay - gravel mixtures change from 7 to 57 kPa. All of these findings show that it is unusual to encounter low shear strengths, like the young western Anatolian alluvial deposits, except for a few sites in Geyve. When these parameters are taken into account, the allowable bearing capacity is $\sigma_{all} \geq 100$ kPa, if the depth of embedment is kept to at least 1 m (Fig. 8b).

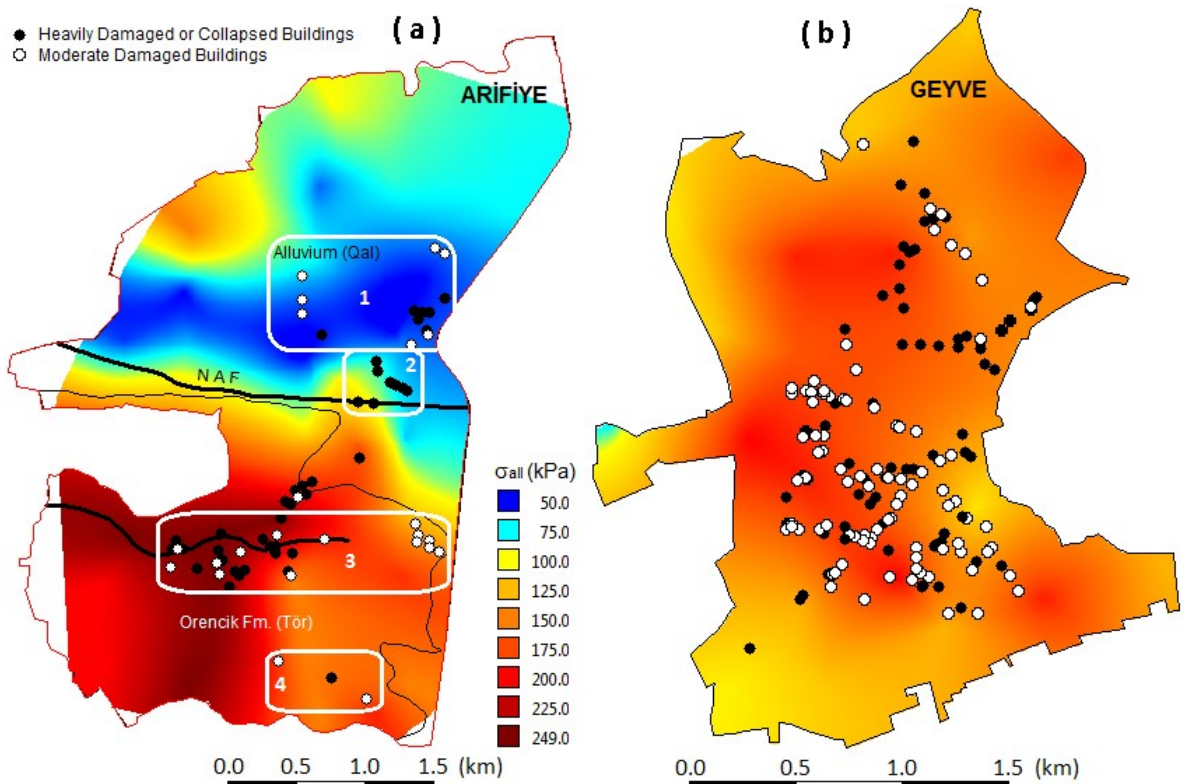


Figure 8. Allowable bearing capacity maps and damage distribution (a) Arifiye (b) Geyve

6. DAMAGE PATTERN AND DISCUSSION

It may appear that this study places heavier emphasis on the properties of soils in comparison to the structural properties of the buildings. However, the quality of the buildings in the areas studied show significant differences, having been designed with three different building codes during the past 40 years, and assessing their quality would have been practically impossible. It is clear that the structural features of the buildings cannot possibly be incorporated into this type of study because there was no detailed inventory of the collapsed and surviving buildings in the study area.

The condition of the building stock in both districts was evaluated by examining the post earthquake structural damage and records of the ministry officials. The classification was implemented in four categories: heavily damaged/collapsed, moderate damage, lightly damaged and sound. The medium damage category was the controversial item because it was defined as a "building that will function after retrofitting". In this study, heavily damaged/collapsed and moderate damaged buildings have been taken into consideration.

Damaged buildings have been recorded both in Arifiye and Geyve by official institutions [19] [21]. The damage distribution maps were prepared using data obtained from studies after the 1999 earthquake in Arifiye and Geyve and are presented in Fig. 6 and Fig. 8 for town centers, showing the standard penetration resistance and allowable bearing capacity respectively. Available information shows that earthquake hazard and destruction increases linearly with the decrease in distance to the source fault. In this case, Arifiye should be more adversely affected than Geyve because of its proximity to the NAF. However, in this earthquake, no deaths were recorded but a few injured people were reported in Arifiye [30]. It is not that the damage was not widespread, but merely due to low density of habitation. Along with low habitation, the number of buildings with more than four floors was much less existent.

It was decided to separate hazard clusters into four regions in the map of Arifiye town center (Fig. 8a) because the reasons that caused the destruction of buildings in each region is different. The soil in the first region consists of soft alluvial deposits and by considering the bearing capacity map in Fig. 8a, it can be deduced that soils of low shear strength may be the primary contributing factor to the damage observed. It is apparent that the proximity to the fault caused the damage in the second and third regions, where the soil properties are not inferior. So, any damage encountered in the fourth region, must have been caused by low quality of structures, considering the high bearing capacity of the soil and greater distance from the fault.

Today, it is prohibited to build on and around active faults. In addition, it continues to be a controversial topic of how close to the main and secondary faults should be permitted. On the other hand, according to observations, that the structural earthquake hazard is low for well-designed buildings with a limited number of flats, even when soil conditions are adverse.

The map of the damage in the Geyve town center is given in Fig. 6b and Fig. 8b. If taken into account the soil classes and high SPT blow counts of Geyve soils, the town carries no risk of liquefaction phenomena. In addition, soil failure did not occur in Geyve because of high bearing capacities. The distribution of damage in Geyve is not associated with soil properties because there is no fault affecting the region, and soft soils are not encountered in the region. It is concluded that this is due to slipshod settlements and inadequate projected structures. The most significant proof of this is that the death toll was 15, and 24 buildings were destroyed.

7. CONCLUSION

Local soil conditions affect the earthquake consequence on buildings. The number of buildings with heavy damage decrease with increasing bearing capacity. Liquefaction phonomena has not occurred in clayey areas, as expected. In the case of Arifiye, the proximity to the fault increases the damage, although high bearing capacity of soils are encountered. In addition, the proximity to the fault and the quality of the buildings, have a great importance in the areas where the same soil conditions are encountered. Nevertheless, the results of this study can be applied in similar areas of alluvial origins in the future and necessary precautions can then be recommended to avoid extensive damage. Through the study presented here, one can confidently warn the authorities of the concern regarding zones of possible damage leading to potential disaster dimensions in the future.

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