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GEOTECHNICAL ISSUES OF THE JUNE 27, 1998 ADANA-CEYHAN EARTHQUAKE

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SUMMARY

On June 27, 1998, a moderate earthquake measuring 5.9 on the Richter scale struck the alluvial plains of Cukurova at Adana-Ceyhan region of Turkey. The earthquake was felt as far as in Cyprus, Syria, Israel and Jordan. However, the severe shaking was within 150-km radius, and most of the damage was within 40-km radius of the epicenter. The earthquake resulted in 145 deaths, about a thousand injuries and significant damage to more than ten thousand structures. The coincidence of the earthquake epicenter and the fault with a very vulnerable geological surface formation, thick alluvial deposits of Ceyhan River containing loose sand layers, provided for a substantial thickness and areal distribution of liquefied sediments. Consequently, liquefaction associated ground deformations such as lateral spreading, flow failures, ground fissures and extensional cracking, sand boils, ground subsidence and slope failures were widespread. The extent of liquefaction also provided a significant amount of data useful for analyzing the effects of ground liquefaction on the structures typical of rural areas of Turkey. This paper presents and analyses the geotechnical aspects of this earthquake with the main emphasis on the observed liquefaction and associated ground deformations along with the earthquake characteristics. The observed liquefaction mechanisms provide valuable information on the seismic response of the alluvial soils covering most of the Cukurova plains, an important industrialized and agricultural area with more than 2 million inhabitants. A through analysis of case histories reported herein would establish a valuable benchmark for liquefaction susceptibility analyses of the river sedimented soils in the region. Despite the preliminary nature of the study, the observations indicate that liquefaction should be considered in seismic designs in the large areas of Cukurova Plains. Microzonation for Cukurova region is needed to improve risk assessments due to liquefaction and/or ground motion amplification.

INTRODUCTION

The June 27, 1998 Adana-Ceyhan Earthquake (Richter Magnitude, M_L = 5.9 and Surface Wave Magnitude, M_s= 6.3) occurred at 4:56 p.m. local time resulting in 145 deaths, about a thousand injuries and a significant damage to more than 10,000 mostly poorly constructed structures. The epicenter region where the earthquake was most strongly felt was “Cukurova”, which means “low plain” in Turkish. Cukurova is a large alluvial plain formed by the rivers Seyhan which runs through City of Adana (population: 1,200,000), and Ceyhan which runs near the Town of Ceyhan (population: 100,000). Covered with fertile soils with abundant water sources and located on the crossways of main trade routes, Cukurova has always been an important settlement area in the Asia Minor and Middle East for thousands of years. Today, with more than two million population, the area is one of the most important industrialized and agricultural regions of Republic of Turkey. After the June 27, 1998 earthquake, widespread soil liquefaction and associated ground deformations were observed especially in the low lying areas along the Ceyhan River, where the water table was very shallow and the soils were young alluvial deposits. The extensive nature of ground deformations observed during this earthquake, unseen before in any other recorded Turkish earthquake, significantly increased the public awareness to earthquake hazards associated with foundations and soils.

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This paper is a result of extensive post-earthquake field investigations and office studies of the authors, and presents the geotechnical aspects of this earthquake with a main emphasis on the observed liquefaction and associated ground deformations. The regional seismicity and tectonics, local geology, and main earthquake characteristics are also briefly discussed. An extensive version of this study can be found in Adalier and Aydingun (1998). Detailed information on the seismological and structural engineering aspects of this earthquake is given by Adalier and Aydingun (1998), ERD (1998), and METU (1998).

GEOTECTONICS AND SEISMICITY

Turkey lies within the Mediterranean segment of the Alpine-Himalayan orogenic system, which is the second major earthquake belt following the Pacific-Belt. According to the seismicity map of Turkey, 92% of the Turkish land, 95% of the population, and 98% of the industry lies on the seismically active ground. In this century alone, earthquakes in Turkey caused about 67,000 deaths, 150,000 injuries and destruction of 500,000 structures. Figure 1 shows the major tectonic elements of Turkey along with the earthquake epicenters for magnitudes Ms > 5.5 during the 1881-1998 period. The tectonics of Turkey is greatly influenced by the movements of Arabian, Eurasian, and African plates (Figure 1). The Arabian plate moves in NNE and pushes the Eurasian plate along the Bitlis Thrust and Fault Zone. Due to this continuing movement of the Arabian plate, the Anatolian block shifts westward along the North and the Northeast Anatolian faults. On the other hand, African plate moves in NE direction and collides with the Eurasian plate and subducts along the Hellenic-Cyprus Arc, somewhat retarding the westward movement of the Anatolian block and initiating its tendency to rotate to the SW. The interaction of these complex plate motions caused several E-W trending blocks bounded by oblique normal faults in Southwest Turkey. Consequently, this region covering the Cyprus-Hellenic Arc and the Aegean Graben System has very high seismicity. Although the frequency of seismic events within the North and the Northeast Anatolian Faults and the Eastern Anatolian Contractional province has been less, these tectonic belts have produced more destructive earthquakes, the biggest event being the 1939 Erzincan Earthquake of magnitude 8.0 (Ms). More detailed information on the tectonics of the region is given by McKenzie (1972), Ambraseys (1976), Jackson and McKenzie (1984), and Saroglu et al. (1987).

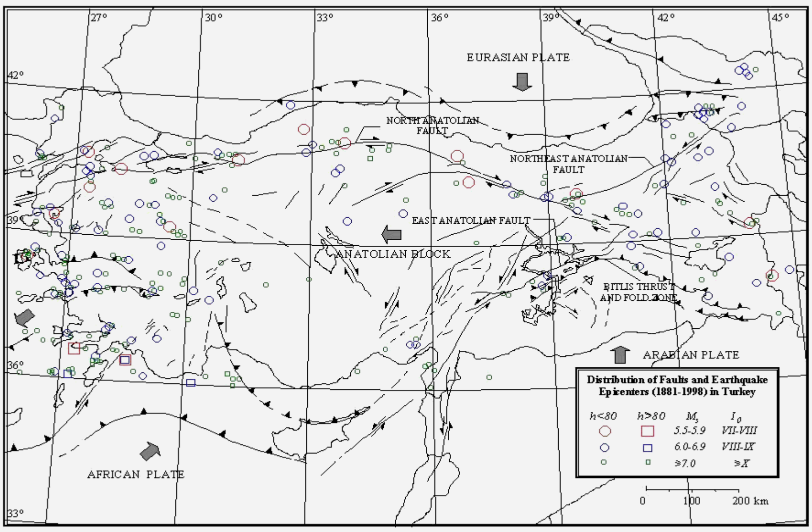

Figure 1: Major tectonic elements and distribution of epicenters for earthquakes with Ms>5.5 (during 1881-1998) in Turkey (created based on data by Barka 1992 and Kalafat 1995).

Tectonically, the Adana-Ceyhan earthquake zone is located at a quite complex transitional zone between the Cyprian Arc on the west, and the Bitlis Thrust and Fault Zone and the East Anatolian Fault on the east. Therefore, the region has tectonic characteristics of the Toros and Southeast Anatolian regions, and can be characterized as a fracture zone. Figure 2 shows the main tectonic and geological features in the earthquake-affected area. The main tectonic structures in this region are the Narlioren Fault, the Cicekli-Savrun Fault zone, and the Goksu Fault zone, all three lying mainly in the NE-SW direction [Kozlu, 1987]. The Adana-Ceyhan (June 27, 1998) earthquake was caused by the left-lateral strike-slip faulting of the Goksu Fault. More detailed information about this fault is given by Kozlu (1987) and ERD (1998). Being on a tectonically active zone, the Adana-Ceyhan region had experienced similar destructive earthquakes in 1945 (M_s = 6.5) and 1952 (M_s = 5.6).

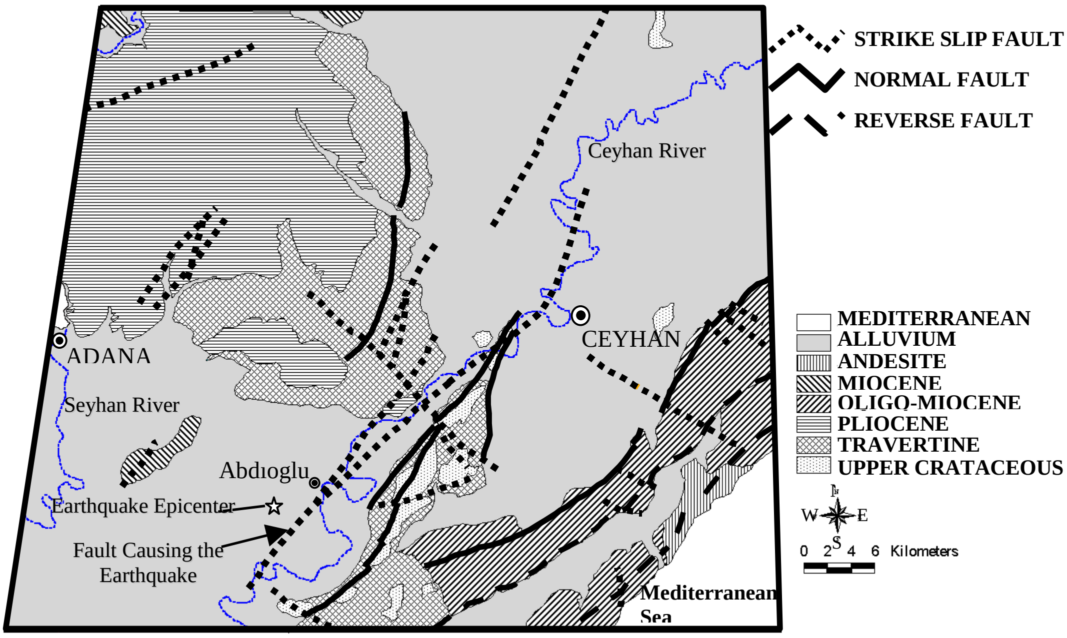

Figure 2: Main geological and tectonic elements of the earthquake region (modified after ERD 1998).

GEOLOGICAL SETTING

The main geological elements in the earthquake-affected area are shown in Figure 2. The earthquake epicenter was located on thick Quaternary alluvial soils covering most of the area where the earthquake was strongly felt. In the areas along the Ceyhan River, where the widespread liquefaction was observed, the ground was formed by young alluvial soils of mainly silty clay, overlying loose to medium dense fine sands with some silt and gravel content. According to some geologists of the Turkish Geological Survey, thickness of the sediments in this area varies from place to place, but is estimated to be at least 50 m at most locations. More detailed information about the geology/stratigraphy of the region is given by Schmidt (1961), Ayhan and Bilgin (1988), and Yeti (1988).

EARTHQUAKE AND STRONG GROUND MOTION

The instrumentally determined (by Turkish Earthquake Research Department-ERD based on regional seismogram data) earthquake epicenter was located at coordinates of 36.85N and 35.55E, at the outskirts of Abdioglu Village (see Fig. 2). The focal depth was estimated by ERD to be 23 kms. The earthquake magnitude was measured as: Richter Magnitude (M_L) = 5.9, Surface Wave Magnitude (M_s) = 6.3, and Seismic Moment (M_o) = 3.3×10^{18} N.m [ERD, 1998]. From the observed damage, an intensity of VIII on the MMI (Modified Mercalli Intensity) scale can be assigned to the affected areas in the vicinity of the epicenter. No foreshocks were detected before the earthquake. However, hundreds of aftershocks were measured with ten events greater than M_s = 3.8. Fortunately, none were big enough to cause further damage. The ground motion-acceleration record (digital data provided by ERD) nearest to the epicenter obtained at Ceyhan Station (32-km away from the epicenter at coordinates of 37.05N-35.81E) is shown in Figure 3. This station was founded on a flat ground of young alluvial soils; 1-1.5 m clayey silt with high organic content, 5-6 m soft silty clays, underlain by silty loose sand layers

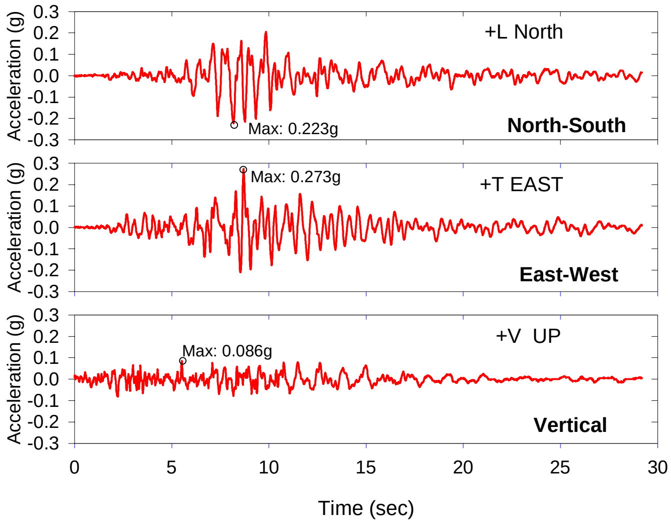

Figure 3: Acceleration time histories recorded at Ceyhan Station.

[ERD, 1998]. In general, similar soil conditions prevail at most areas where earthquake was effective. At this location, the duration of the strong ground motion was about 25 seconds with maximum accelerations of 0.223g in N-S, 0.273g in E-W, and 0.086g in the vertical directions. The bracketed duration (threshold acceleration of 0.05g) was about 13.5 and 16 seconds in N-S and E-W directions, respectively.

GEOTECHNICAL OBSERVATIONS

The authors obtained substantial amounts of data on the occurrence of ground failures including ground fissures, and sand boiling activity which are fundamental to clarify the mechanism of generation of liquefaction-induced ground deformations, by interviewing tens of local residents who witnessed the earthquake and by conducting post-earthquake site inspection during the first week after the earthquake.

Numerous rock-falls and landslides were reported in the nearby Cebelinur-Misis Mountains. No fault related surface fracturing was observed in the field, probably due to the rather soft and deep alluvial soil layer covering the area and the depth of the fault plane. Almost all of the significant geological deformations were associated with soil liquefaction. Most of the liquefaction related subsidence, lateral spreading, slope failures, and sand boils happened in the low lying areas of the epicentral region along the Ceyhan river (concentrated mainly within a zone of less than 1 km from the river banks). Liquefaction was observed as far as 50 km from the epicenter at the Buyuk Almagolu district. Based on the distribution of liquefaction during past earthquakes, several researchers have proposed upper bound relationships for farthest epicentral distance to a liquefied site versus the earthquake magnitude (Figure 4). It is clearly seen that, during the Adana-Ceyhan earthquake of June 27, 1997, liquefaction occurred far from the threshold predicted by all except Wakamatsu (1991). This further indicates the very high liquefaction susceptibility of the river sedimented young alluvial sands in the region.

Cursory field investigations revealed that in the region near the river where widespread liquefaction was observed, the ground was young alluvial soils generally consisting of 3.0 to 6.0 m of clayey silt and silty clay overlying a thick stratum of mainly fine sand with some silt and gravel content. In these regions, soil liquefaction and related lateral spread and uneven subsidence caused damage to some buildings and buried utilities. However, in general, the damage to man-made structures resulting from liquefaction induced ground failures was rather limited due to sparse development in many of the affected areas. Only one of the three dams in the vicinity (but far away from the widespread liquefaction areas) sustained minor damage in the form of longitudinal cracking at the crest of the earth filled section [METU, 1998]. The most striking and much publicized geotechnical aspects of 1998 Adana-Ceyhan earthquake were liquefaction associated sand boils (or “soil volcanoes” as termed by the locals) and lateral spreads. In the following paragraphs, due to the limitation of space, only these geotechnical aspects are presented along with a brief discussion on the effects of liquefaction on the built environment in the rural areas of Ceyhan.

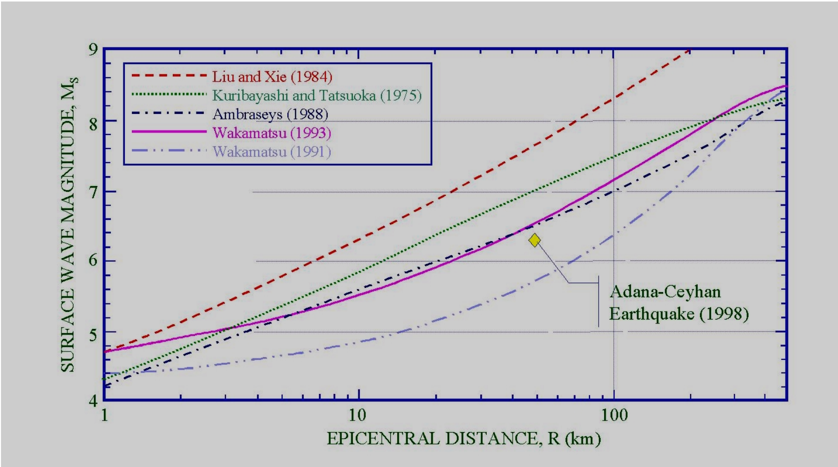

Figure 4: Epicentral distance to farthest liquefied sites predicted by different researchers and the Adana-Ceyhan case.

Sand Boils

One of the most commonly observed manifestations of soil liquefaction is the occurrence of sand boils along the ground surface. Soil craters or sand boils have been observed after every major earthquake (e.g., Charleston, 1886; San Francisco, 1906; Alaska and Niigata, 1964; Loma Prieta, 1989; Northridge, 1994; and Kobe, 1995). These volcano-like features indicate that the earthquake shaking has generated high excess pore water pressures within the soil deposit (liquefaction), causing upward flow of water laden with soil sediments. Such flow, which is apt to concentrate in channels of relatively higher permeability (due to soil inhomogeneity), eventually erupts to the surface in the form of a sand boil [Youd and Hoose, 1976; Elgamal et al., 1989; Adalier, 1992]. The outflowing water typically carries sediments from the liquefied and overlying layers.

During 1998 Adana-Ceyhan earthquake, liquefaction of loose sand layers were usually accompanied by the formation of sand boils due to the low permeability and cohesion of an overlying silty-clay layer. Sand boiling of different sizes were widespread in the areas of MMI VII-VIII, and some of them were witnessed in action by the locals. In some cases, the ejection of sand and water from fissures began during the earthquake shaking, and in others the fissures formed and grew right after the earthquake motions stopped. According to eyewitnesses, at some locations, jets of water/sand mixture rose up as high as 1.5 to 2 meters from the fissures. The height of the ejected water and sand diminished rapidly, but the ejection itself continued for up to an hour. However, at most locations sand boiling continued only for 10-15 minutes after the shaking of the ground had ceased.

Some of the most spectacular sand boiling activities were observed in the epicentral area near the Abdioglu Village (see Figure 2), where our site investigations were most comprehensive. According to the eyewitnesses, almost all of these sand boil activities were initiated towards the end of the shaking or immediately after and continued for 10 to 60 minutes. The ejected soil was found to spread evenly by run-off, and in some cases cover a large area of ground surface (e.g., at one site few kms from the village, a single elongated fissure ejected more than 600 m^3 sandy soil that covered more than 3000 m^2 surface area, Figure 5) around the fissure. The eyewitnesses reported water flooding reaching even much larger areas. The long duration of sand boil activity and the very large amount of fluid extruded to the ground surface suggests a high degree of liquefaction and slow pore pressure dissipation in the loose fine granular soil sublayer [Elgamal and Adalier, 1999]. At several sites, the materials brought up by the fluid were recognized to be the same as those of stratums encountered by nearby wells at depths greater than 4-5 meters (and in one extreme case 10 m, indicating the high degree of liquefaction). The ejected soil was distinctly gray in color (original ground-surface soil was brown). The grain size analysis showed that the ejected sediments were consistently fine sand with 10 to 15% fines content (mostly silt as noted by visual inspection). These fine particles appear to have remained in suspension after ejection, and were thus spread along the ground surface by the observed run-off process. The observed long duration of sand boil activity might have been influenced by the presence of this significant fine-particle content. Such fine particles were shown to reduce permeability and greatly prolong the post-liquefaction soil re-solidification phase [Adalier, 1992].

The lateral spreading appeared to have helped the occurrence of the sand boils by providing cracks of easy path in the overlying cohesive silty clay layer (acting as a capping layer) for the liquefied underlying sandy soils to escape. However, in the extreme case of large lateral spreading areas (high extensional strain usually encountered near river channel) too much cross-sectional area of cracking led to lower hydraulic gradients in the upflowing liquefied soils which was not enough to carry these soils to surface. On the other extreme side, in the areas where no lateral spreading existed, the sand boils tended to appear more in forms of circular volcanoes (craters) and were reported to eject soils to higher levels (jets reaching 2 m or more in the air) and stayed activated for longer periods compared to the elongated fissure type sand boils that were usually encountered in areas with moderate lateral spreading (minor to moderate extensional strain).

Figure 5: A major sand boil formation in the epicentral area.

Observed Lateral Spreading

Slope failures or collapses at many locations along the Ceyhan River were observed. Large volumes of soil both settled vertically and moved laterally towards the river (Figure 6), apparently due to the flow of the liquefied silty sand sublayer (i.e., lateral spreading). In many locations, long fissures in the ground parallel to the river channel (mainly concentrated within 200-300 m inland) indicated lateral spreading of the ground toward the river. Lateral spreadings due to mildly sloping ground far from any incised channel were also observed at several isolated sites, but to a much lesser extent.

Figure 6: Lateral spreads in an orchard along Ceyhan River near Abdioglu.

Effects of Liquefaction on the Built-Environment

Sand boiling by itself caused minor structural damage in few cases, and only when it led to localized differential settlements in foundation soils (e.g., due to sediment migration). In some cases, sand boils emerged at the periphery of buildings or were forced through exceptionally thin unreinforced concrete floors of the houses and literally filled them with fine sand and water.

Worst cases of lateral spreading (which involved not only large horizontal displacements but large vertical settlements as well) and slope failures were concentrated on the banks of Ceyhan River. Fortuitously, since most of the riversides in the earthquake-affected area were used for plantation alone, damage to man-made structures from these types of ground failures was rather limited. At areas away from incised river channels (or any other free face) and any slope where principal effect of liquefaction was vertical ground settlements, surprisingly little damage to man-made structures was observed. However, at areas not far from river channels or sloping ground, where liquefaction generated lateral ground displacements, foundation performance was typically poor. Tension cracks associated with lateral spreading and uneven subsidence displaced and fractured foundations of several homes, ruptured sewers, water pipelines and irrigation canals, damaged small concrete bridges and pavements. It was observed clearly in vast majority of these cases that the specific locations of these types of damages closely matched the zones of ground failures, suggesting that the ground failure rather than ground shaking was the dominant cause.

Although number of observations was rather limited due to sparse development in the affected area, buildings (mostly 1-2 story houses) with strong continuos mat foundations or thick strong base slab performed noticeably better in areas subjected to minor to moderate effects of liquefaction, such as lateral spreading, sand boils, and ground subsidence. In these instances, the foundation behaved as a diaphragm, preventing differential ground displacements from propagating upward into the superstructure. Where foundation or base elements were weak and not well tied together, differential ground displacements broke base slabs and pulled apart structures mainly fracturing the walls. However, no total collapse case related to liquefaction induced hazards were observed. Since majority of the severe liquefaction effects was concentrated along the river and only minor to moderate effects were observed at developed areas.

CONCLUSIONS

The observed liquefaction mechanisms provide valuable information on the seismic response of the alluvial soils covering most of the Cukurova plains, an important industrialized and agricultural area with more than 2 million inhabitants. Despite the preliminary nature of the study, the observations indicate that liquefaction should be considered in seismic designs in the large areas of Cukurova Plains. Microzonation for Cukurova region is needed to improve risk assessments due to liquefaction and/or ground motion amplification. A more thorough program of site investigation (e.g., accurate continuous boring data and CPT/SPT results) and laboratory dynamic testing is needed in order to further clarify the involved liquefaction mechanisms at the site. It was observed that the nature of the sand boils mainly depends on factors such as depth, volume and grain composition of the liquefied layer and the nature of inhomogenities in permeability in the overlying nonliquefied layer. Sand boiling by itself seldom caused structural damage only when it led to localized differential settlements (e.g., due to sediment migration). Ground straining associated with lateral spreads, rather than ground shaking caused the majority of the damages to buried utilities. Structures with well tied foundation elements survived well under the minor to moderate effects of lateral spreading.

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