Liquefaction and Ground Failure During the 1998 Adana (Turkey) Earthquake and Lab Model Simulations

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ABSTRACT

Although the June 27, 1998 Adana (Turkey) earthquake event was moderate in magnitude (5.9 on the Richter scale) and in the resulting damage, it contains significant valuable data for geotechnical earthquake engineering. 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-silt layers, accounted for 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. This paper presents and analyses the liquefaction and associated ground deformations observed during this earthquake. Field data on the occurrence of liquefaction-induced ground failures are used in conjunction with laboratory small-scale model testing results to help to improve our understanding of the mechanisms of generation of several forms of liquefaction-induced ground failure. In this context, valuable observations were made particularly for the sand boiling mechanisms.

KEYWORDS

Earthquake effects, liquefaction, ground failures, case history, model testing.

INTRODUCTION

On June 27, 1998, a moderate earthquake measuring 5.9 on the Richter scale struck the alluvial plains of Cukurova region of Turkey. The earthquake resulted in 145 deaths, about a thousand injuries and damage to more than ten thousand mostly poorly constructed structures (Adalier and Aydingun 2000). Although this earthquake was considered as moderate in magnitude and in the resulting damage, it contained significant geotechnical data for soil liquefaction and associated ground failures. The coincidence of the earthquake epicenter and the zone of energy release with young alluvial surficial sediments resulted in widespread soil liquefaction and associated ground failures, at a scale rarely seen in Turkey previously. Indeed, some of the most vivid and widely publicized examples of the effects of this earthquake were the liquefaction induced lateral spreads and the sand boils. The epicenter region where the earthquake was most strongly felt was "Cukurova", which means "low plain" in Turkish. Cukurova is a large alluvial plain-basin 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). Both of these rivers carry substantial flow of water and sediment throughout the year.

This paper presents and analyses the liquefaction and associated ground deformations observed during this earthquake. The reconnaissance team headed by the author obtained substantial amounts of data on the occurrence of ground failures including ground fissures and sand boiling activity. Tens of local residents who witnessed the earthquake were interviewed and a post-earthquake site inspection was conducted during the first week after the earthquake. 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. In this paper, the extensive field data obtained on the occurrence of liquefaction-induced ground failures is used in conjunction with laboratory small-scale model testing results to improve our understanding of the mechanisms of generation of several forms of liquefaction-induced ground failure. A set of test results especially on the stratified layer post-liquefaction response is presented illustrating the involved mechanisms. In this context, valuable observations were made particularly for the sand boiling mechanisms. The regional seismicity and tectonics, local geology, and main earthquake characteristics are also very briefly discussed. A detailed analysis of the seismological, structural and geotechnical engineering aspects of this earthquake can be found in Adalier and Aydingun (1998, 2000).

REGIONAL SEISMICITY AND GEOLOGY

Figure 1 shows the main tectonic and geological features in the earthquake-affected area. As seen, most of the active major faults in the region lay essentially in the NE-SW direction. The June 27, 1998 event was caused by the left-lateral strike-slip faulting of socalled "Goksu Fault" (ERD 1998). Being on a tectonically active zone, this region had experienced eight significant earthquakes with magnitudes between 5.5 to 6.2 during 1907 to 1952.

The earthquake epicenter was located on thick Quaternary alluvial soils covering most of the area where the earthquake was strongly felt (Fig. 1). In the areas along the Ceyhan River, where widespread liquefaction was observed, the ground was typically formed by young alluvial soils of mainly silty clay, overlying silty fine sands with occasional gravel. According to the Turkish Geological Survey, the thickness of the sediments in this area varies from 50 to 250 m with shear wave velocities typically ranging from 100 to 300 m/s.

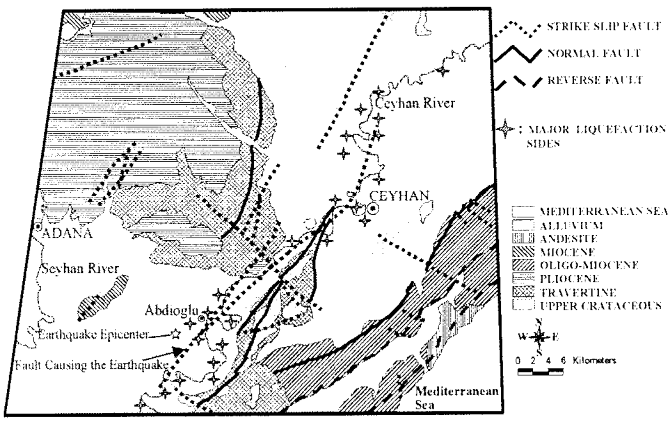


Fig. 1 Main geological and tectonic elements of the earthquake region (modified after ERD 1998) along with the major liquefaction sites observed after 1998 Adana earthquake.

THE EARTHQUAKE AND STRONG GROUND MOTION

Based on regional seismogram data, Turkish Earthquake Research Department-ERD estimated the earthquake epicenter at the outskirts of Abdioglu Village (see Fig. 1) and the focal depth as 23 kms. The earthquake was measured 5.9 on the Richter Scale (M_L) and had a Surface Wave Magnitude (M_s) of 6.3 (ERD 1998). From the observed damage, an intensity of VIII on the Modified Mercalli Intensity (MMI) 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 but none was strong enough to cause further damage or liquefaction. The ground motion-acceleration record (digital data provided by ERD) nearest to the epicenter obtained at Ceyhan Station (32-km away from the epicenter and about 10-km from the fault line) is shown in Fig. 2. 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. 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. Some important ground motion parameters for the Ceyhan strong motion is given in Table 1.

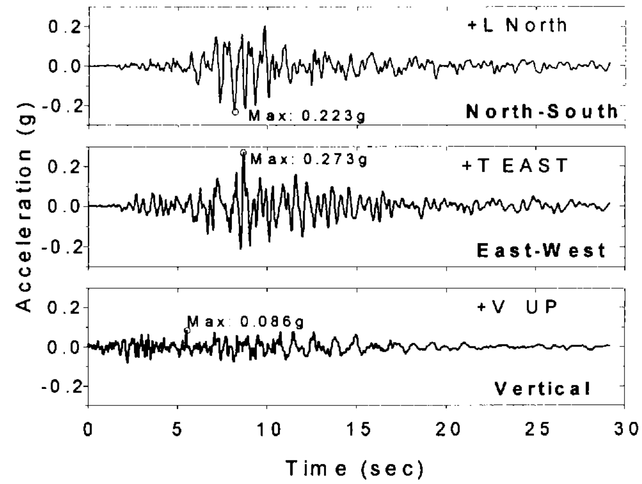


Fig. 2 Acceleration time histories recorded at Ceyhan Station.

Table 1 Some ground motion characteristics for Ceyhan.

Ground Motion Parameters	***North-South***	***East-West***
Peak Horizontal Acceleration, PHA	0.223g	0.273g
Max. Resultant PHA	0.32g	
Bracketed Duration[1]	13.5 s	16 s
Dominant Periods, T_p	0.65, 1, 2.9 s	0.5, 0.7, 1.2 s
Arias Intensity	0.91 m/s	1.02 m/s
rms acceleration[2], a_{rms}	0.064g	0.062g

1: Threshold acceleration of 0.05g. 2: For the bracketed duration.

GEOTECHNICAL OBSERVATIONS

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, although some rock-falls and landslides were reported in the nearby Cebelinur Mountains. The fault rupture and the projected location of the release of earthquake energy essentially followed the Ceyhan River, propagating from SW of Abdioglu (pop: 3,000) to NE of Ceyhan (see Fig. 1). As aforementioned, most of these areas were formed of river deposited alluvial soils containing loose to medium dense sandy soil sublayers blanketed by 3 to 6 m thick clayey silt and silty clay. The depth of the water table was rather shallow varying between 1 to 4 m. Consequently, the area of liquefaction development was essentially concentrated in the low lying areas of the epicentral and fault near-regions along the Ceyhan River (concentrated mainly within a zone of 1-2 kilometers from the riverbanks), stretching from 10-km SW to 50-km NE of the epicenter (Fig. 1). However, it should be noted that the incidence of liquefaction in a soil deposit at a particular site was determined by its manifestations on the ground surface (e.g., sand boils, lateral spreads, flows). The real extent of liquefaction during this earthquake was probably considerably more than that readily observed through these surface expressions. As at many sites (especially level-ground away from incised river channels or any other free face) the presence of a non-liquefiable intact surface layer is believed to have prevented liquefaction effects reaching the surface.

Subsurface Soil Conditions

Most comprehensive field reconnaissance for surface and subsurface information was made in the areas around Abdioglu Village, where some of the most spectacular liquefaction effects were observed. Subsurface soil investigations included mainly trench studies and some laboratory testing. In determining soil information, maximum use of exposures such as riverbanks and fault/cuts caused by large lateral spread of thick blocks of soil was made. Such features provided a natural trench to study the nature and the thickness of soil strata in some cases as deep as 6 m. Torvane and proving ring penetrometer tests on the walls of the trenches were used (for preliminary strength classifications) to estimate shear strength of cohesive soil and density of the cohesionless soil layers respectively. Due to the rural nature of the zone affected by ground failures, pre-earthquake boring logs are very rare. One standard penetration test (SPT) profile was found dating back to about four years before the earthquake. The boring was done at a location less than a km away from Abdioglu about 100 m from the river. Based on this pre-earthquake SPT boring and the post-earthquake trench data Fig. 3 presents a typical soil profile near Abdioglu. The spatial variation of soil conditions around Abdioglu was practically insignificant. Furthermore, cursory field investigations revealed that the soil conditions at most of the sites liquefied during this earthquake bear close similarity to the ones around Abdioglu. Typical grain size distribution curves for the underlying loose sand layer and ejected sand boil material are shown in Fig. 4. As seen, the liquefied layer was composed of poorly graded fine sand with about 10% fines, a soil type that has been categorized as highly susceptible to liquefaction (Iwasaki 1986). The ejected material and the soil in the liquefied silty sand layer were almost identical with the exception that the ejected material had typically 3-5% more fines and did not contain any gravel. This was obviously expected as the upward flow of water in sand boil channels would usually erode and carry some material from the overlying clay layer to the surface. However, this channel flow is usually not strong enough to carry gravel size particles to the surface.

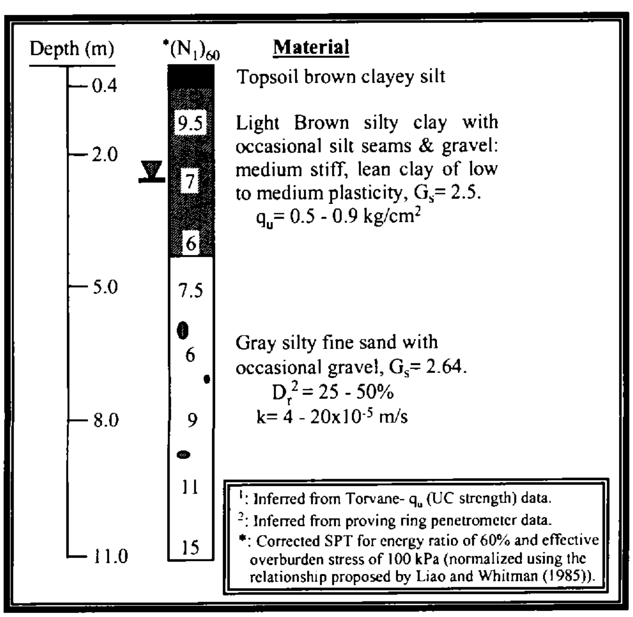


Fig. 3 A typical soil profile near Abdioglu.

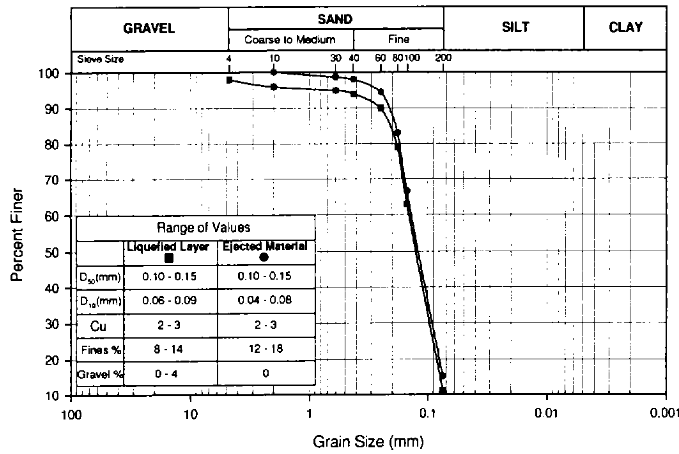


Fig. 4 Grain size distribution of liquefied layer and ejected material.

Liquefaction Potential

Liquefaction potential at Abdioglu site was evaluated using the cyclic stress approach (Seed et al. 1985). At locations where the cyclic shear stress exceeds the cyclic shear strength, liquefaction is expected to occur. The cyclic stresses induced in the sandy layer were estimated using the simplified equation presented by Seed and Idriss (1971):

$$\tau_{cyc} = 0.65 \frac{a_{\max}}{g} \sigma_v r_d \tag{1}$$

Where a_{max} is the peak ground acceleration, g is the gravitational acceleration, σ_v is the total overburden stress, r_d is a stress reduction coefficient that relates the behavior of a deformable soil mass to that of rigid mass. Within a close proximity of the epicenter and the fault line, this site is estimated to have experienced peak ground acceleration (a_{max}) of about 0.3g. This estimate is based on the: ground motion record (Fig. 2) at Ceyhan Station (which sits on similar soil formation not far from the fault) and the effects of ground shaking on structures and their contents located in the area. The reduction factor r_d was approximated using the Japanese practice where r_d= 1-0.015z (where z = depth in meters). The cyclic shear strength was estimated based on SPT-N values as suggested by Seed et al. (1985). Figure 5 shows the variation of the earthquake induced cyclic shear stress and the cyclic shear strength with depth. Based on this analysis, liquefaction did occur in at least the upper 10 m within the underlying sand stratum (ele. -4.5 to 10 m). The conditions of this example are representative of those in the Abdioglu area and many other areas along the Ceyhan River. The extensive liquefaction predicted in this example is consistent with what was actually observed in the 1998 earthquake.

Lateral Spreading, Slope Failures and Ground Fracturing

Fracturing induced by ground oscillations and lateral spreading was widespread. Numerous slope failures or collapses along the Ceyhan River were observed. Large volumes of soil both settled vertically (up to 4 m) and moved laterally (up to 10 m) towards the river (Fig. 6), apparently due to the flow of the liquefied silty sand sublayer (i.e., lateral spreading). Almost all the slides in the area were initiated within the underlying loose sand layer at depths varying from 3 to 8 m. In many locations, long fissures in the ground parallel to the river channel were observed as far as 300 m inland, indicating lateral spreading of the ground toward the river. Lateral spreading due to mildly sloping ground remote from free faces (e.g., incised channels) or known areas of cut and fill were also observed at several isolated sites, but to a much lesser extent. Permanent ground deformations were predominantly extensional although at several inland sites failure by compression was observed.

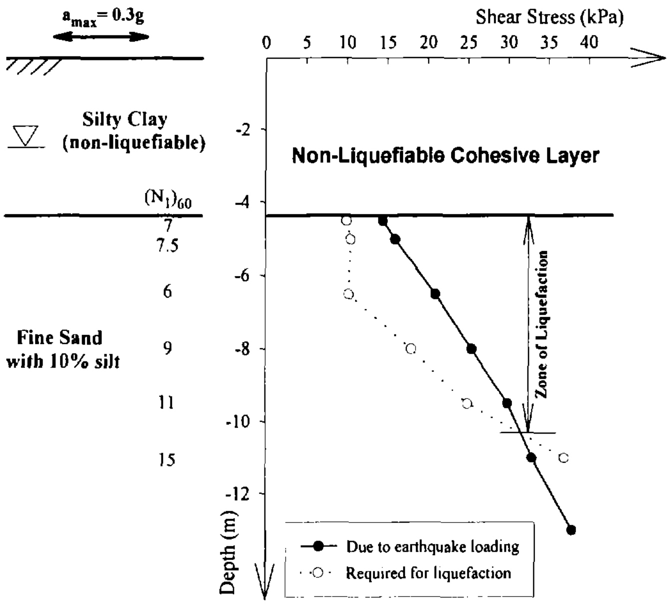


Fig. 5 Evaluation of liquefaction potential at Abdioglu.

Fig. 6 Lateral spreading along Ceyhan River near Abdioglu.

Sand Boil Formation

Liquefaction of loose sand layers due to the 1998 Adana earthquake was usually accompanied by the formation of sand boils due to the low permeability and cohesion of the overlying silty clay layer. In some cases, the ejection of sand and water from fissures began during the earthquake event (mostly towards the end). In other cases the fissures formed and grew immediately after the earthquake motion stopped. According to eyewitnesses, at some locations, jets of water/sand mixture from the fissures (sand boils) rose to as high as 2 meters above the ground (although up to 8 m was reported). The height of the ejected water and sand diminished rapidly, but the ejection itself continued for up to an hour or two. However, at most locations, sand boiling continued only for 10-15 minutes after the shaking of the ground had ceased. The grain size analysis (Fig. 4) showed that the ejected sediments were consistently fine sand with 12 to 18% fines content (mostly silt). 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, in some cases covering large areas of ground surface (e.g., at one site few kms from Abdioglu, a single elongated fissure ejected more than 600 m^3 sandy soil that covered more than 3000 m^2 surface area) around fissures. 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 surface expressions of the sand boils were mainly in three different forms. They appeared as individual volcanoes (tending to be relatively big), volcanoes coalescing in ridges (tending to be relatively small), and elongated masses along minor fractures induced by lateral spreading or ground oscillations. The lateral spreading appeared to have helped the occurrence of the sand boils by providing cracks, and hence an easy path through 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 the river channel), too much cross-sectional area of cracking led to lower hydraulic gradients in the upflowing liquefied soils which were not enough to carry these soils to the surface. On the other extreme side, in areas where no lateral spreading existed, the sand boils tended to appear more in the form of circular volcanoes (craters) and were reported to have ejected soils to higher elevations (jets reaching 2 m or more in the air). They also appeared to have stayed active 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). The diameter of these circular craters ranged from 5 to 50 cms. However, at a site NE of Ceyhan on a flat ground, significantly larger size craters (tended to be individual craters) were observed (dia.= 50-100 cm). Unfortunately, no eyewitness reports are available as to the timing of the initiation of these large sand boils. However, they appeared to have relatively small amounts of vented material (i.e., sediments from underlying liquefied layer). Cursory field investigations at this site revealed that the subsurface soil conditions were essentially similar to that of the Abdioglu (Fig. 3), with an exception that the overlying silty clay layer appeared to have higher plasticity (i.e., medium to high). Although it is recognized that the information collected in this study is insufficient to clearly determine all possible contributing factors to the large (and possibly delayed) sand boil formation, it appears that high plasticity and intactness of the blanket layer and large extend of liquefaction of the underlying layer are the necessary factors.

Sand boiling by itself caused minor structural damage in a few cases, but only when it led to localized differential settlements in foundation soils (e.g., due to sediment migration, Fig. 7). 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. The 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 the Ceyhan River. 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 the principal effect of the 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 the foundations of several homes (Fig. 7), ruptured sewers, water pipelines and irrigation canals, and damaged small concrete bridges and pavements. In the vast majority of these cases, it was clearly observed that the specific locations of these types of damage closely matched the zones of ground failure, suggesting that ground failure rather than ground shaking was the dominant cause.

The number of observations was rather limited due to sparse development in the affected area and did not permit a quantitative analysis of ground failure structure interaction. However, it was noticeable that the buildings (mostly 1-2 story houses) with strong continuous mat foundations or thick strong base slabs performed significantly better in areas subjected to minor to moderate effects of liquefaction, such as lateral spreading, sand boils, and ground subsidence. 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, as only minor to moderate effects of liquefaction were observed in developed areas.

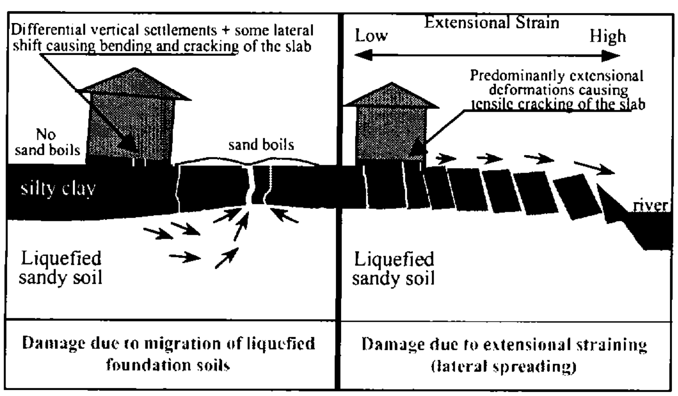
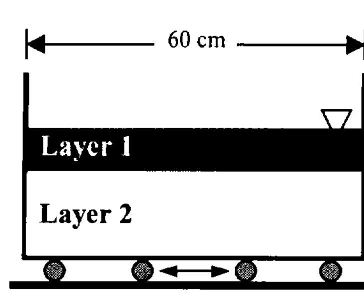


Fig. 7 Some liquefaction-induced structural damage mechanisms observed after 1998 Adana earthquake.

PRELIMINARY SMALL-SCALE SOIL MODEL TESTS

A series of qualitative small-scale 1-g tests were performed with the primary aim of exploring some of the basic post-liquefaction mechanisms involved in soil formations resembling to that of observed in the 1998 Adana-Ceyhan earthquake area (Fig. 3). A transparent rectangular box (a commercial fish tank of 60 cm x 30 cm x 45 cm) was employed. Dynamic excitation was imparted by rolling the box (supported on cylindrical steel tubes of 2.5 cm in diameter) on a roughened flat surface. Model preparation procedures explained previously by Adalier (1992) were employed generally. Based on previous experience (Adalier 1992), the imparted horizontal motion is estimated to be 0.5-0.7 Hz at 0.2-0.3g. Figure 8 shows the performed model tests conditions. Due to the limitation of space, only the main conclusions-observations from this on-going study will be presented herein, as follows:

i) Water gap or a very loose zone of soil develops at the interface between the sand (layer 2) and relatively impervious clay/silt layer (layer 1) as the liquefied sand reconsolidates. This accumulated water eventually escapes to the surface in the form of a sand boil (Fig. 9). Such loose zones in a soil domain with an initial static driving shear stress may lead to instabilities (e.g., slope failures and lateral spreading) as were observed during the 1998 Adana earthquake among others.
ii) Sand boils initiate under the less permeable blanket layer, and by "cavity formation" in the shaking induced fractures or zone of weaknesses travel up to regions of lower total head, e.g., ground surface (opposite of "piping").
iii) Highly plastic-cohesive and intact blanket layer is conducive to large and delayed (as cohesion inhibits the cavity formation) sand boils. Lesser amount of liquefied sediments is carried to the surface in delayed sand boils (as more pure water is available) as compared to sand boils that occur during or right after shaking (see Fig. 9).
iv) If the blanket layer is thick and absorbent enough and the liquefied stratum is thin enough to provide only a limited reservoir of water, then the sand boil may never reach to the ground surface.
v) The duration of sand boiling mainly depends on the settlement of the underlying liquefied layer (volume of water expelled due to densification) and number and size of boils formed.
vi) The nature of the sand boil mainly depends on the characteristics of both the overlying-blanket and the liquefied underlying layers, and the topography of the area and the intensity of ground shaking.



Test #	Layer #	Soil	Thickness (cm)	Plasticity
1	1 2	SC LS	5 20	Low --
2	1 2	SC LS	10 20	Low --
3	1 2	SC LS	15 20	Low --
4	1 2	C LS	5 20	High --
5	1 2	C LS	10 20	High --
6	1 2	C LS	15 20	High --

Legend: SC-silty clay; C-clay; LS-loose sand.

Fig. 8 Setup of the performed model tests.

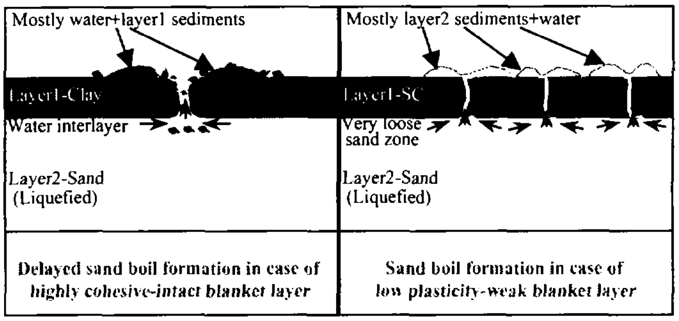


Fig. 9 The two main sand boil mechanisms observed in the model tests.

SUMMARY AND 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. After this earthquake, it was observed that the 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.

The small-scale model tests presented herein provided a very useful framework for conceptual understanding of some of the important post-liquefaction deformation mechanisms in stratified soil formation, such as observed in the 1998 Adana-Ceyhan earthquake area. The observations from these lab tests were consistent with the post-earthquake field observations. Although the available field and lab test data is insufficient to permit a quantitative analysis of most of the observed ground failure mechanisms, they certainly provide a useful general guide for this purpose. Accordingly, the following main observations were made:

i) The nature of the sand boil mainly depends on the characteristics of both the overlying-blanket (e.g., thickness, inhomogenities in permeability, cohesion-plasticity, and intactness) and the liquefied underlying layers (e.g., extent of liquefaction, post-liquefaction re-consolidation volumetric strains, and soil grain sizes), and the topography of the area and the intensity of ground shaking.
ii) During an earthquake, stratified soil systems are prone to generate water or very loose soil interlayers with extremely low shear strengths. If such a condition develops in a soil deposit with an initial static driving shear stresses (e.g., inclined ground or banks of a river) large flow deformations may be inevitable.

ACKNOWLEDGEMENTS

The author acknowledges the Engineering School of Eastern Mediterranean University (EMU), his former employer, for providing travel arrangements to conduct the earthquake reconnaissance and laboratory facilities for soil testing. Particularly the assistance of Mr. Ogun Aydingun of EMU during the reconnaissance and afterwards is gratefully acknowledged. The assistance of the Mayor of Abdioglu, Serefettin Ucar, personnel Yusuf Sarsilmaz and Mehmet Atun, Mayoral Engineer Haydar Beytimur of Yakapinar district, and the Adana Chamber of Architects and Civil Engineers personnel in the acquisition of the field data is gratefully acknowledged. Adana State Hydraulics Department (DSI) is acknowledged for providing some of the regional geological data. Finally, the support provided by Nanyang Technological University of Singapore, author's current employer, during the preparation of this document is acknowledged.

REFERENCES

Adalier, K. [1992]. "*Post Liquefaction Behavior of Soil Systems.*" M.S. Thesis, Rensselaer Polytechnic Institute, Troy, NY, USA.

Adalier, K. and O. Aydingun [1998]. "*June 27, 1998 Adana-Ceyhan (Turkey) Earthquake: Engineering Reconnaissance Report.*" Eastern Mediterranean University, N. Cyprus, Mersin-10, Turkey.

Adalier, K. and O. Aydingun [2000]. "Structural engineering aspects of the June 27, 1998 Adana-Ceyhan (Turkey) earthquake." J. of Engineering Structures, JEST 930, Vol. 23.

Elgamal, A.W., R. Dobry and K. Adalier [1989]. "Study of effects of clay layers on liquefaction of sand deposits using small-scale models." Proc. 2nd US-Japan Works. on Liq. Large Ground Def. and Their Eff. on Lifel., Rourke and Hamada (eds.), pp. 233-245.

ERD [1998]. "Preliminary Report on Adana-Ceyhan Earthquake." *Internet Web Site of Earthquake Research Department*, Directorate of Disaster Affairs, Turkish Ministry of Public Works and Settlement (in Turkish).

Iwasaki, T. [1986]. "Liquefaction and flow during earthquakes." Geotechnique, 43(3), pp. 351-415.

Liao, S.C. and R.V. Whitman [1985]. "Overburden correction factors for SPT in sand." J. of Geotech. Engrg., ASCE, 112(3), pp. 373-377.

Seed, H.B. and I.M. Idriss [1971]. "Simplified procedure for evaluating soil liquefaction potential." J. Soil Mech. and Found. Div., ASCE, 97(9), pp. 1249-1273.

Seed, H.B., K. Tokimatsu, L.F. Harder and R.M. Chung [1985]. "Influence of SPT procedures in soil liquefaction resistance evaluations." J. Geotech. Engrg., ASCE, 111(12), pp. 861-878.