13th World Conference on Earthquake Engineering
Vancouver, B.C., Canada
August 1-6, 2004
Paper No. 2921

# THE LIQUEFACTION AND FLOW OF VOLCANIC SEDIMENTS AT HANOÇAYIRI INDUCED BY THE MAY 1, 2003 BİNGÖL EARTHQUAKE

**Reşat ULUSAY[1], Ömer AYDAN[2], Masakatsu MIYAJIMA[3]**

## SUMMARY

An earthquake with a magnitude of 6.4 ($M_w$) occurred on May 1, 2003 in Bingöl province of Turkey and caused the loss of 176 lives. The earthquake triggered landslides, earth flows and rock falls, and very limited number of sand boils and liquefaction-induced lateral spreading also occurred. In this study, a typical lateral spreading of volcanic sediments at Hanoçayırı, which is located near the epicenter of the earthquake was described and evaluated. Silt and sand sized material, which is the weathering product of the tuffs covering the lower altitudes, liquefied during the earthquake. The loose material, which was also saturated due to heavy rains in the region within two weeks before the earthquake, flowed down approximately 600 m. This ground deformation was evaluated using the data both from geotechnical boreholes and laboratory geomechanical tests. Back analysis of the liquefaction was carried out to estimate the minimum value of the horizontal ground acceleration ($a_{max}$), which might have caused to initiate liquefaction. Back analysis of liquefaction using the method based on field performance data indicated that $a_{max}$ values between 193 gal and 263 gal seem to be necessary for initiating the liquefaction at the site.

## INTRODUCTION

The magnitude $M_w$=6.4 earthquake struck 3:27 a.m. local time on May 1, 2003 with a epicenter located about 15 km N-NW of Bingöl city of Turkey (Figure 1) and was officially called Bingöl Earthquake. The province was also hit by an earthquake, which occurred in 1971 and caused heavy damages and loss of life particularly in Bingöl. Most of the 176 fatalities and 520 injuries occurred in Bingöl city. The earthquake trigged landslides, earth flows and rock falls, which were generally concentrated close to the epicenter were reported (Aydan et al. [2]). A very limited number of liquefaction and liquefaction-induced lateral spreading and ground flow were also observed some locations (Figure 2).

[1]Professor, Hacettepe University, Geological Engineering Department, Ankara, Turkey.
Email: resat@hacettepe.edu.tr
[2]Professor, Tokai University, Marine Civil Engineering Department, Shizuoka, Japan.
Email: aydan@scc.u-tokai.ac.jp
[3]Professor, Kanazawa University, Civil Engineering Department, Kanazawa, Japan.
Email: miyajima@t.kanazawa-u.ac.jp

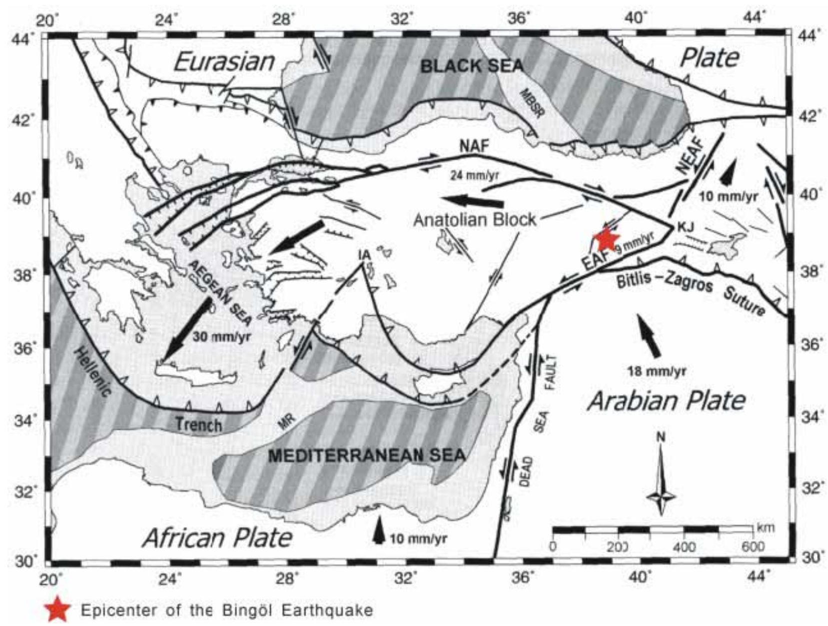
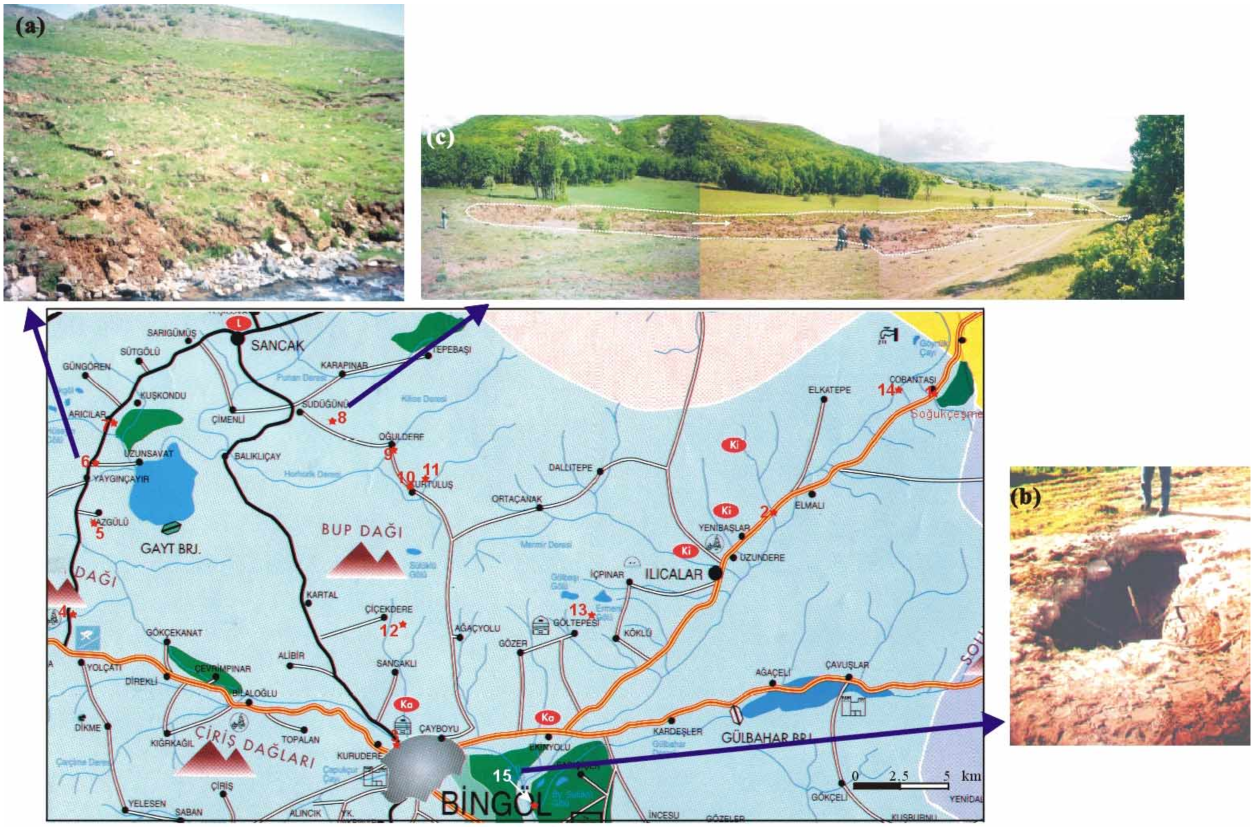



Figure 1. Simplified tectonic map of the Eastern Mediterranean Region ( Gülen et al. [1]) and location of the 2003 Bingöl earthquake.

Since these deformations occurred in rural areas, they did not cause any structural damage. A small lateral spreading near Yaygınçayır village occurred on a stream bank with an inclination of about $10^0$-$15^0$ (Figure 2a). The failure pattern and a local sand accumulation suggested that this failure could probably be due to liquefaction. At this location, the displacements due to lateral spreading in three zones with a total width of 60 m ranged between 16.5 cm and 30 cm, respectively. Very local sand boiling also occurred at Bingöl Plain at a field consisting of alluvial deposits (Figure 2b). The second but a significant lateral spreading occurred at a location called Hanoçayırı, which is located very close to the epicenter of the earthquake (Figure 2c). It was typical and interesting particularly due to type of the failed material, which is the weathering product of tuffs. In this study, this ground deformation is described evaluated. In addition to deformation measurements taken at the site, two geotechnical boreholes were drilled and goemechanical laboratory tests were performed both on the ejected and flowed materials, and SPT samples. Back analysis of the liquefaction was carried out to estimate the minimum value of the $a_{max}$ which might have caused to initiate liquefaction.

## GEOLOGY AND SEISMOTECTONICS

The Bingöl province is located at the Upper Murat Section of the East Anatolian Region of Turkey, where there are closely or widely spaced ridges, cut-through valleys, and some plains. The earthquake-affected region is mainly covered by the Upper Oligocene-Lower Miocene aged volcanic rocks as seen from the simplified geological map in Figure 3. Various metamorphic rocks at the south, and acid intrusions, serpantinites, ophiolites and flysch rocks in different ages, Neogene continental deposits and Quaternary-aged old and new alluvial deposits with limited extent are also observed in this region. Basalts and andesites mainly represent these volcanic rocks (Seymen and Aydın [4]). Basalts exhibit pillow and columnar structures and spheroidical weathering. Mostly tuffs are found interbedded with lava flows. The Bingöl Plain has been formed by the lateral jointing of the composite alluvial cones. The Quaternary deposits are only observed in this plain and consist of Pliocene terrace deposits and recent alluvium.




1,2,3,5,9: Rotational slide; 4,7,10,12,13: Rock fall; 6,8: Liquefaction and lateral spreading;1,14,8: Flow; 15: Liquefaction

Figure 2. Locations of the liquefaction and liquefaction-induced ground failures: (a) lateral spreading near Yaygınçayır village, (b) liquefaction at Bingöl Plain, and (c) lateral spreading and flow failure at Hanoçayırı.

The earthquake-affected region is located at a tectonically very active part of Turkey and two main strike-slip faults, North Anatolian Fault (NAF) and East Anatolian Fault (EAF), are intersected (Figure 4). While NAF is a right lateral-strike slip fault zone, EAF is left-lateral strike slip fault zone. The EAF is composed of a number of segments trending NE-SW. Of the three segments are located in the earthquake region and its close vicinity. These are Göynük, Genç and Palu faults as shown in Figure 4. There are also conjugate faults striking NE-SW and NW-SE parallel to the NAF and EAF, respectively. These faults bound the earthquake affected region from its south, west and northwest. NE-SW trending faults, which possess left-lateral strike slip characteristics, are Sancak-Uzunpınar, Kilisedere and Çevrimpınar faults (Figure 4). According to active fault map of the Turkey (Şaroğlu et al. [5]) NW-SE trending Bingöl-Karakoçan and Sudüğünü faults are the right-lateral strike slip faults in the earthquake region.

Bingöl and its vicinity were assigned to the first degree zone on the seismic map of Turkey prepared by the Earthquake Research Department of Turkey (ERD [8]). In the last century, many earthquakes affected particularly the provinces of Erzincan, Bingöl and Tunceli. The 1957 ($M_s$=5.1), 1968 ($M_s$=5.7) and 1995 ($M_s$=5.7) Kigi earthquakes and May 22, 1971 ($M_s$=6.8) Bingöl earthquake are the earthquakes resulted in loss of life and heavy damages in the investigated earthquake region. The 1971 Bingöl earthquake caused a total loss of 775 people and heavy damages particularly in Bingöl city. Its epicenter was 10-12 km at the east of Bingöl and causative fault was the Göynük segment of the EAF (Aktan et al. [9]; Seymen ve Aydın [4]). During the 1971 earthquake, surface ruptures and liquefaction were also observed (Seymen ve Aydın [4]).

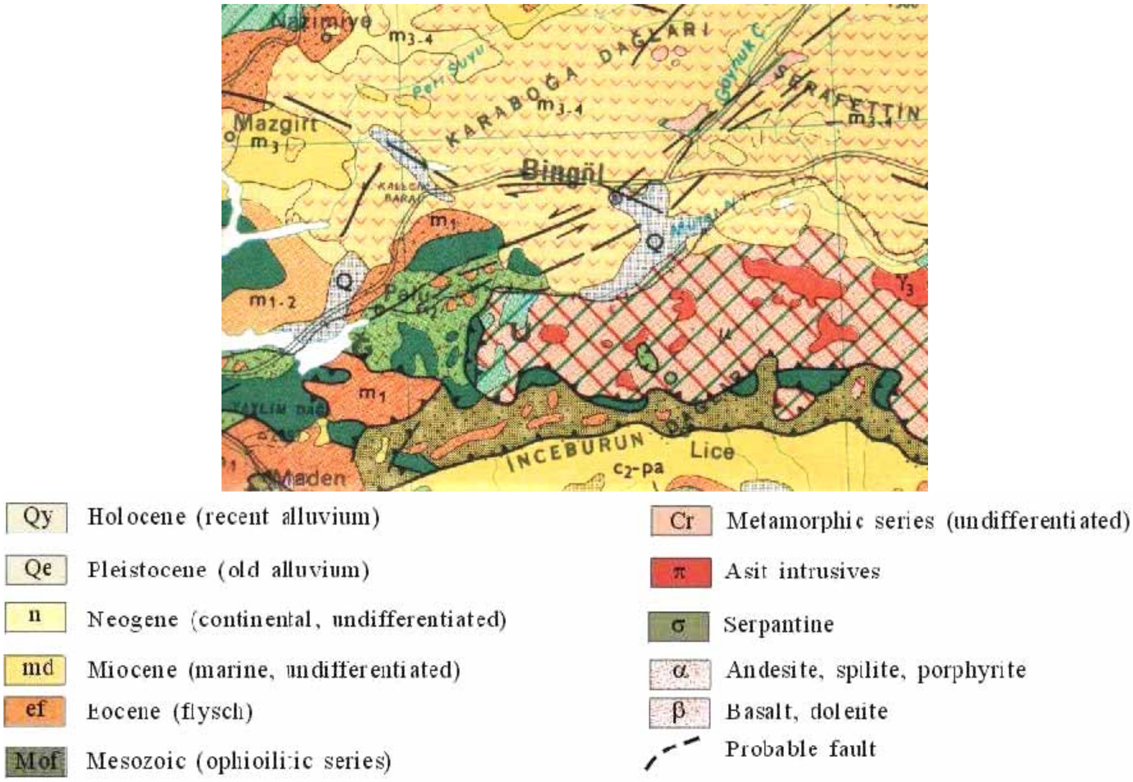



Figure 3. Geological map of the Bingöl province (after MTA [6]).

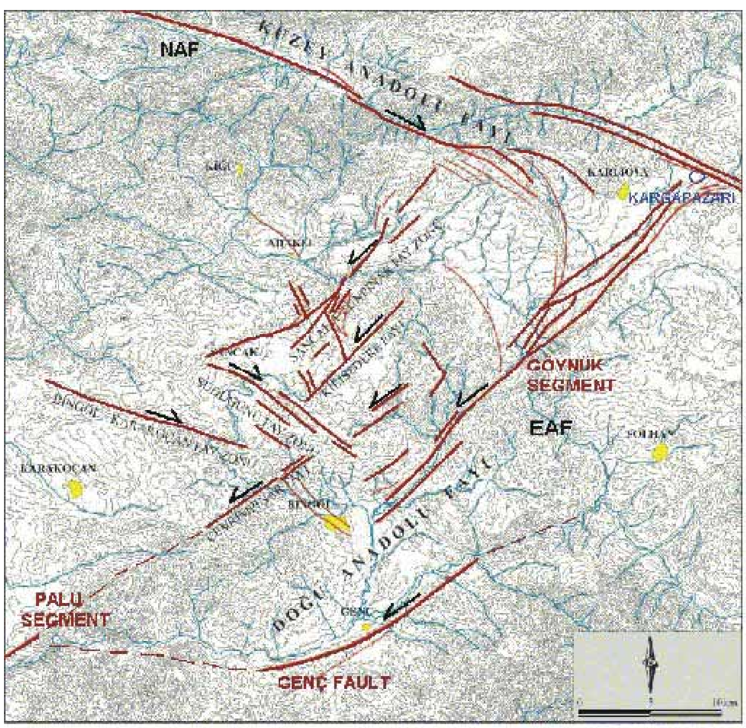



Figure 4. Active faults in the earthquake affected region (modified from Emre et al. [7]).

## CHARACTERISTICS OF THE EARTHQUAKE AND STRONG GROUND MOTION

The main shock of the Bingöl earthquake occurred at 03:27 on Turkish Standard Time on May 1, 2003. Various institutions in Turkey and other countries determined the hypocenter of the earthquake and its faulting mechanism. The locations of the epicenters predicted by various institutions are mostly scattered at the north of Bingöl city closed to Hanoçayırı location. Table 1 compares the hypocenter parameters of focal plane solutions. The focal plane solutions suggest a right-lateral strike slip fault. However, they indicate two possible faults striking in NW-SE and NE-SW.

Table 1. Parameters of the 2003 Bingöl earthquake estimated by different institutes

| Institute | Latitude | Longitude | Depth (km) | Magnitude | Strike | Dip | Slip |
|---|---|---|---|---|---|---|---|
| KOERI | 39.01 | 40.49 | 10 | $M_s$=6.4 | NP1 225 | 90 | 28 |
| | | | | | NP2 135 | 62 | 180 |
| ERD | 38.94 | 40.51 | 6 | $M_d$=6.1 | - | - | - |
| USGS | 38.99 | 40.46 | 10 | $M_w$=6.4 | NP1 64 | 88 | 0 |
| | | | | | NP2 154 | 90 | -178 |

KOERI: Kandilli Observatory and Earthquake Research Institute

The distribution of the aftershocks with M>4.1, which was released by KOERI (2003), shows a trend in NW-SE direction, which has good agreement with one of the fault striking in NW-SE as obtained from local plane solutions. Although no evident surface rupture was observed, some small surface cracks observed by the authors at Hanoçayırı location very close to the epicenter and the epicenters' distribution suggest that the Sudüğünü fault striking in NW-SE direction (Figure 4) may be the probable causative fault.

The main shock of the earthquake was recorded by GRS-16 type accelerometer with three components in one-storey building next to the local office of the Ministry of Public Works and Settlement in Bingöl City. This station is at a distance of about 15 km away from the epicenter of the earthquake and founded on a flat-lying hill composed of stiff terrace deposits. The NS, EW and UD accelerations recorded at this station are 545.5 gal, 276.8 gal and 472.3 gal, respectively. The UD component is also quite high probably due to one of the characteristics of inland earthquakes. Collapsed and heavily damaged buildings in Bingöl are concentrated on the cliff sides of terraces, which are about 40-45 m high and have slope angles of $45^0$-$50^0$, and are bounded by two creeks. This situation suggests a possible amplification at the cliff sides due to topographical effects. Although topographical effects may also be responsible from the considerably high peak horizontal ground accelerations observed at the Bingöl station which is located close to the cliff side (Aydan et al. [2]), it should be representative strong motions acted at the heavily damaged areas in Bingöl city.

## ASSESMENT OF LIQUEFACTION AND ASSOCIATED GROUND DEFORMATIONS

During the 2003 Bingöl earthquake a lateral spreading occurred at a location called Hanoçayırı, which is very close to the epicenter. It is surrounded by topographical undulations consisting of white-to-beige colored tuffs. Silt and sand sized loose surficial material, which is the weathering product of the tuffs, cover the lower altitudes. The presence of this shallow-seated, silt and sand sized, non-plastic material and shallow groundwater table, which was evident during site observations at a water well very close to the failure, resulted in highly susceptible environment to liquefaction. Inclination of the ground was about $3^0$-$4^0$, where liquefaction-induced lateral spreading was transformed into a flow type movement (Figure 5a). The loose surficial material, which was saturated due to heavy rains occurred within two weeks just before the earthquake, transformed into a flow and flowed down in S55W direction about 300 m and then directed towards SE. A set of ground fractures associated with lateral spreading, which was resulted in 30-35 cm vertical drops (Figure 5b) and separations of 10-20 cm in the ground behind the crest and near the flanks of the failure (Figure 5c), was observed. The total amount of the fracture separation was estimated about 1 m from the measurements taken at the crest and its vicinity. The length, width and maximum depth of the flow were approximately 600 m, 35 m and 3 m, respectively. Traceable sand accumulations, observed near the eastern flank of the failure and in the lateral spreading area, were evaluated as the indicator of liquefaction.

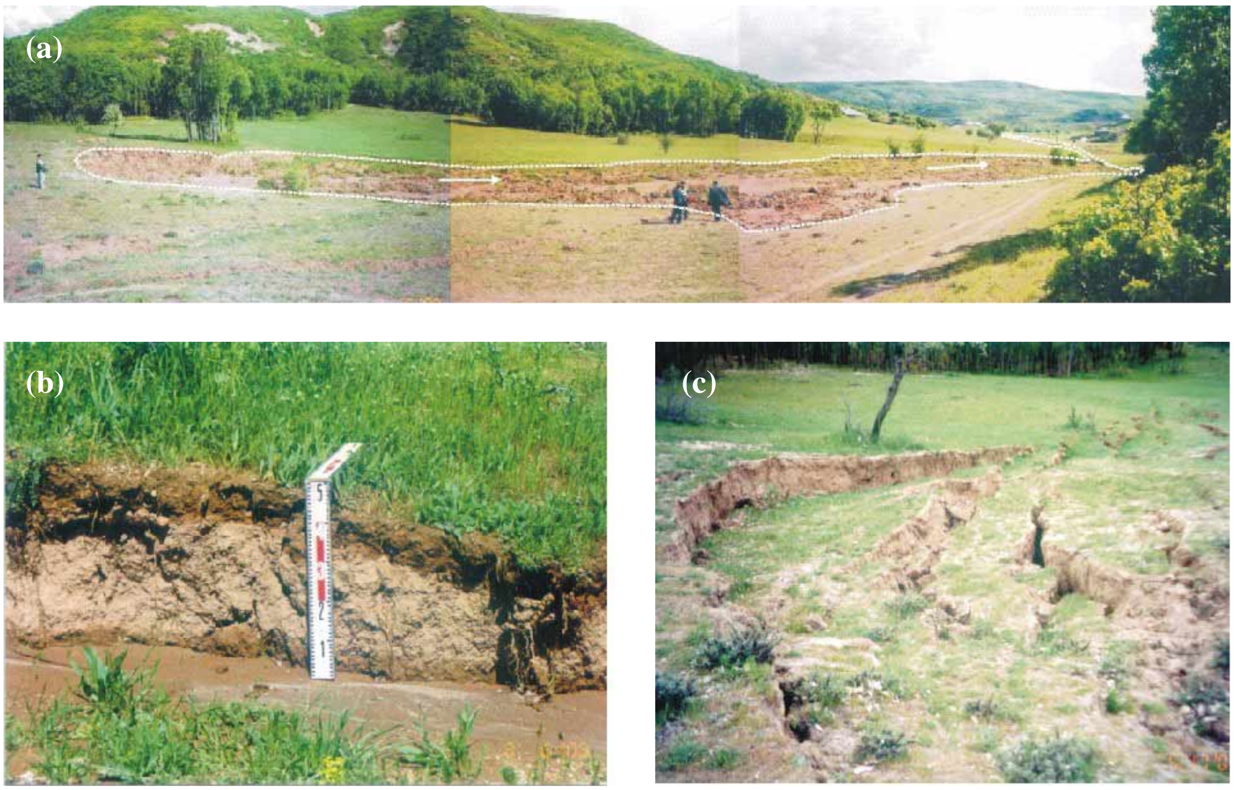



Figure 5. (a) A general view of the lateral spreading and flow at Hanoçayırı, (b) vertical drops and (c) separations due to lateral spreading.

A total of three specimens from the ejected and flowed materials were collected for laboratory tests. In addition, two boreholes (denoted by H1 and H2), 6.65 m and 5.25 m deep, respectively, were drilled at a few meters behind the crest and western flank of the failure in June 2003 to assess the subsurface conditions. The distance between the boreholes was about 100 m. The whole sample mineralogy, based on the XRD analysis, indicated that these three samples from the surface mainly comprised of feldspars, and lesser amount of quartz and calcite. This composition and site observations suggest that the liquefied and flowed material was the weathering product of the tuffs surrounding the Hanoçayırı location.

Specific gravity of two ejected and one flowed soil samples was obtained as 2.5 and 2.4, respectively. Grain size distribution curves of these samples were plotted onto the grain size distribution of liquefiable soils proposed by Japan Port and Harbor Research Institute [11]. It is evident from Figure 6 that sand sized material with fines content of 7-12 % (SP group soil) is dominant in the liquefied soil, and the flowed surficial material involves slightly greater amount of fines (SM group soil). However, all the samples fall into the limits designated by most liquefiable. Three specimens prepared from each sample obtained from the surface were tested in shear box at a shear strain of 0.25 mm/min. Failure envelopes of all samples show a consistency indicating that the samples are cohesionless soils with internal friction angle ranging between $42^0$ and $44^0$.

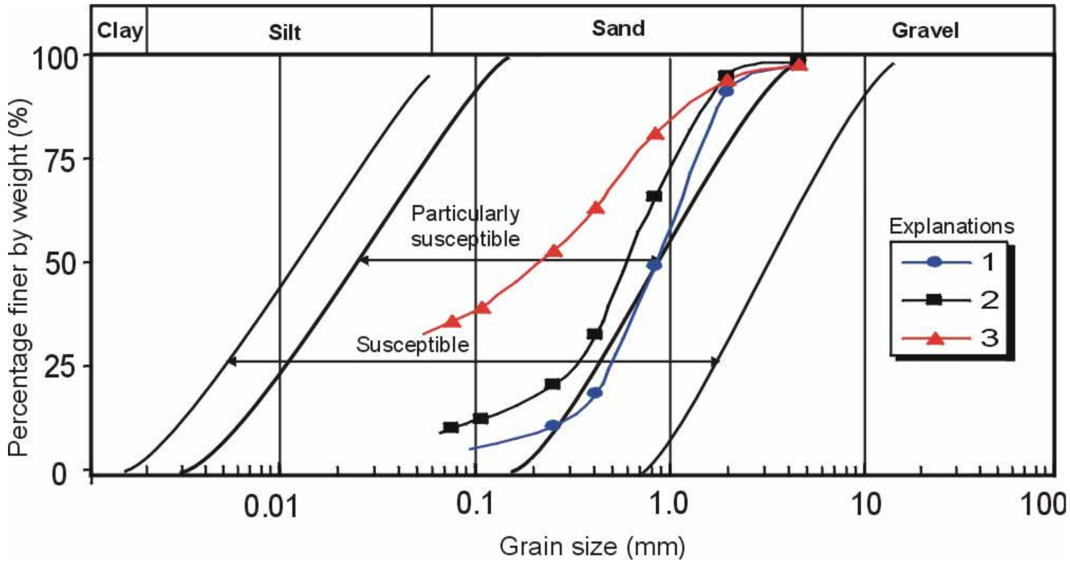



Figure 6. Grain size distribution of the ejected (samples 1 and 2) and flowed (sample 3) material.

As noted from the simplified geotechnical borehole logs (Figure 7), the uppermost level of the sequence, approximately between 0 and 5.5 m, consists of light brown-to-beige, very loose-to-loose sand size material originated from the tuffs. This material is moist-wet, fine-to-coarse grained, and involves angular-sub angular grains with some fines. SPT tests were carried out at every 50 cm interval throughout both boreholes. In this material, very low SPT-N values, which ranged between 2 and 8, and generally between 2 and 4 near to the surface, indicated a very loose state suitable for liquefaction. The bedrock (fresh tuff) lies about 5 m from the surface. The groundwater table was 5.5 m and 2.25 m at the time of drilling (4 weeks after the earthquake) at the locations of boreholes H1 and H2, respectively. If the relative elevations of both boreholes and topographical inclination are considered, it can be concluded that position of the groundwater table was nearly parallel to the surface at the time of drilling. However, it is expected that depth of the groundwater table could have been shallower during the earthquake than that measured from the boreholes, probably due to heavy rains occurred within two weeks before the earthquake.

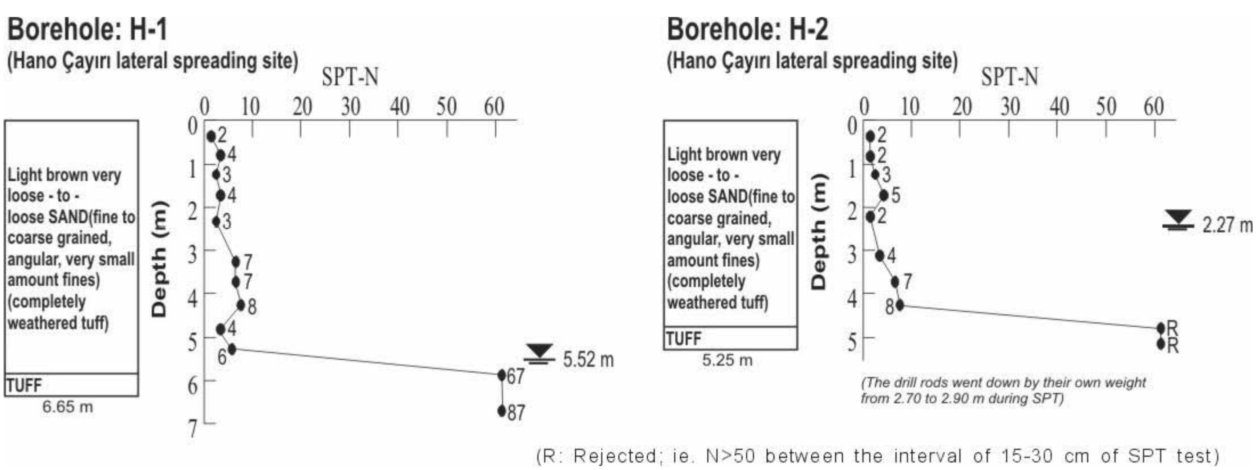



Figure 7. Simplified geotechnical borehole logs at Hanoçayırı.

The laboratory soil classification tests on the SPT samples suggest that the loose and shallow-seated material overlying the bedrock falls into SM group, which is defined as silty sand. This material also includes silt and clay sized fine grains in the range of 24-43 % with ignorable amount of gravel, and shows a close similarity to those of the soils collected from the ejected and flow materials. Figure 8 depicts the grain size distribution range of the SPT samples from both boreholes. These samples fall into the limits designated by most liquefiable.

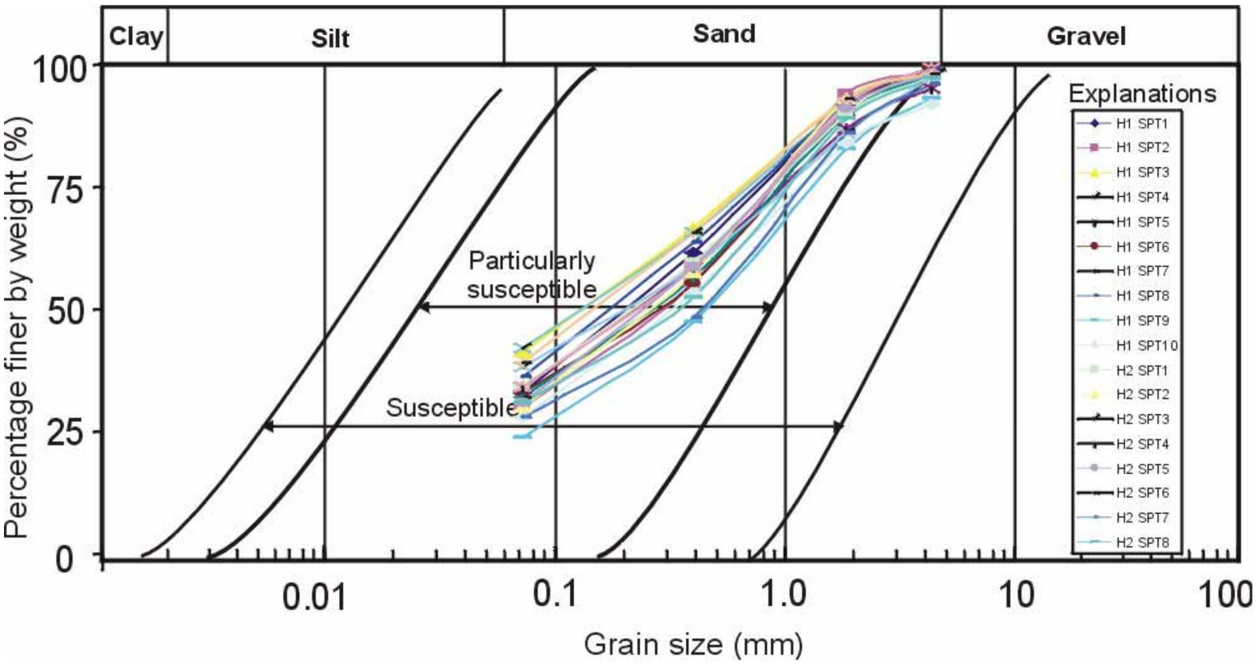


Figure 8. Grain size distribution of the SPT samples.

Back analysis of the liquefaction was carried out to estimate the minimum value of the horizontal ground acceleration ($a_{max}$) which might have caused to initiate liquefaction at Hanoçayırı. For the purpose, the data from both boreholes and the laboratory tests, and the method based on the filed performance data (Youd et al. [12]) as a means of evaluating $a_{max}$ were employed. Necessary corrections for the SPT-N, energy ratio and overburden pressure were all considered and normalized SPT-N values $(N_1)_{60}$, were calculated. Assuming that the factor of safety against liquefaction is equal to unity at the time of liquefaction, $a_{max}$ values for each SPT interval, which lies below the groundwater table, was found. Depending on the SPT-N values and fines content, $a_{max}$ values ranging between 193 gal and 263 gal were calculated. Based on the back calculations, an $a_{max}$ value of about 200 gal seems to be necessary for initiating the liquefaction at the site. If very close location of Hanoçayırı to the epicenter of the earthquake is remembered, an $a_{max}$ value, which was probably much greater than those back calculated, might have affected Hanoçayırı and its vicinity. The above mentioned assessments suggest that liquefaction at Hanoçayırı has occurred in a saturated silty sand of surficial weathering product of the tuffs with a thickness of 5 m and the liquefied material laterally spreaded, then it has transformed into a flow type movement with the contribution of its very high moisture content increased after heavy rains.

In this study, a comparison was also made between the observed cumulative fracture separations at Hanoçayırı and the results from a prediction equation suggested by Hamada et al. [3]. These investigators predict the amplitude of horizontal ground deformation only in terms of slope and thickness of liquefied layer as given below.

$$D = 0.75\ H^{0.5}\ \theta^{0.33} \tag{1}$$

Where D is the horizontal displacement (m), θ is the slope (%) of ground surface or base of liquefied soil and H is the thickness (m) of saturated zone below the ground surface. By considering that the thickness of the saturated zone below the ground surface in borehole H2 is 2 m and θ is 1%, the magnitude of the lateral displacement was estimated as 1.05 m from Eq.1. This predicted value is similar to the total crack separation at the crest of the flowed ground body. Nevertheless, such a simple procedure is not suitable to predict the flow movement of liquefied ground.

## CONCLUSIONS

In this study, a large-scale lateral spreading of volcanic sediments, induced by the May 1, 2003 Bingöl earthquake in Turkey is described and evaluated. The most interesting features of this failure are that it occurred in a soil originated from pyroclastic volcanics and transformed into a flow type movement after liquefaction-induced lateral spreading has occurred. Based on the assessments both from site investigations and laboratory tests, it can be concluded that liquefaction has occurred in a saturated silty sand layer, which is the weathering product of tuffs and has a thickness of about 5 m, and the liquefied material laterally spreaded about one meter along a very gentle slope, then it has transformed into a flow type movement. Heavy rains in the region within two weeks before the earthquake are considered to contribute to softening of the surficial materials before they subjected to dynamic loads and made easy such a failure to transform into mudflow. Since these deformations occurred in rural areas, they did not cause any structural damage.

Back analysis of the liquefaction indicated that the minimum value of the horizontal ground acceleration, which might have caused to initiate liquefaction, should be around 200 gal. In addition, the observed ground deformations due to lateral spreading showed a good consistency with that found from a prediction equation.

## ACKNOWLEDGEMENTS

The authors would like to their sincerely thanks and gratitude to the Japan Society of Civil Engineers who financially supported the authors for visiting the earthquake region and encouraged publishing their findings and observations.

## REFERENCES

1. Gülen L. Pınar A. Kalafat D. Özel N. Horasan G. Yılmazer M. Işıkara M. “Surface fault breaks aftershock distribution and rupture process of the 17 August 1999 Ýzmit, Turkey earthquake”. Bulletin of Seismological Society of America 2002; 92(1): 230-244.
2. Aydan Ö. Ulusay R. Miyajima M. “The Bingöl Earthquake of May 1, 2003” Report of Japan Society of Civil Engineers, 2003; http://www.jsce.org.jp/report/19/frame.html.
3. Hamada M. Yasuda S. Isoyama R. Emoto K. “Study on liquefaction induced permanent ground displacements”. Report for the Japan Association for the Development of Earthquake Prediction., 1986
4. Seymen I. Aydın A. “Bingöl deprem fayı ve bunun Kuzey Anadolu Fay Zonu ile ilişkisi”. MTA Dergisi. 1972; 79: 1-8 (in Turkish).
5. Şaroğlu F. Emre Ö. Kuşçu Ý. “The East Anatolian fault zone of Turkey”. Annales Tectonicae 1992; Special Issue-Supplement to Volume VI: 99-125.
6. MTA. http://www.mta.gov.tr/.2003.
7. Emre Ö. Herece E. Doğan A. Parlak O. Özaksoy V. Çıplak R. Ozalp S. “1 Mayıs Bingöl Depremi” http://www.mta.gov.tr/Bingöl/Bingöl.asp.2003 (unpublished report in Turkish)

8. ERD. http://www.deprem.gov.tr.2003
9. Aktan H. Bayülke N. Gül A. Ergünay O. Tabban A. Yurdatapan O. "22.5.1971 Bingöl Depremi". Deprem Araştırma Dairesi, Ankara, 1972; 79 p (in Turkish).
10. KOERI. Kandilli Observatory and Earthquake Research Institute. "Bingöl earthquake" http://www.koeri.boun.edu.tr/, 2003
11. Japan Port Harbor Research Institute. "Handbook on Liquefaction Remedition of Reclaimed Land". A. A. Balkema, Rotterdam, 1997: 312 p.
12. Youd TL. Idriss IM. Andrus RD. Arango I. Castro G. Christian JT. Dobry R. Finn WDL. Harder LE. Hynes ME. Ishihara K. Koester JP. Liao SSC. Marcuson WF. Martin GR. Mitchell JK. Moriwaki Y. Power MS. Robertson PK. Seed RB. Stokoe KH. "Liquefaction resistance of soils: Summary report from the 1996 NCEER/NSE workshops on evaluation of liquefaction resistance of soils". Journal of Geotechnical and Geoenvironmental Engineering ASCE 2001; 127(4): 817-833.