GEOTECHNICAL ASPECTS OF THE JUNE 20, 1990 MANJIL EARTHQUAKE IN IRAN

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ABSTRACT

General feature of the Manjil earthquake of June 21, 1990 in Iran and its effects on the ground damage are described putting emphasis on the liquefaction of sand deposits and landsliding which occurred in natural slopes. The liquefaction developed on the fluvial plain in the lower reaches of the Sefidrud river is shown to have exhibited several features in common with those ever encountered in other areas under similar conditions. The landslides which occurred in the mountain flanks in the epicentral area seem to have addressed some new features on the triggering mechanism of the slide intrinsic to earthquake environments.

Key words: earthquake, landslide, liquefaction (IGC: B4/D7)

INTRODUCTION

Liquefaction of the level ground and landsliding in hilly slopes are two major natural phenomena of geotechnical significance associated with the damage during earthquakes. In fact, in most of the large earthquakes in recent years having a magnitude greater than 6.5, the damage to properties and loss of human lives have been associated more or less with what may be summed up as "ground failure" as represented by liquefaction and landsliding. It is already well known that, in the Loma Prieta earthquake of 1989, a large part of the damage to houses and public facilities in the reclaimed sand deposits in the area of San Francisco bay which is located as far as 90 km away from the

epicenter is attributed to the occurrence of liquefaction. In the most recent earthquake in Philippines, it has been known that the extensive occurrence of liquefaction in the city of Dagupan was indeed a sole cause of all kinds of destruction incurred to buildings, bridges, lifelines and so forth. In this earthquake, a number of landslides occurred in the mountain area, paralyzing the traffic and leaving some large cities utterly inaccessible. These two earthquakes served as grim reminders of what happened for the umpteenth of time in the past and reemphasized the importance of these two phenomenon in the geotechnical engineering.

In view of the circumstances as above, it was considered highly desirable to conduct a

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Manuscript was received for review on July 19, 1991.

Written discussions on this paper should be submitted before April 1, 1993, to the Japanese Society of Soil Mechanics and Foundation Engineering, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

careful ground reconnaissance over the area devastated by the Manjil earthquake of June 20, 1990 in Iran and leave written records on the results of the field survey. Urged by the incentives as above, the authors planned and executed rounds of field trips to the earthquake-inflicted area in the northern Iran for investigating the ground damage and collecting any information on the soil conditions in this area.

The results of the investigation and some considerations on the effects of this earthquake will be described in the following pages of this paper.

Manjil Earthquake of June 20, 1990

A disastrous earthquake occurred on June 20, 1990 in the Caspian provinces of Gilan and Zanzan, Iran (Fig. 1), with the epicenter about 200 km northwest of Tehran. Its magnitude 7.3 placed this event among the strongest to have occurred in densely populated areas in Iran in recent decades (Moinfar and Naderzadeh, 1990). The epicenter is reportedly located in the mountain several kilometers northwest of the city of Manjil as indicated in Fig.

2. This is the seismically active region in the Elburz Mountains which is a part of the

Fig. 1. Epicenter of the Manjil earthquake

Fig. 2. Intensity of shaking in terms of MSK

Alpine-Himalian seismic belt. The focal depth of the hypocenter is estimated to have been about 20 to 30 km. The tremor was felt over a wide area covering 600 km from Tabriz to Tehran in the northwest part of Iranian territory. Intensity of shaking in terms of the Russian MSK scale which is similar to the Modified Mercalli scale were 10 at Manjil and Rudbar. The approximate intensity assigned to the earthquake-inflicted area is indicated in

the isoseismal map in Fig. 2. The intensity distribution is mapped out mainly based on the damage degree and observed manifestation of faults on the ground surface. As indicated in Fig. 3, the ground rupture line extends through a distance of about 100 km from the northwest end at Backlor as far east-southward as Girandeh. This surface faulting was not continuous and made up of many complexly laid-out segments. The

Fig. 3. Major cities in the affected area

Fig. 4. Surface rupture on the mountain top at Backlor (Viewing southwestwards)

Fig. 5. Acceleration record at Ab bar

faulting is right-lateral thrust type with the maximum horizontal offset of about 20 cm occurring in the mountain north of Harzevil and also in the eastern end near Pakdeh. The maximum vertical offset was 50 cm. The ground rupture on the mountain top north of Backlor is shown in Fig. 4.

During the 1990 earthquake, a series of strong motion accelerographs was triggered and recorded motions at several stations in the affected area. The strongest motions recorded were on a rock site at Ab bar where the peak accelerations were 0.65 g and 0.62 g in two horizontal directions and 0.52 g in the vertical direction. Unfortunately, records on photo films were so much smeared that it was not possible to read off time histories in the transverse and vertical directions. With respect to the record on the longitudinal direction, attempts were made to read off the original unclear records by Professor T. Ohmachi of Tokyo Institute of Technology and also by Public Works Research Institute of Japan Government. Independently conducted readings turned out to yield almost the same spectrum characteristics, although they were slightly different in details. Shown in Fig. 5 is one of the horizontal motions at Ab bar read off by Professor Ohmachi where only the portion of main shaking is presented. The corresponding acceleration spectrum is shown in Fig. 6 which indicates predominant periods of 0.17, 0.35, 0.65 and 1.5 sec. The time histories

Fig. 6. Acceleration response spectra of the motion at Ab bar

of two horizontal accelerations obtained at Lahijan in the area of alluvial plain facing the Caspian sea are presented in Fig. 7, together with the response spectra in Fig. 8. They were also read off by Professor Ohmachi from somewhat unclear photo films. It is noted in Fig. 8 that there commonly exist predominant periods of 0.32 and 0.85 sec., but a long period motion with a period of 2.3 sec. exists only in the transverse component.

Fig. 7. Acceleration records at Lahijan

Fig. 8. Acceleration response spectra of the motions at Lahijan

GENERAL FEATURE OF DAMAGE

Most destructive damage took place in the city of Rudbar, Manjil and Harzevil which are located in the epicentral area as shown in Figs. 9 and 10. Part of the Harzevil town located on the flank of a mountain east of Manjil was

completely razed to the ground. All of the houses on the slope made of stone and sun-dried mud brick walls with wooden pole rooves were smashed down and turned into the sliding debris. Similar cataclysmic disruption took place in small villages at Backlor and Girandeh located, respectively, on the west

Fig. 9. Locations of surface ruptures and landslides

Fig. 10. Map in the vicinity of Manjil lake

and east edges of the fault alignment. In Rudbar and Manjil, a number of one or two-story buildings constructed of cement block or stone walls with steel beam jack arches were tumbled down, leading to many casualties and loss of properties. In the city of Rasht 60 km

north of the epicenter, the damage was minor to medium, but concentrated on some of the tall buildings with more than four stories. Several steel and reinforced concrete buildings have sustained damage due to weakness in joints and probably because of poor workmanship in the phase of construction.

One of the most noteworthy features of this earthquake was the performance of Sefidrud dam which had undergone an extraordinarily strong shaking, because of its location being in close proximity to the major fault line. This dam is a buttress-type concrete dam constructed in 1963 and has a height of 106 m and a crest length of 425 m. The water impounding capacity of the reservoir amounts to 1.8×10^9 m³. The seismic coefficient used for the design was 0.25 g. At the time of the earthquake the Sefidrud dam, located just 300 m south of the major fault line, stored the water nearly to its full capacity with a water level 5 m below the normal elevation.

Fortunately, the dam safely withstood the strong shaking and there was no fatal damage endangering the integrity of the dam, but several minor damage was incurred such as some horizontal and diagonal cracks developed near the top part of some buttress. Parts of parapet walls at the crest was also tilted in the downstream direction.

GROUND DAMAGE DUE TO LIQUEFACTION

A vast expanse of fluvial fan topography develops towards the Caspian sea along the Sefidrud river which crosses the Elburz Mountains through the gorge near Rudbar, as shown in Fig. 9. The river collects water from the valleys in the southern slopes of the Elburz and supplies water for irrigation over the farmlands developed in the alluvial plain area north of the Elburz. Many patches of rice fields are developed in the villages over the vast area in the lower reaches of the Sefidrud river. The low-lying area near Astaneh, Lahijan and Langarud appears to be underlain by a thick deposit of alluvial origin consisting of layers of soft clays and loose sands. The villages are surrounded by a complex network of sluggish streams and small canals constructed for irrigation purposes and the ground water table is generally high close to the surface. Thus, the ground conditions in this area were such that they satisfied the requirements for liquefaction to easily take place at any time whenever subjected to a sufficiently strong shaking during an earthquake. The area of the deltaic deposit in the lower reaches of the Sefidrud river is briefly

shown in Fig. 11, together with an approximate zone where evidences of liquefaction such as sand boiling and tilting of farmer's houses were observed following the earthquake. It may be seen that the zone of liquefaction covers a wide area along the main stream of the Sefidrud river. A more detailed map indicating locations of observed damage due apparently to liquefaction is shown in Fig. 12. The farmlands in the area are so vast that it has been impossible to traverse everywhere and establish thorough-going records of all traces of liquefaction-associated damage with equal level of confidence. Indicated in Fig. 12 by solid circles are the locations where clear

Fig. 11. Zone of liquefaction in the flood plain of the Sefidrud river

Fig. 12. Locations of soil liquefaction and exploratory borings

evidences of liquefaction were observed during the ground reconnaissance by the authors following the earthquake. It appears highly likely that there existed many more undiscovered places of liquefaction, but they were scattered probably within the zone indicated by dashed lines in Fig. 12. It may be seen that the major places of liquefaction-induced damage were concentrated in a belt zone along abandoned Sefidrud canal extending eastwards from Astaneh, Rudbaneh through Pahmedan.

Astaneh

In the religious town of Astaneh, severe damage to residential houses due to liquefaction of the ground occurred in two particular sections, as indicated in Fig. 13. In the northeast section of the town about 250 m by 500 m wide, floors of wooden-framed brick houses were tilted, torn apart or crushed due to uneven settlements or lateral movements of the ground. A tremendous amount of sand and water was seen gushing on the ground surface through cracks or holes created by the ground deformation. Fig. 14 shows the tilting of a private house due to the differential movements of the ground caused by liquefaction. About 100 houses were destroyed more or less equally. Each house in the town had a well of its own to take water for domestic use. In the liquefaction-devastated section, local people testified that the sand mixed with water came up from the bottom and completely filled the well. All the wells in the devastated area were filled with sand and rendered unusable.

The southwest part of Astaneh shown in Fig. 13 also experienced severe damage due to uneven movements of the ground caused by liquefaction. The feature of the damage in this section was the same as that in the northeast section of the town. A typical example of the damage to a well buried by the sand filling is shown in Fig. 15.

In the remaining part of the town where there was no liquefaction, practically no damage was incurred whatsoever to private houses although they were constructed of the same materials and by the same methods as those in the liquefied area. This means that no structural type damage was incurred to private

Fig. 13. Locations of boring and areas of liquefaction in Astaneh

Fig. 14. Sinking of a farmer's house in the liquefied ground (Northeast section at Astaneh)

houses, no matter whether they were located in the liquefied area or non-liquefied zone in the town of Astaneh. In view of the fact that many of the private houses safely withstood the earthquake, it would appear that the intensity of shaking was not very strong and the peak acceleration developed in this area was probably in the range of about 0.15 g to 0.20 g. In fact, as demonstrated in Fig. 7, the peak acceleration recorded in Lahijan about 10 km southeast of Astaneh was of the order of 0.17 g.

Fig. 15. A well buried by sand in Astaneh

In the west of Astaneh town area, large excavation of trench was underway for the installation of sewage conduits and the soil profile was exposed in dry conditions to a depth of about 3 m. Visual observation showed that a silt layer of loessal origin covers the ground surface to a depth of 0.5 to 1.0 m, underlain by medium to dense sand deposit of fluvial origin which is strong enough not to cause liquefaction. In the area of Astaneh where there was no damage, the soil deposit appears to have similar profile, but in the two particular sections where damage was disastrous, the sand underlying the surface soil appeared to be loose. This fact has proved to be true as a result of recent in-situ investigations conducted at sites indicated in Fig. 13. The soil profiles obtained there by boring are shown in Fig. 16, where it can be seen that the sand deposit is loose with N -values of 3 to 10 to a depth of 7 m in the two sections where the liquefaction-induced damage was disastrous. In the rest of the area where there was no liquefaction, the soil profile was shown to consist of the clayey silts near the surface as indicated by boring BH4, in Fig. 16. It is to be noted that the elevation of the ground water table observed during drilling is coincident with that estimated from the resident's testimony regarding the water level within the wells before they were buried by liquefied sand. Judging from complexly meandered pattern of tributaries of the Sefidrud river, it is conceivable that the sites of considerable liquefaction had been old river channels which were later filled by sands.

The manner of excavating a well adopted

Fig. 16. Soil profiles in the town area of Astaneh

widely in the Astaneh area is illustrated in Fig. 17. The excavation is generally advanced to an elevation about 1.0 to 2.0 m below the ground water table. Thus, if a well with a given depth is known to have been filled by liquefied sand, it implies that the liquefaction have taken place at least at that depth. Therefore, the performances of wells with different depths may be used to approximately estimate the depth of liquefaction as illustrated in Fig. 17. In the Astaneh area, most of the wells had a depth of 3 to 4 m and they were filled with the sand. Therefore, assuming the thickness of unliquefied surface layer to be about 1 m, it is conjectured that the liquefaction occurred in the sand deposit having a thickness greater than 2–3 m. This conjecture was, in fact, substantiated by the exploratory boring data shown in Fig. 16 which indicate the thickness of liquefied sand deposits being about 4 to 8 m.

Rudbaneh

Rudbaneh is a small local town about 7 km east of Astaneh as shown in Fig. 12. Somewhat detailed layout of the town is

Fig. 17. Sand filling in wells due to liquefaction

schematically shown in Fig. 18, where it is seen that a small sluggish canal, Heshmat rud, about 7 m wide flows eastwards in parallel with the main road through the town. The area south of the road is a lowland. At the time of the earthquake, lateral spreading of the ground occurred towards the canal accompanied by streaks of parallel fissures all the way along the southern bank of the canal extending about 20 to 50 m rearwards to the location of the roadfill. The lateral spreading also occurred towards the southern lowland. The lateral spreading in the western part involved the breakdown of the houses on the roadside. The damage to these houses is typically shown in Fig. 19. The slide in the eastern part appeared to have encroached from the canal on the adjacent premise of a primary school and utterly destroyed the buildings, as sketched in Fig. 20. The slumping of the roadfill south of the buildings seems to have been associated with the overall slide movement of the ground towards the canal. Over the playground west

Fig. 18. Schematic map of Rudbaneh town

Fig. 19. Tilting of houses towards the canal (Viewing the west part of Rudbaneh from southeast)

Fig. 20. Approximate feature of the ground rupture in the town of Rudbaneh

of the buildings, traces of sand boils and fissures were observed on the ground surface. The cross-sections A-A' and B-B' in this area shown in Fig. 18 appear to be such as those shown in Fig. 20. The amount of the lateral spread at the bank of the canal is estimated to have been probably on the order of 2 m. In view of the wide-spread appearance of sand boils and fissures on the adjacent ground surface, it may be inferred that the liquefaction was the major cause for the lateral spread of the ground, and particularly in the area of cross sections A-A' and B-B', the movement seems to have extended as far rearward as 80 m, as indicated in Fig. 20.

Other areas

The liquefaction-associated damage to houses and facilities during the 1990 Manjil earthquake was concentrated mainly in the towns of Astaneh and Rudbaneh. However, there were numerous evidences of liquefaction manifest on the ground surface in other surrounding areas as indicated in Fig. 12. For example, the roadway fill between Astaneh and Rudbaneh failed and slumped at several sections due probably to liquefaction of underlying soils. Concrete-lined irrigation channel crossing the roadway between Astaneh and Rudbaneh was destroyed severely almost through its entire length of installation as long as several kilometers. Fig. 21 shows the damage to the irrigation channel which had been pushed up by uplift force from the liquefied sand.

The villages of Pahmedan and Temchal also suffered the damage due to liquefaction, but

Fig. 21. Concrete-lined aquaduct buried in the liquefied sand (between Astaneh and Rudbaneh)

most of the destruction were failure of foundations of farmer's houses and sand deposition in small wells.

GENERAL CONSIDERATION OF SOIL CONDITIONS AND LIQUEFACTION-INDUCED GROUND DAMAGE

Subsurface soil conditions in the fluvial plain of the Sefidrud river have been investigated by various agencies on different occasions. The sites of soil investigation indicated by No. 1 through No. 6 in Fig. 12 are those obtained at the time of deep well excavation. Some of these soil profiles are shown in Figs. 22 through 26, where it may be commonly seen that there exists a surface layer of clay of about 1 to 2 m in thickness, underlain by a soil deposit containing less fines such as clayey sand, silty clay or sand. The deepest soil profile data at No. 3 and No. 6 sites indicate the presence of gravel-containing deposit below the depth of about 30 m to 40 m which appears to be a common geological regime existing in this region. The ground water table is located at a depth between 1.0 and 5 m below the ground surface, but this difference is due mainly to the local relief of the ground surface from which the boring was started and also due to the seasonal variation of the ground water regime. A log of boring obtained in the suburb of Astaneh in connection with soil investigation for a bridge design is presented in Fig. 25 which contains the information of N -value in the Standard Penetration Test (SPT).

Fig. 22. Exploratory boring in the fluvial plain of the Sufidrud river

Fig. 24. Deep boring in the fluvial plain of the Sufidrud river

Fig. 23. Deep boring in the fluvial plain of the Sufidrud river

The practice of SPT in Iran generally employs the method of automatic free-fall or two turns of rope around the cathead in operating the hammer blow. The SPT log shown in Fig. 25 is that obtained by means of the automatic free-fall and therefore seems to indicate the N -value which is comparative to that by Japanese practice (Yoshimi and Tokimatsu, 1983) and to the U.S. practice as well using the safety hammer. The SPT data in Fig. 25 indicates that there exists a silty layer containing clay or sand around a depth of 1 to 2 m, which has a blow count of about 3. The figure also indicates that a sand layer with a N -value of 5 to 8 exists at a depth around 10 m, underlain by a thick clay layer having a N -value of about 5 to 10. The observations as above reveal the fact that the near-surface soil profile is generally complex being of locally varying nature and their stiffness is generally soft to medium. The clay stratum existing below the depth of about 10 m has medium stiffness, but because of its

Fig. 25. Exploratory boring in the fluvial plain of the Sufidrud river

thickness being more than 20 m, it might have conducted toward amplifying long-period components of motions during the Manjil earthquake. At the particular place where the log of boring No. 10 was obtained, no clear evidence of liquefaction was observed during the earthquake, but at any place in their vicinity where the sand deposit is predominant near the surface, there is no wonder to expect any damage associated with liquefaction as was actually the case in the town of Astaneh.

Another set of boring logs with SPT was available at sites No. 17, 19 and 21 near the village of Pahmedan shown in Fig. 12. They were obtained in conjunction with *in-situ* investigations for the construction of irrigation channel. Therefore, the depth of boring was generally shallow to a depth of about 5 m. One of the soil profiles with the *N*-value in SPT are shown in Fig. 26. This profile indicates as well a complex nature of subsurface stratification, but it may be seen that the near-surface deposits contain some amount of sand

Fig. 26. Exploratory boring in the fluvial plain of the Sufidrud river

with a low *N*-value mostly less than 5. In addition, the laboratory tests on consistency of silty sand disclosed that the fines are of low plasticity with a plasticity index of less than 10. With these facts taken together with the shallow depth of the ground water, there are good reasons to expect the occurrence of liquefaction and associated damage during any strong shaking of an earthquake. In fact the high level of potential for liquefaction as above was manifested as a reality and numerous damages to roadways and farmer's houses were observed in the area of Pahmedan at the time of the Manjil earthquake of 1990.

LATERAL SPREADING DUE TO LIQUEFACTION

It is apparent that the liquefaction-caused ground damage in Rudbaneh described in the foregoing section has a characteristics that it occurred in a belt zone encompassed by the canal on the north and by a marshy lowland in the south with a roadfill in the middle, as illustrated in Fig. 18. Thus, it is highly likely that the liquefied soils had moved laterally towards the canal and also to the lowland in the south. In fact, numerous longitudinal cracks were observed near the southern bank of the canal accompanied by a horizontal movement of about 2 m and also settlements of about 50 cm had occurred in the roadfill. With all these observations taken together, it might be possible to define a scenario in which a lateral spreading could have occurred through the liquefied soil deposit by the combined actions of seismic shaking and gravity-

induced lateral force due to the presence of the canal and the roadfill. Based on the approximate sketches of typical cross sections shown in Fig. 20, the scenario of the lateral displacement may be described as a long-stretched slide of massive soils beginning at the roadfill and ending at the canal location, as shown in Fig. 20. It is assumed with reasons that the roadfill slumped sideways leaving 1 m thick surcharge and the sliding plane ran through the liquefied sand deposit at a depth of 3 m. The length of the flow slide is assumed to be about $l=80$ m. Since the overall ground is considered to have developed liquefaction accompanied by a large lateral deformation, the static shear stress mobilized along the assumed sliding plane after the cessation of the seismic shaking can be calculated by considering the lateral forces acting at the roadfill and at the water front. By assuming a geometrical configuration of the soil movement as shown in Fig. 27, the equilibrium of forces in the horizontal direction leads to an equation

$$\tau \cdot l = \frac{1}{2} [\gamma_t H_1^2 - \gamma_w H_2^2] \quad (1)$$

where H_1 and H_2 denote, respectively, the depth to the sliding plane from the top of the slumped roadfill and from the water surface in the canal. γ_w is the unit weight of water and γ_t denotes the gross unit weight of the soil. Introducing a set of the dimensions indicated in Fig. 27 and $\gamma_t=18$ kN/m³ into Eq. (1), the value of the mobilized shear stress can be evaluated as $\tau=1.55$ kN/m². It is worthy of note that this back-calculated value of shear stress is significantly smaller than the value of the residual strength or steady-state strength obtained from other case studies of similar flow slides (Ishihara et al., 1990; Ishihara-

Fig. 27. Calculation of shear stress along the assumed failure plane in the slide area at Rudbaneh

Takeuchi, 1991). Therefore, the shear stress back-calculated above should be interpreted simply as the shear stress which was mobilized in the soil when the seismic shaking stopped, and since this value is smaller than the residual strength, it is inferred with good reasons that continued deformation did not occur after the seismic shaking stopped. Thus, it is conjectured that most of the lateral displacement in Rudbaneh, being of the order of 2 to 3 m, had probably taken place during the relatively long period of seismic shaking which lasted for about 30 seconds, and consequently this lateral displacement was not of flow type.

LANDSLIDES

The landsliding and rockfalls are another type of damage of geotechnical significance which is caused by the shaking during earthquakes. During the Manjil earthquake, many small landslides and rockfalls occurred on the side of the highway between Manjil and Rasht, as indicated in Fig. 9 and blocked roadways and passes at many places. The large-scale landslides were mostly induced on relatively steep slopes in the mountains located in the epicentral area as shown in Fig. 9.

Galdian Landslide

A colossal landslide took place in the neighborhood of the village of Galdian on the mountain slope east of Rudbar as shown in Fig. 9. The slide encompassed an area approximately 300 m in width and 3 km long.

Assuming the average depth of sliding plane to have been 15 m, the slide involved a huge mass of soils amounting to approximately 20 million cubic meters. The frontal view of the landslide is roughly sketched in Fig. 28 and the longitudinal cross section is approximately as shown in Fig. 29. The slide started west-southward at the head and veered to the west in the middle of the slide area. According to the account by witnesses, the uppermost portion of the slide started gradually to move about one day after the earthquake. The uphill portion of the slide viewing downwards from the headscarp is shown in Fig. 30. The oil pipe line crossing the valley was broken off

leading to leakage of a large quantity of oil. The mass of soils detached from the initial slide at the headscarp appears to have created additional force to push down the soil deposit immediately downhill. This force had probably been transmitted in sequence to several blocks of soils farther downhill and produced

a long-stretched landslide. The slide movement stopped at a valley-like location about 50 m uphill the city of Rudbar, where a pressure ridge about 30 m high was formed with many withered uprooted trees perching thereupon. The villagers living in the downhill part testified that the slide movement was very slow and it took about 10 days before a huge wall of soil mass bulged encroaching upon their residential area.

The landslide at Galdian occurred on a moderately sloped hillside having a buried valley-like topography. The area had been cultivated as farmlands and patches of small forests were developed. This region has a semi-arid climate and mountains are generally barren and rugged with only few trees. The fact that the green area had developed at Galdian amid dry sterile environments indicates that there are water supply from springs and in fact the inhabitants in this village live on water coming from springs at various loca-

Fig. 28. Approximate sketch of frontal view of the landslide in Galdian

Fig. 29. Approximate cross section of the Galdian landslide

Fig. 30. Landslide at Galdian viewing downhill from the headscarp

tions on the hillside. After the landslide, two small ponds were formed in the upper part of the slide area, collecting water from the springs. Unfortunately, exact locations of the springs are not known. Nor is known of the regime of underground water migration. However, it is probably reasonable to assume that the ground water conditions must have changed anyhow as a result of small distortions in the ground created by the shaking during the Manjil earthquake. In fact, the area of Galidian is in close proximity to the epicenter being only 5 km away from the major fault line as indicated in Fig. 10. An intense tremor with an acceleration on the order of 0.7 g is estimated to have hit the village area and the resulting ground distortions such as cracking appear to have changed the underground water regime in ways that detracted from the marginal stability of the slope being existent before the earthquake.

The subsurface soils in Galdian consist mainly of weathered marl and clearly-defined slickenside was visible on a sliding plane through a clay deposit which was exposed in the uphill part near the northern rim of the slide area. It is not known whether or not this dark blue clay prevails in the sliding zone and was responsible for triggering the slide. However, rough estimate may be made on the average strength of a soil involved in the slide on the basis of back-calculation using the known geometry shown in Fig. 29. From the equilibrium condition assuming a straight-line sliding plane, the undrained strength of the soil, S_u , is back-calculated as

$$\begin{aligned} S_u &= \gamma_t H \times \cos \alpha \times \sin \alpha \\ &= 1.7 \times 15 \times \cos 25^\circ \times \sin 25^\circ \\ &= 98 \text{ kN/m}^2 \end{aligned}$$

where H is the average thickness being taken as 15 m, $\gamma_t = 17 \text{ kN/m}^3$ is the unit weight of the soil and α is the average angle of slope.

Fatalak Landslide

By far dreadful and appalling was the large-scale landslide which occurred in the village of Fatalak over the west-facing flank of a hill about 15 km distant from the major fault line

as shown in Fig. 10. A huge mass of soils amounting approximately to 1 million cubic meters slid down the slope all of a sudden simultaneously with the main shaking of the earthquake and buried all the houses in the village developed at the foot of the hill. The casualty amounted to 137 people and only 14 persons were able to elude the disaster. Frontal view of the landslide is sketched in Fig. 31 and a closer view of the headwall scarp is shown in Fig. 32. Two cross sections, A-A' and B-B' in Fig. 31 are drawn approximately as those shown in Fig. 33. It is apparent that the slide consists of two parts: the western half with a vertical headscarp about 25 m high and the eastern half with a smaller headscarp about 10 m high but having a ledge extending rearwards from the shoulder of the hill. The villagers were living on water taken from a stream flowing northward just in front of the village, and some small springs were purportedly coming out in the slide area. However, it may be mentioned that the landslide was triggered solely by the dynamic force due to the shaking of the earthquake, without being affected in any way by water. In fact, the debris of the slide consisted of fractured pieces of almost dry soils, and without a strong shaking such as that encountered during the Manjil earthquake, the landslide in the village of Fatalak would have never occurred. The soil deposit involved in the landslide are those derived from weathering of limestone and contained occasionally gravels or stones. The soil is non-plastic silt. It is conceivable that at the

Fig. 31. Approximate sketch of the frontal view of the Fatalak landslide

Fig. 32. Headscarp of the landslide at Fatalak

Fig. 33. Approximate cross sections of the landslide at Fatalak

hilltop weathering had penetrated deep into the rock, whereas the intact hard rocks were existent nearer to the surface on the hillside. Thus, it is likely that the thickly weathered portion at the hilltop was stripped off by a tensile force generated by the extraordinarily high-intensity seismic shaking and the massive soils slid down the hillslope as debris. This scenario of the landslide may be the most tenable explanation for the peculiar feature of the collapse observed at the head of the landslide, as illustrated in the cross sections of Fig. 33.

CONCLUSIONS

The general feature of the damage of geotechnical significance during the 1990 Manjil earthquake in Iran has been described and

several issues of interest were addressed. Firstly, the liquefaction developed widely in the deltaic deposits over the vast low-lying plain in the area of the lower reaches of the Sefidrud river. Although highly variable from one place to another, the soil profile is generally composed of a near-surface layer of silty or sandy soils and an underlying thick deposit of clay extending to a depth of 30 to 40 m. The ground water table is about 0.5 to 2 m below the surface. The area of liquefaction-induced damage is located 80 to 100 km distant from the epicenter and assigned the intensity VI in MSK scale. The maximum acceleration on the ground is estimated to have been of the order of 0.17 g in this area. Even with this intensity of shaking being low to moderate, liquefaction was indeed found to have developed in the near-surface deposit consisting of sand and low-plasticity silt, if the ground water table is high. This is probably considered as a critical circumstance under which the phenomenon of liquefaction could barely develop in the field with such a low intensity of shaking. It is of interest to notice that the conditions as above are very much similar to those encountered in the San Francisco bay area at the time of the Loma Prieta earthquake (Seed et al., 1991). Analysis of the seismic motions recorded in the deltaic plain area indicated a tendency of long-period components being significantly amplified in accord with the presence of a thick clay deposit underlying this

area. This characteristics was also shown to be analogous to that encountered in the San Francisco bay area. The liquefaction in Rudbaneh was found to have induced a small-scale slide resulting in lateral movements of the ground. A significantly low value of mobilized shear stress in the liquefied soil was obtained as a result of back-calculation considering a shallow-depth sliding plane. This value of shear stress was shown to be significantly smaller than the values of residual strength obtained from other studies of similar cases. Thus, it was conjectured that there was no significant flow of soil mass having occurred after the seismic shaking and that most of the lateral spreading of the order of 2 to 3 m might have taken place by the action of the static shear stress plus the dynamically applied stress during the period of main shaking of the Manjil earthquake.

Two large-scale landslides which occurred on the hillsides near the epicenter were described and some considerations were given, although speculative, to possible causes of the slides. In the case of the landslide at Galdian, it was suggested that the change in the ground water conditions brought about by the high-intensity shaking might have acted toward detracting from the stability of the ground in the slope. In the case of the landslide at Fatalak, deeply weathered deposits of limestone-derived soil at the hilltop seems to have been in a state susceptible to collapse under the action of a tensile force induced by an extraordinary high intensity of seismic shaking.

ACKNOWLEDGMENTS

In carrying out the ground reconnaissance in the earthquake-inflicted area in Iran, the overall cooperation by Dr. Jamsid Farjoodi, Assistant Professor of University of Tehran was very much helpful. Dr. T. Amirsoleymani

of Mandro Company, Tehran and Mr. C. Heidari of the Construction Industry Consortium of Iran kindly offered the unreserved logistical and technical support for traversing the earthquake-inflicted areas. Acknowledgment is also given to the International Institute of Earthquake Engineering and Seismology and Housing Foundation of Islamic Republic of Iran for their financial support for conducting the field investigations. The digitization and analyses of the acceleration records obtained at Ab bar and Lahijan were made by Professors T. Ohmachi and S. Midorikawa of Tokyo Institute of Technology. The digitization was also attempted by the courtesy of Dr. Y. Sasaki, Public Works Research Institute. The soil profile data were obtained by the courtesy of Gilam Regional Water Board, and Soil Mechanics Laboratory of Ministry of Road and Transportation in Rasht. The authors wish to express their deep gratitude for the assistance and camaraderie of these persons and organizations.

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