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THE GEOTECHNICAL HAZARD INDUCED BY 8.1 EARTHQUAKE IN WEST PASS OF KUNLUN MOUNTATIN IN CHINA IN 2001

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ABSTRACT
On November 14, 2001, a great earthquake with a magnitude of Ms=8.1 occurred in the Qinhai-Tibet Plateau, China, which is called as the west pass of Kunlun mountain Ms8.1 earthquake. This earthquake is the largest and the first one with a magnitude greater than 8.0 in mainland China in the recent 50 years. It caused a large-scale deformation zone with a length of 426 km in frozen soil deposit in the plateau with a height of 4000-5500 meters above sea level. Some geotechnical hazards induced in the meizoseismal area, such as compression and tension failure of soil deposit, shaking landslides (collapse of slope and cliff), seismic settlement, sliding of glacier and snow. Unexpectedly, liquefaction occurred within the melting sand layer in frozen soil deposit on the banks of lakes and rivers. All the hazards were investigated in the field by the authors. This paper presents the results of the field investigation and tests made.

1. INTRODUCTION

In November 14, 2001, an earthquake(Fig 1) with Ms scale 8.1 occurred in the west pass of Kunlun mountation in the north of Qinghai-Tibet plateau. It is the first the largest earthquake in mainland China after the Dangxiong 8.0 great earthquake in Tibet in 1951. This earthquake caused the formation of a large ground deformation belt, which starts from the Bukadaban peak at the west and extends toward east passing Hongshui River, North side of Kusai lake, the south of Yuxu peak, the site around the 2894km milestone of Qinghai-Tibet highway in pass of Kunlun Mountain, the south of Yuzhu peak and finally stops at the site around 70km milestone of Qinghai-Tibet highway on the east. This deformation zone has a strike of N80°W and is over 400Km in length. In this paper, results on field investigation of the geotechnical hazard caused by the earthquake and the tests has been done on the soil as well have been presented.

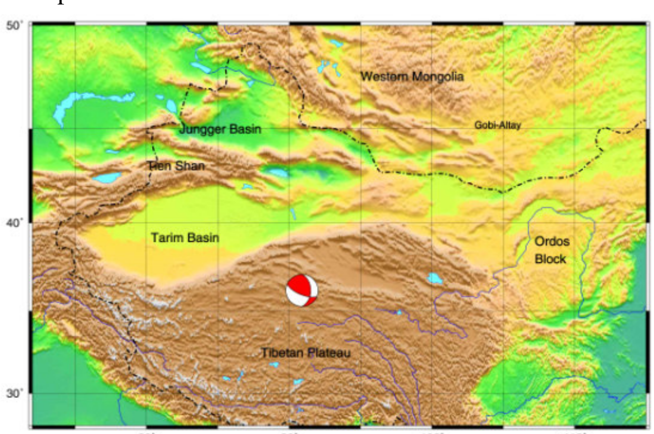


Fig.1. The epicenter of the 8.1 earthquake

2.GEOGRAPHIC ENVIRONMENT IN AREA AFFECTED BY THE EARTHQUAKE

The most affect area lies on the south of east Kunlun Mountatin, where is in the hinterland of Qinghai-Tibet Plateau. It meets east Kunlun Mountain on the north and high-elevation plain of headstream of three rivers (Yellow River, Yangtz River and Yaluzangbu River). So the area is between Kunlun Mountain and Tanggula Moutain and forms a catchment basin of an undulating plain with high elevation.

The area is relatively level and mainly with lakes and frozen soil desert landscapes. The elevation in this area ranges from 4300 m to 5200m. The climate is of typical continent climate, which is cold, oxygen-deficient, dry, windy with large day to night temperature difference. Meteorological records show that the average annual temperature is from –5°C to –6°C. January, the coldest month of a year, has an average temperature of around -20°C and the lowest temperature could be below –35°C. The average temperature in July is 5°C to 6°C and the highest temperature is above 20°C. The climate changes between seasons are not distinctive. The frost-free period is very short. The annual rainfall is less than 300mm with 80% of it concentrates in period from June to September. The thick cloud is seldom seen and the sunlight days are common. At the elevation of 4600m, the oxygen of the atmosphere is only about 61% of that at the sea level.

There is no much trees in the area. Grasses are the major vegetation. Animals like wild yak, wild ass, Tibet antelope, wolf, fox and rat can be found in the area.

3.FROZEN SOIL AND ITS DISTRIBUTION IN AREA AFFECTED BY THE EARTHQUAKE

The classification of frozen soil can be based on different criteria. From the time length of frozen, the frozen soil can be classified as seasonal frozen soil and perennial frozen soil. Namely, the former thaws in summer and the latter won't. Take the size of grain as standard, frozen soil can be classified as large grain frozen soil, coarse frozen soil and fine frozen soil. From the point of view of formation, frozen soil can be classified as alluvial/diluvial frozen soil, lacustrine frozen soil, moraine frozen soil and Aeolian frozen soil. Based on the status of frozen, there are stiff frozen soil and plastic frozen soil. According to their engineering properties, frozen soil can be classified as unthawing frozen soil, slight thawing frozen soil, moderate thawing frozen soil, easily thawing frozen and intensive thawing frozen soil.

There are mainly four kind of frozen soil in the area affected by the 8.1 earthquake at West pass of Kunlun Mountain.

Moraine large grain frozen soil

In the area, melted ice, moraine deposit and modern glaciers are well developed. Because of the effect of tectonic movement and the coverage of Quaternary deposit, the glaciers formed in the much earlier period can be hardly seen on the surface. The most recognizable glaciers are the modern glaciers, which can be found at places like the Yuzhu Peak, Yuxu Peak, North of Kusai Lake, Great Snow Peak, Bukadaban Peak, etc. At the front edge of the modern glaciers, moraine large grain frozen soil often presents. The main source of the moraine large grain frozen soil is the debris of bedrock, which is at where the moraine is developed and physically weathered. The debris were transported by melted ice and deposited. The size of grain is very uneven and grains of different size mixes together. Rocks with maximum diameter amounting to 2m can be found in the moraine large grain frozen soil.

Alluvial coarse frozen soil

This kind of frozen soil is mainly distributed at the riverbed and terrace of rivers. It is composed of sand, gravel, cobble and silt. The material source of this kind of frozen soil is the bedrock along the rivers and from the mountains near the riverheads. The psephicity of the gravels are closely related to distance of transportation. At the upper reach, it is highly angular. At the middle and low reaches, it is less angular or spherical. The thickness of the deposit is to some extent determined by transportation capacity of the rivers. The more powerful a river is, the thicker the deposit will be. The most powerful rivers in terms of transportation capacity are Hongshui River, Kusai River, Small Nanchuan River and Gangqianqu River. In large rivers like Hongshui River, the alluvial terrace is more than 25m above the river, and the modern riverbed deposit is around 10m in thickness. Hence, the thickness of the alluvial coarse frozen soil ranges from 5 to 35m.

Diluvial sandy frozen soil

This kind of frozen soil is commonly found at the south and north piedmont of Kunlun Mountain and it is the main frozen soil in large part of the area affected by the 8.1 earthquake. From surface to underground, the frozen soil is composed of loam sand, sandy gravel and gravel. The vegetation is in good condition in some place. The thickness of loam sand ranges from 0.2 to 1 m. The size of gravel is usually from 10 cm to 30cm, but the maximum size can be as large as 80cm. The lithology of these gravels is mainly andesite, granodiorite, marble, migmatite, and gneiss. The psephicity of the frozen soil is from highly angular to less angular. The gradation is poor. In terms of geomorphology, the frozen soil forms diluvial fans with inclination from 1° to 8°. In part of these fans, Aeolian loam sand presents. The thickness of the diluvial layer varies much from several meters to over one hundred meters depending on the size of diluvial fans. The surface layer with thickness 1m to 2m is seasonal frozen soil and underneath it is perennial frozen soil.

Lacustrine gravelly fine frozen soil

This kind of frozen soil presents around the lakes in the area affected by the earthquake. It is composed of yellowy brown or gray brown gravelly silty sand, sand and silt. The distribution of grading can be divided into several belts surrounding the lakes. From the bank of lakes to the centers of lakes, the size of grain becomes finer. Since most of the lakes in the affected area are salty water lakes, the frozen soil around has high contents of minerals, which are commonly found in the lakes.

4.THE GEOTECHNICAL HAZARDS CAUSED BY THE GREAT EARTHQUAKE AND ITS CHARACTERISTICS

The great earthquake caused various kinds of geotechnical hazards. Based on the filed investigation, we classified these geotechnical hazards into two categories: ground deformation caused by tectonic movement during the earthquake and non-tectonic geotechnical events caused by the shaking of ground. In the first category, there are several kinds of ground deformation like earthquake fractures, depression and horizontal displacement etc. Phenomena like liquefaction, seismic subsidence, seismic landslide and fissures caused by the ground motion all fall into the second category.

4.1 Ground deformations and their patterns

The ground deformation zone (Fig. 2.) caused by the great earthquake starts from the 6860m high Bukadaban Peak on the border between the Xinjiang Uigur Autonomous Region and Qinghai Province and extends east passing the Red River, North of Kusai Lake, south piedmont of Yuxu Peak, the site around the 2894Km milestone on Qinghai-Tibet Highway, south piedmont of Yuzhu Peak and finally stops nearby the 70Km milestone on Qinghai-Tibet highway. The strike of this deformation belt caused by the tectonic movement during the earthquake is at about 100˚ ± 10 and it is over 400Km in length. The deformations can be identified through field investigation include almost all types of ruptures known to present during an strike-slip earthquake.

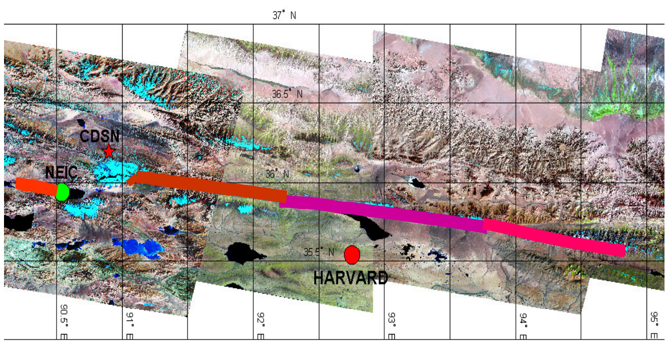


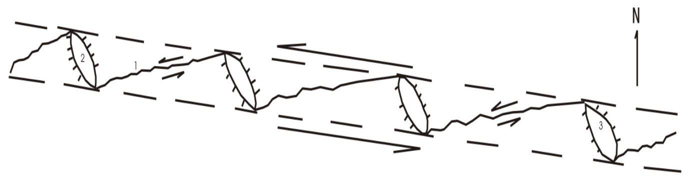
Fig. 2. Deformation belt caused by the 8.1 great earthquake

Earthquake fractures. (Fig. 3.) This is the most commonly recognized deformation. It has been found that there are three groups of earthquake fractures. The first group has a strike of N70˚~80˚W, which has a small difference with the strike of the main rupture of fault. The fractures of this group are relatively straight and smooth. Horizontal scratches can be found on the fracture surface, which indicate the sinistral movement of ground on two sides of the fracture.

Fig. 3. Earthquake fractures

This group of fractures is also big in scale. Sometimes a single large fracture presented alone, which can be well identified. But it can be presented as a group of small fractures, too. This ground of fractures is several meters to over one hundred meters long and scores of centimeters to over three meters wide. They are deep, too. On the cross section, the fractures often become narrower from the surface to underground. The large fracture is very deep while the small one wedge out gradually underneath.

The second group of earthquake fractures has a strike ranging between N70˚~90˚E. They formed a 30˚ angle with the strike of the main deformation zone. They are often found in concomitancy with the mole track (Fig. 4).



1. Compressing-torsional plane; 2. Tension fissure; 3. Earthquake depression;

Fig. 4. The combination of earthquake fractures and mole tracks along the main deformation zone of the 8.1 great earthquake

The third group of factures has a strike of about N50˚E. Often, they are found lying besides the two groups of NWW earthquake fractures and mole tracks accompanying them. They intercept the first two groups of earthquake fractures and form sphenoid pattern on the surface, which presents extensively in the middle-west part of the deformation zone.

Earthquake mole tracks.(Fig. 5) They often coexist with earthquake fractures along the deformation zone. It is 0.5~3.0 m high, several meters to over ten meters wide and several meters to over one hundred meters long. The length to width ratio ranges from 2:1 to 5:1. Because of the frozen soil, almost all of the mole tracks are results of brittle deformation.

Fig. 5. Mole track caused by the 8.1 great earthquake

Earthquake depressions. These depressions are often found in coexistence with earthquake fractures. Most of them are found in Pass of Kunlun Mountain, the west of Kusai Lake. The depression are formed by the sinking of the whole of a patch of land, which is usually not very big in area and in rhombic shape. A couple of mutual parallel edges of the rhombus extend in the similar direction with the main rapture. NWW earthquake fractures are also developed along the two edges.

Horizontal displacement. (Fig. 6) As other earthquake caused by the strike-slip fault, horizontal displacement is the most commonly seen phenomenon, which can be well identified from the displacement of linear structures like riverbed, gully, ridge and track. All geological bodies meet the main rupture zone were displaced to some extent and show signs of the sinistral movement. Scratches found on the rupture planes tell us that the movement is predominately horizontal.

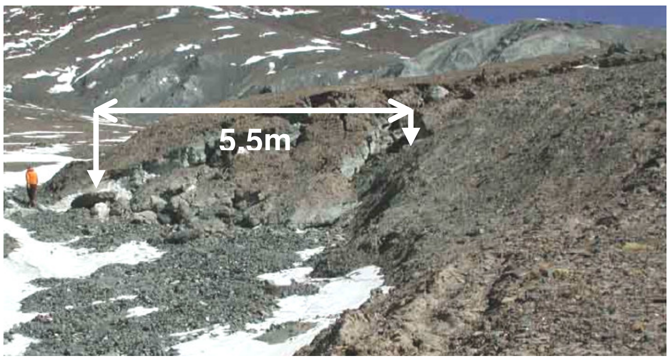


Fig.6. Horizontal displacement caused by the 8.1 great earthquake

Fig. 7 gives the value of horizontal displacement measured along the main deformation zone of the 8.1 great earthquake. It can be found that the horizontal displacement is unevenly distributed along the deformation zone from west to east.

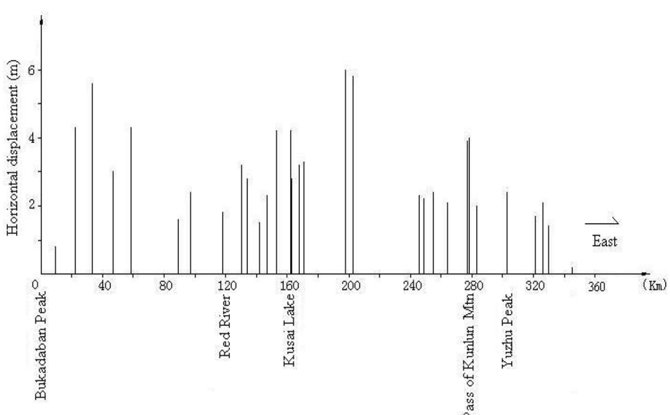


Fig. 7. The distribution of horizontal displacement along the deformation zone from west to east

Earthquake scarps. Earthquake scarps are not well developed in this case. They hardly extend continuously and often too short. Even in the same section of the deformation zone, the strike of the earthquake scarps can be north or south. This is related to the media difference underground and the subsiding of the fault on one side; therefore it does not represent the vertical displacement of the fault. The height of the scarps ranges from scores centimeters to over one meter.

4.2 Non-tectonic Geotechnical hazards.

Shaking caused Fissures.(Fig. 8) They are mainly found in the Northeast of Kusai Lake and part of riverbed of the Red River.

Fig.8. Shaking caused fissure

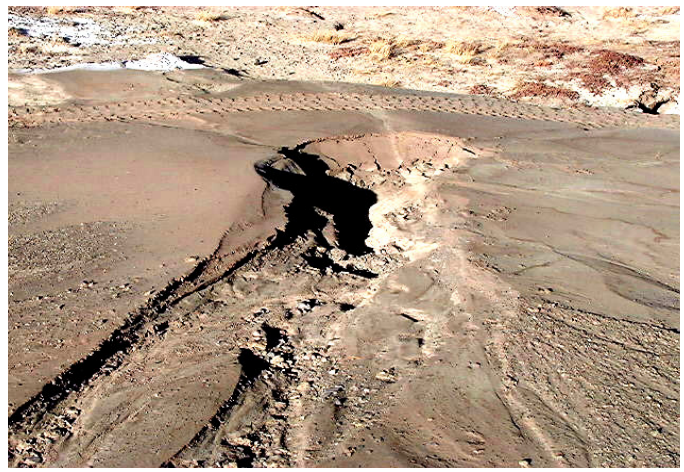
The scale and the direction of extending of these shaking caused fissures varies depending on the where they are. In northeast of Kusai Lake, the fissures are developed in the middle of the diluvial fan and flood plain. They have two dominate directions: NE and NW. The width of these fissures is from 10 to 30cm and their length is from several meters to hundred meters. The walls of these fissures are in shape of gentle wave. There is no relative movement between the two sides of the fissure. When they present in the flood plain of the rivers, they are often wider and cover a relatively large portion of the area. But the shaking caused fissures are relatively narrow and can only be found in a small part of the diluvial fan if there are any. Also, this kind of fissures does not developed nearby the main deformation zone. They often formed in places which are several kilometers away from the main deformation zone. Tests have shown that the failure strength of frozen soil is much higher than that of the thawed soil. In the mainly frozen soil area, there are still thaw soils, which are the cause of the development of the shaking caused fissures. The failure of the thaw soil under the frozen soil make such fissures developed. The areas nearby the main deformation zone are in the high altitude slopes and foothills, where the soil layer is less in thickness than areas further away. Usually, the soil layer is less than 20m in thickness. At the same time, almost the entire soil layer is frozen. To the deeper, the bedrock presents. These facts explain why even the shaking intensity of the deformation zone is higher, there is yet hardly any shaking caused fissures developed. Away from the main deformation zone, the soil layer is much thicker and underlying the frozen soil, there is thaw soil layer sometimes. When the ground shakes during the earthquake, the thaw soil failures and induces the formation of the shaking caused fissures in the frozen soil above. Also, in places around rivers and lakes, since there are thaw soil in some place and the frozen soil layer is not very thick or even without frozen soil layer, it is easily to develop shaking caused fissures in these places. In the North of Kusai Lake, the development of shaking caused fissures is in a pattern of encircling the lake. The shaking caused fissures also indicate certain vertical movement toward the bottom of the lake, which formed ladderlike stripes on ground. In the riverbed of the Red River, shaking caused fissures are also developed in large number. They are of the similar mechanism of engendering.

Seismic subsidence and its mechanism. (Fig.9) The seismic subsidence is mainly found at the north of Kusai Lake. It is distributed encircling the lake. The width of the elongated area showing seismic subsidence is about 1~2Km on different section of the area. The maximum vertical fall between fissures can be as larger as 20cm while the accumulating vertical fall reaches 1.5m. The mechanism of the seismic subsidence is: under the 1 to 2 meter thick frozen soil layer there are thaw area which is created by the thermal conduction of the water. So the strong ground motion causes large amount of residual deformation, namely, seismic subsidence in these places. The nearer to the bank of the lake it is, the thinner the frozen would be and the thicker the thaw soil layer will. This is why the seismic subsidence is larger from relatively far away from the bank of the lake to the bank of the lake. The ladderlike stripes caused by the seismic subsidence are also caused by the same reason.

Fig. 9. Seismic subsidence caused ladderlike stripes in the North of the Kusai Lake

Liquefaction. One of the most worthy to pay attention geotechnical hazard is liquefaction developed in sand (Fig.10). Liquefaction is not very hard to be found in the frozen soil area.

(a)



(b)

Fig. 10. Sand boiling craters formed by the liquefaction

The places where liquefaction is mostly found are in north of Kusai Lake and in riverbed of Red River. The liquefaction occurs in mainly the deformation zone in riverbed and lakefront. The frozen boiling cones are composed of ice and sand. The sand is mainly of medium and fine sand. It has high sphericity and is well graded. Geological radar exploration shows that the liquefaction layer lies at around 3m underground and sand the water move upward along some of the channels (fissures or pores) (Fig.11). Obviously, the frozen soil layer is thin at the riverbed and the lakefront. The thaw soil layer below has high water content. During the earthquake, the pore water pressure in the thaw soil layer increases and liquefaction develops, which eject the sand out to the surface.

Further study on the liquefaction potential of the sand in Kusai Lake was carried out through laboratory test on the sample secured from the site where liquefaction occurred. The test apparatus used is composed of the following parts as Fig. 12 shows.

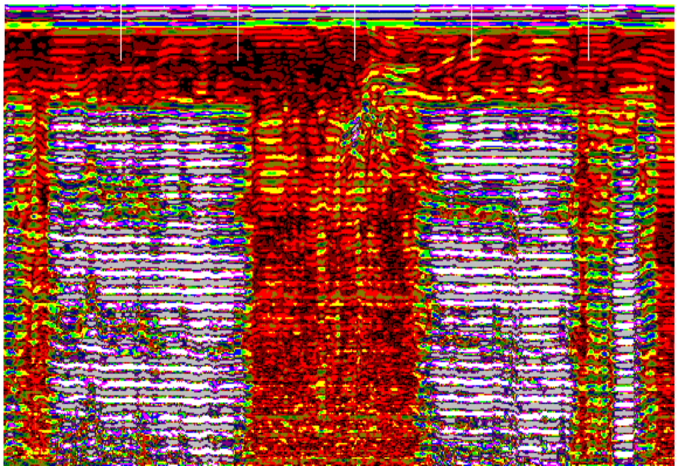


Fig. 11. Liquefied sand bodies underground which are light in the geological radar image

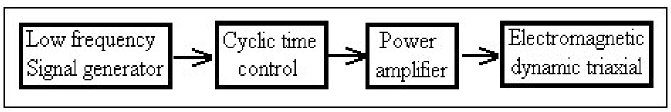


Fig. 12. The test apparatus used in liquefaction test

Through liquefaction test, the cyclic stress ratio obtained for different cyclic times. The consolidation stress for the samples is respectively 80, 140 and 200Kpa. The consolidation ratio Kc equals 1.0. The results are shown in Fig. 13.

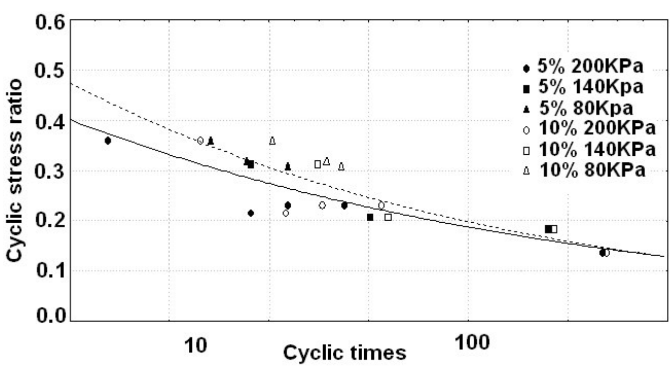


Fig. 13. The liquefaction test results for the sand in lakefron of the Kusai Lake

Based on the liquefaction test results, the calculation using the method proposed by the author (1997) shows that the minimum peak ground acceleration of triggering the liquefaction of thaw sand layer in Qinghai-Tibet plateau is 0.2g, which corresponds to intensity scale of VIII. Since many areas in the Qinghai-Tibet are in VIII intensity in the seismic zoning map of China, the problem of liquefaction of ground and roadbed should be take into consideration.

Rockfalls, earthfall and avalanche. Landslides are classified into five types according to their pattern of movement. These are slides, topples, falls, flows and lateral spread. The only type of landslide occurs in the area affected by the 8.1 great earthquake is fall (Fig. 14 to 16).

Fig. 14. The rockfall induced by the earthquake

Fig. 15. The earth fall induced by the earthquake

Fig 16. The avalanche induced by the earthquake

Most of the falls are of small scale. Rockfalls are mainly found in the riverbed of the Hongshui River. The rocks are the brick red sandy mudstone of Tertiary, which often formed steep landform.

The earthfalls of the frozen soil are mainly found in the North terrace of Kusai Lake, south piedmont of Yuantou Mountain and the terrace of Hongshui River. Most of sites where earthfalls developed are steep. The water content of frozen soil is relatively low and there are also fissures produced by the physical weathering.

Most of the avalanches induced by the earthquake locates in deformation zone of the south piedmont of Yuzhu Peak and the southeast piedmont of Bukadaban Peak. In south piedmont of Yuzhu Peak, the earthquake deformation zone cuts the Modern glaciers and induced the avalanches and the sliding of glaciers. The similar situation exists in the area near the deformation zone in the southeast piedmont of Bukadaban Peak.

5.CHARACTERISTICS OF GEOTECHNICAL HAZARD

5.1 The deformation zone is very large

The deformation caused by this earthquake is over 400Km in length, which overshadows the 240Km deformation zone of the 8.6 Haiyuan earthquake in 1920. The maximum width of the deformation zone is over 500m and the maximum horizontal displacement is around 6m. The overall scale of deformation zone and displacement of this earthquake is unprecedented in mainland China.

5.2 The intensity attenuates sharply from the fault

Not only the intensity attenuates quickly from the fault, but also the distribution of intensity on two sides of the fault is asymmetric. In the section around the Pass of Kunlun Mountain, record indicates that the seismic intensity at site 10Km north to the fault is already less than VIII. The width of the area with intensity VIII stands at around 30Km.

5.3 Geotechnical conditions clearly affect the distribution of the hazards

On the sites of bedrock or the sites with thick layer of frozen soil, the damage caused by the earthquake is slighter than that on the sites of thin frozen layer and, particularly, the riverbed and lakefront. Topographic condition also affects the intensity of the hazards. The steep landform incurs worse earthquake damage than the relatively flat landform. Finally, compared with other soils, frozen soil has higher seismic resistance.

6 CONCLUSIONS

- the geotechnical hazard caused by the 8.1 West Pass of Kunlun Mountain earthquake is plentiful. Both tectonic and non-tectonic hazards are widely found. The tectonic caused hazards are controlled by the rapture of the strike-slip fault. Non-tectonic hazards are determined by the intensity of the ground motion and the geotechnical condition.

- although the frozen soil has a higher strength and can stands higher seismic intensity before it fails, the existence of thaw soil layer and at certain sites like those of riverbed and lakefront, the seismic hazard could still be very high.

- the active tectonic movement in the Qinghai-Tibet Plateau makes the great earthquake like this inevitable. And the large ground displacement caused in such earthquake is really a problem for the seismic safety of important infrastructures and facilities.

REFENCES

Chen, W.B. [2002], “Preliminary Investigation on the Ms8.1 earthquake occurred on Qinghai-Xinjiang border”, Journal of Northwest Seismology, Vol. 24, No.1.

Dang, G.M and WANG, Z.J, [2002] “The basic characteristics of rapture and main earthquake hazard of the M8.1 earthquake in Kusai Lake of Kunlun Mountain in 14, November, 2001”, Letter of geology (China), Vol. 21, No.2.

Wang, L.M, Wang, J. and Li, L, [1999] “The method of liquefaction evaluation for loess sites in cities”, Journal of Northwest Seismology, Vol. 19, Supplement.

Xu, X.W and Chen, W.B, [2002] “The characteristics of the raptue of the Kusai Lake Ms8.1earthquake in Kunlun Mountain in 12, November, 2001”, Earthquake Geology, Vol 24. No.1.