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Seismically Induced Slope Instabilities and the Corresponding Treatments: the Case of a Road in the Wenchuan Earthquake Hit Region

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Abstract: On May 12, 2008, a magnitude 8.0 earthquake hit Wenchuan County, Sichuan Province resulted in great loss of life and properties. Besides, abundant landslides and slope failures were triggered in the most seriously hit areas and caused disastrous damages to infrastructures and public facilities. Moreover, abundant unstable slopes caused by the quake have the potential to cause damages for a considerable long period of time. The variety of these slopes and the corresponding treatments are connected with the topographical and geological conditions of the sites. It is decided to document and identify some of these major slope instabilities caused by the earthquake and their treatments. The paper shows the condition of a road in Dujiangyan through in situ explorations. The case history showed significant implications to the reconstruction of the quake-hit regions and future disaster prevention and management works.

Keywords: Slope failure; slope reinforcement; design; the Wenchuan earthquake; China

Introduction

The 2008 Wenchuan earthquake led to one of the major disasters in China. The severe ground shaking destroyed many buildings, and resulted in great casualties and properties. Besides, due to the mountainous terrain and geological conditions of the hardest hit areas, the magnitude 8.0 earthquake and many strong aftershocks triggered extensive slope failures due to the mountainous nature of terrain and unfavorable geological conditions in the hardest hit areas. These geohazards caused serious damages by burying houses even villages, blocking roads and rivers, destroying communication facilities and degenerating vegetation. Moreover, a large number of instable slopes caused by the quake have the potential to develop secondary hazards for a considerable long period of time in the future.

This paper is focused on the discussions of slope failures and instabilities induced by the earthquake and the corresponding treatments along a road, which were not documented following the Wenchuan earthquake. It is one of the first publications that provide a comprehensive view of slope failures and instabilities associated with the earthquake. As the rehabilitation of the quake-hit regions will begin soon, this paper is of significance for making reconstruction plan for these regions. Moreover, the case history shows significant implications to future disaster prevention and management works.

The 2008 Wenchuan earthquake, or Great Sichuan Earthquake which measured at 8.0 Ms, occurred on 12 May 2008 in Sichuan province of China. It occurred as the result of the motion on the Longmenshan faults (CEA 2008) on the northwestern margin of the Sichuan Basin. The earthquake reflected the tectonic stresses resulting

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from the convergence of crustal material slowly moving from the high Tibetan Plateau to the west, against the strong crust underlying the Sichuan Basin and southeastern China (USGS 2008).

There were certain special features of the Wenchuan earthquake that led to catastrophic events:

(1) The shallowness of the focus and the density of population greatly increased the severity of the earthquake (Wikipedia 2008). The Wenchuan earthquake is a shallow-focus earthquake with a focus depth of 19 km.

(2) Numerous aftershocks. Fifty-two major aftershocks, ranging in magnitude from 4.4 to 6.0, were recorded within 72 hours of the main tremor.

(3) Earthquake triggered geohazards. The epicenter is located in the mountains of the eastern margin of the Qinghai-Tibet Plateau at the northwestern margin of the Sichuan Basin. A large number of slope failures were triggered by the severe shaking, contributed by the geological and terrain conditions. In Beichuan County, a village with approximately 700 inhabitants was buried by a large landslide. Slope failures blocked all the roads in the most seriously hit areas closest to the epicenter, thus the time taken by rescue forces to enter the heavily affected areas is greatly prolonged due to traffic problems.

(4) Bad weather and persistent heavy rain in the earthquake hit areas made the condition of the geohazards more serious. Besides, the rescue efforts from air force were badly affected by the rainy weather.

Dujiangyan city is located at the foot of the Longmenshan Mountains, about 60 km northwest of Chengdu City, about 20 km east from the epicenter (Figure 1). The hillslopes, which were more vulnerable to slope failures by having favourable geological conditions, were chosen in the reconnaissance to explore the features and failures associated with earthquakes. This paper focuses on the issues of slope failures associated with the earthquake along a road. The studied case is the quarry road of a cement factory which is seated in Dujiangyan. The road was seriously damaged by the Wenchuan earthquake and the field was completely blocked off.

1 Types of Instable Slopes along the Road and the Corresponding Treatments

According to the exploration of the road, the geology of this area is dominated by sedimentary rocks. The elevation of the road ranges from about 910 to 1,300 above sea level in its 50 km length. The area is geologically composed of sandstone, breccia and limestone. Several types of instable slopes are seen and they can be categorized by potential failing mode as: shallow failure of soil slope, landslide, rock avalanche, surficial failure of rock slope and rock fall.

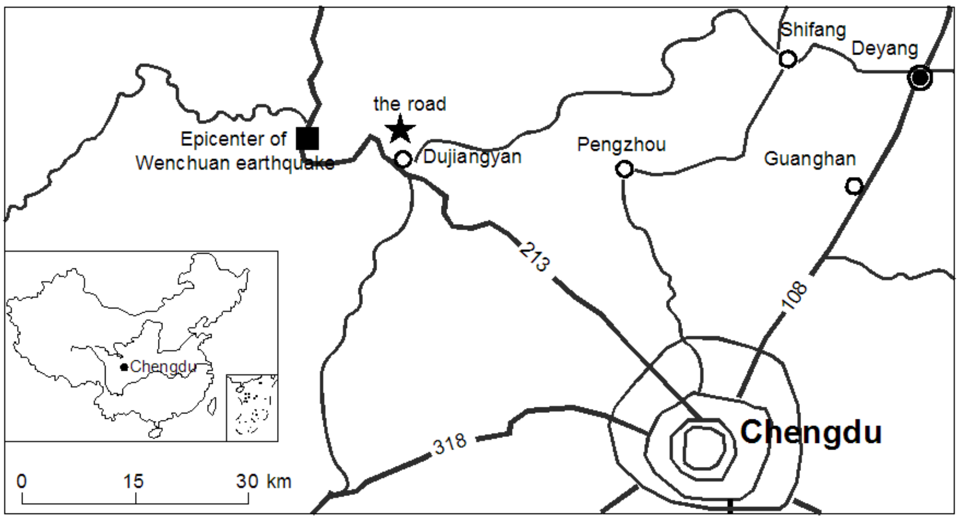

Figure 1 Location of the study road.

1.1 Shallow failure of soil slope

As shown in Figure 2, the slope is mainly composed of soil, and is considerably gentle. Due to the shaking caused by the earthquake the soil became loose, but the geometry of the slope results in a low probability of developing to deep seated landslide. So, retaining walls built of concrete or cemented rock blocks can be used to stabilize the slope. As the slope is stable, the scar surface will soon be recovered by vegetation because there are plenty rainfalls in the area.

Figure 2 Shallow failure of soil slope

1.2 Landslide

Earthquake induced ground shaking is one of the most frequent causes of landslides. Generally, soils composed mainly of fine grains are not considered to liquefy during earthquakes under any kind of cyclic loading (Zhang 2007). In this view, the shear strength of the slope shown in Figure 3 may have considerable high value, but as the soil has been disturbed by the quake and there is obvious deformation with the soil mass, the slope is in danger. Because the potential slip surface is deep, anchor bolt is not long enough to reach the stable ground beneath the failed surface, and thus can not prevent the slope from slipping downward. As a result, anchor ropes with or without prestresses will be used to provide sufficient resistant force to the instable soil mass. The reinforcing mechanism of anchors in slopes can be explained by the additional shear resistance, induced by the axial tension, on the slip surface (Cai & Ugai 2003). So this landslide can be treated by pretensioned anchor ropes and retaining walls.

1.3 Rock avalanche

Rock avalanches, sometimes called sturzstroms, involve the failure and disintegration of a large rock mass on a mountain slope and the

Figure 3 Potential landslide

Figure 4 A steep rock slope with fully developed cracks

rapid movement of this debris downslope and into a valley. The picture (Figure 4) shows a high and steep rock slope with fully developed joints and cracks, and thus is vulnerable to failures, such as rock avalanches and rock topples. As the cracks are deep in the rock mass, long anchor ropes are needed to fix the instable rock mass to the stable bed rock. So pretensioned anchor ropes with bolts are suggested to stabilize the slope. Besides, shotcrete may be applied to protect the slope surface.

Figure 5 Surficial failure of rock slope

1.4 Surficial failure of rock slope

Figure 5 shows a fractured rock slope face which is prone to surficial failure. Due to the intensive earthquake shaking and the undesirable geological conditions, this type of slope failure is very common in the studied area. As the slope as a whole is stable, slope surface protection method such as short rock bolts with shotcrete can solve the problem.

Figure 6 Large rock blocks and boulders fallen from the slope

1.5 Rock falls

The downward movement of rocks that fall off after separating from the bedrock is called rock fall(1). Limestone, siltstone and sandstone rocks fallen from the upslope can be seen along the road (Figure 6). The fallen rocks range greatly in size from over 1 m to several cm. To stop the boulders, very robust barrier fences with huge energy absorbing capacity are introduced in this place (Whittaker 2003). The design of these fences requires factors, such as slope geometry, the coefficients of restitution, the size and shape of rock boulders, and the coefficients of friction of the rock surfaces to be known. Rock traps work well in catching rockfalls, provided that there is sufficient room at the toe of the slope to accommodate these rock traps.

Figure 7 Development of cracks along the road indicates the instability of down slope of the road

1.6 Instability of down slope of the road

Site investigation shows that ground cracks, most of them were resulted from the earthquake, are intensively developed in the roadbed. As shown in Figure 7, cracks are seen extending

(1) Analysis of rockfall hazards, www.rocscience.com/library/pdf/RF_2.pdf [Accessed 15/6/2008]

along the road for about 50 meters, and settlement of the roadbed also is obvious. These factors indicate that the down slope of the roadbed may be not stable. Treatment of the down slope problems needs more detailed exploration to the site, and then retaining wall or piles can be chosen to stabilize the roadbed according to the depth of potential slip surface. Moreover, if the down slope has grown into a potential landslide, the investment costs may be very high, and thus it may be a better choice to change the road way provided that there is sufficient room near the old road.

2 Analyses and Conclusions

The major factors contributing to the above-mentioned slope failures are described as follows:

(1) Geological conditions: the geological structures in the studied area are considered young and thus have a high risk of rock falls and rock slides. The presence of joints, bedding planes, faults or other discontinuities may isolate rock blocks from their bedrock, and when the earthquake inertial forces act on these separating rocks, failures may occur in a moment. Moreover, the release of 'keyblocks' can precipitate rockfalls of significant size or, in extreme cases, large scale slope failures.

(2) Topography and geometry: Many near-vertical rock slopes that are susceptible to different types of failures were observed along the roadway. In this respect, the type of failure is primarily controlled by the orientation and spacing of discontinuities within the rock mass as well as the orientation of the excavation and the angle of inclination of the slope.

(3) Slope cuts: Construction of the road made abundant human cut slopes along the road (Figure 4). Slope cutting causes the instability of a slope in several manners. Firstly, high horizontal in-situ stresses acting roughly perpendicular to a cut slope may cause blocks moving outward due to the stress relief provided by the cut. Moreover, rock slopes are commonly excavated by drill and blast techniques. If improperly used, these excavation techniques can significantly alter the material properties of the rock mass comprising the slope. These alterations are more commonly evident as loosened rocks which result in a reduction of strength and a higher risk of earthquake failure.

The types and possible treatments of slope failures along a road in the events of strong earthquakes can be summarized as follows. Shallow failure of soil slope can be supported by soil retaining wall. Landslide can be treated by the combined action of prestressed anchor ropes and retaining wall. Treatment of rock avalanche should employ the coaction of pretensioned anchors, rock bolts and shotcrete. Problems caused by surficial failure of rock slope can be solved by short rock bolts coupled with shotcrete. Rock traps and barrier fences can be used to protect the road from the impact of rock fall.

Eventually, the studies on slope failures may lead to some suggestions for better future slope protection or slope stabilization designs and/or construction methodologies. Meanwhile, the experience gained from this case study also provides opportunities for better development of both earthquake disaster prevention research and practices in the future.

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