Geotechnical Hazards with Emphasis on Seismically-Combined Effects on Slopes

I.Towhata
Department of Civil Engineering, The University of Tokyo, Tokyo, Japan
E-mail: towhata@geot.t.u-tokyo.ac.jp

ABSTRACT: This paper first addresses several examples of complex or compound natural disasters with an emphasis of slope instabilities. In many of them, the first effect was produced by earthquakes and the second one was made by heavy rains. Weathering is another kind of the first event. Because the complex events are of stronger action, it is made more difficult to achieve safety. Hence discussion is often made of the importance of relocation of habitats to safer places and/or emergency evacuation. Technical visits to sites of such "soft" measures revealed that the success of those measures depends on education of people and the administrator's reasonable respect of the people's need for good jobs and reliable income.

1. INTRODUCTION

The recent world is demanding a more extent of safety under natural disasters than in the previous times. As compared with the situation one hundred years ago when the life safety was the most important and unique objective of disaster mitigation, today there are many issues to be achieved in addition. Among such issues are maintaining the functionality of facilities, risk assessment prior to the occurrence of natural disaster, and post-disaster actions. It seems that this change has been driven by the development of education level of people that makes people more valuable than before, and expansion of human habitats into formerly mountainous or soft-soil areas that did not originally suit safe living of people. In this situation, it is getting more important to understand the causative mechanisms of natural disasters so that probability of disasters may be reduced at reasonable cost.

The situation in nature is not stable. Many changes occur and some of them reduce the risk of disaster. However, there are adverse situations in which the risk increases with time. In particular, what is called the complex or compound disaster stands for a situation in which two or more natural disasters are combined and cause negative effects on the natural environment, producing more hazardous situations in an otherwise stable environment. Due to the apparently "stable" situation, little attention is paid to the risk and the induced disaster may be unexpectedly significant. Because most disaster-mitigation handbooks and manuals do not explicitly describe this kind of risk, it is important today to overview the situations and bear in mind what type of complex problem occurs under what situation.

The Asian Technical Committee No. 3 on geotechnical natural hazards, under the auspices of the International Society for Soil Mechanics and Geotechnical Engineering, has been studying the complex natural disaster. As the chairman of this committee, the present author herein describes the knowledge so far obtained through the committee activities and is going to discuss about its implications.

2. COMBINED EFFECTS OF EARTHQUAKE ON RAINFALL-INDUCED LANDSLIDERUCTIONS

There are many kinds of combined disasters in which two or more natural disasters are involved. In one situation, the first event triggers the second one, while in other situations two or more disasters occur independently but the consequence of the second one is made worse by the effects of the first event. The present chapter is going to address the second type with emphasis on the effects of a preceding earthquake loading on slope instabilities that are later caused by rainfall.

Figure 1 illustrates a mountain slope after the 2005 Kashmir earthquake. The big crack forms a channel for rain water to go into ground, increases the soil weight, reduces the effective strength, and possibly deteriorates the mechanical properties of soils (wetting / swelling). Moreover, the same earthquake somehow deteriorated the mechanical properties of a mountain slope behind a local capital of Muzaffarabad City. The failure of the surface started after the 2005 earthquake probably because the material (sedimentary rocks) was disrupted by shaking, many small cracks opened, and mechanical strength of the rock mass was lost. After the quake, the continuous failure of the slope and falling of debris have been a significant threat to the local community.

Figure 1 Earthquake-induced crack in mountain slope (after the 2005 Kashmir earthquake)

Figure 2 Continuous failure of mountain slope initiated by strong earthquake motion (in Muzaffarabad after the 2005 Kashmir earthquake)

As shown in the previous section, a strong earthquake shaking can trigger slope instability problems by means of development of big or small cracks. The duration of this instability may last hundreds of years. For example, the Ohya slope in Japan (Shizuoka Prefecture at about 100 km to the west of Tokyo) was most probably destroyed by the 1707 Ho-ei earthquake of Mw=8.7. Since then, slope instability has continued for 300 years (Figure 3) and produced debris flows upon every heavy rains. Because the present slope surface is still covered by unstable stones and debris (Figure 4), the hazardous situation will continue further unless effective stabilization measure is taken.

One possible mechanism of the long-lasting instability is that the loss of the surface material leads to the reduced effective stress in the underlying medium as well as the reduced surface protection from rain and temperature change. Consequently, the progress of mechanical weathering therein is accelerated. Finally this underlying material falls down and further lower material is exposed to weathering.

Similarly, the city of Beichuan in Sichuan Province of China underwent continuous slope failures and debris flows after the Wenchuan earthquake of Mw=7.9 on May 12th, 2008. Figure 5 illustrates two slope problems in this city. The upper one is a failure of mudstone slope that started after the earthquake and fell down repeatedly upon heavy rains. Another one seen near the bottom of the figure is a debris flow that came down along a valley. Both of them started after the earthquake. Because these geohazards could not be stopped, the local capital was moved from Beichuan to a safer place.

Figure 3 Unstable Ohya slope

Figure 4 Surface of Ohya slope covered by debris

In addition to the mechanical disruption of slope materials caused by earthquake motion, another mechanism of earthquake-induced slope problem is the debris deposits in valleys. Figure 6 illustrates a situation in Wenjiagou Valley of China in November of 2010 where a huge debris deposit was produced after the 2008 Wenchuan earthquake and the debris was washed by heavy rain in August, 2010. This case implies a long-term hazard of debris flow after a strong earthquake-induced falling of slope material into the valley. A similar disaster that occurred in the nearby Zhouqu County in China one week prior to this event (Ma, 2010) claimed more than fourteen hundred victims and was an important lesson to the Wenjiagou people. An early warning at the onset of heavy rain in the Wenjiagou area was able to evacuate people. However, Figure 7 shows that there is a town at the exit of the hazardous valley. Safety planning should relocate human habitations away from this dangerous place.

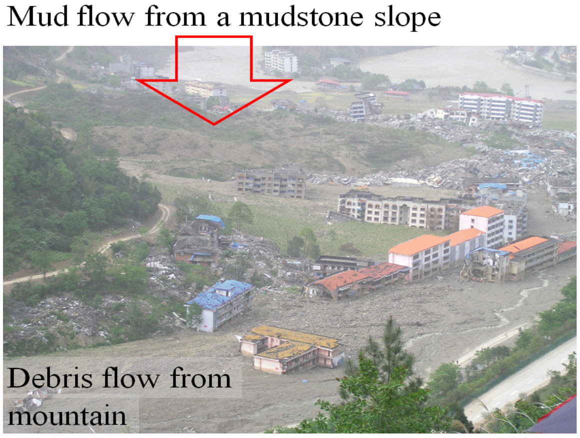

Figure 5 Continued geohazards in Beichuan of Sichuan Province in China after the earthquake on May 12th, 2008
(photograph taken on April 20th, 2009)

Figure 6 Huge volume of debris deposits in the valley bottom at Wenjiagou, Sichuan Province, China

Figure 7 Township located at the exit of a valley prone to debris flow

The cases introduced above make it possible to classify the combined effects of earthquake and rainfall into three groups as shown in Table 1. See the preceding earthquake effects continue for different periods of time, depending upon the mechanism of complexity.

Table 1 Classification of earthquake effects on post-seismic slope instability

Mechanism	**Effects on material properties**	**Lasting time of slope instability**
Crack opening and precipitation of water into soil	Generally no, but, if clay mineral absorbs water, swells, and deteriorates, yes.	Ending when slope with cracks falls down, but swelling effect may continue long.
Seismic disturbance and deterioration of material properties	Yes. Cementation and bonding are destroyed.	Quick recovery of deterioration is unlikely.
Washing out of debris deposits in valley	No.	Ending upon washing out.

3. OTHER COMBINED EFFECTS OF NATURAL DISASTERS

Volcanism is one of the natural phenomenon that lead to slope problems during later rain falls. Figure 8 illustrates a river channel through which "lahar" came from the slope of the Mayon Volcano in the Philippines. Lahar is a kind of mud-flow phenomenon in which fresh volcanic ash that deposits on a volcanic slope during eruption is washed away by heavy rainfall. The case of Figure 8 was caused by the typhoon Reming in 2006. This case will be addressed later from the viewpoint of emergency action.

Earthquake shaking and soil liquefaction may affect the likelihood of further disasters during following events. Figure 9 shows boiled sand at the foot of the Natori River levee near Sendai City immediately after the 2011 East Japan gigantic earthquake. It is easily expected that the stability of this levee was reduced during the tsunami attack that occurred soon after the liquefaction. It is peculiar that this particular levee was able to survive the tsunami attack in reality, but this fortune may not be always the case. Hence, more details should be studied. Note that many evidences of liquefaction in the Sendai area was washed away by the tsunami attack and further studies were made extremely difficult.

Another example is the situation in Figure 10 where buildings with pile foundation was overturned by tsunami pressure. Although no evidence of liquefaction is left available because of the tsunami, the coastal geology here strongly suggests onset of liquefaction. If this is the case, Figure 10 implies that liquefaction in the subsoil reduced the lateral and pull-out resistances of piles and made overturning of buildings easy. Thus, earthquake shaking and tsunami have combined effects.

The 1999 Chi Chi earthquake in Taiwan probably affects today the stability of mountain slopes. Figure 11 illustrates the rate of siltation (soil flux per year) at the Tsengwen Dam Reservoir in south Taiwan. It is interesting that siltation increased around the year of 1999 when the Chi Chi earthquake occurred, suggesting that the mountain slope was disturbed by the seismic shaking and more amount of soils are eroded afterwards during heavy rainfalls.

Figure 8 Lahar channel in Padang Village near Mayon Volcano

Figure 9 Liquefaction under the Natori River levee in 2011 (courtesy of Tohoku Regional Development Bureau, Ministry of Land, Infrastructure, Transport and Tourism)

Figure 10 Base of tsunami-overturned building with pile foundation in Onagawa Township

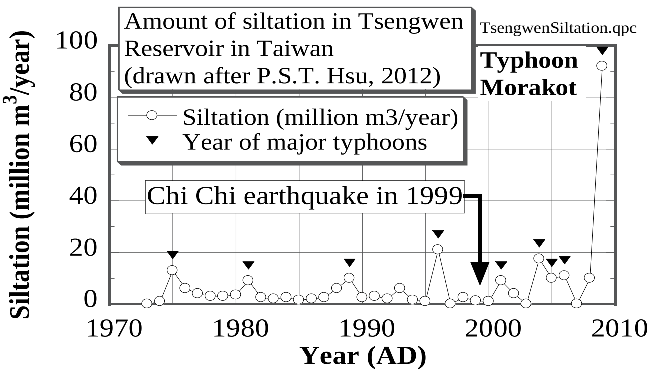

Figure 11 Siltation rate in Tsengwen Dam Reservoir (drawn after Hsu, 2012)

4. NON-SEISMIC DETERIORATION OF GEO-MATERIALS

Deterioration of soil is one of the agents that cause complex effects. Figure 12 illustrates a road embankment that failed upon the 2004 Niigata Chuetsu earthquake of Mw=6.8 in Japan. This road embankment was built across a small stream by using a locally available crushed mudstone. Because of hydration of the stream water, the mudstone turned back to the original mud and lost shear strength with time. Finally, the embankment failed upon earthquake shaking. Because similar failure occurred everywhere in the region during this earthquake, the emergency transportation was stopped and rescue as well as reconstruction of the damaged area was made extremely difficult. This case exhibits a kind of combined effects of physicochemical phenomenon and earthquake. Because mudstone embankment is not rare in the world, it seems that similar problems are going on at many places.

Figure 12 Earthquake-induced failure of road embankment made of crushed mudstone

5. RELOCATION TO SAFER PLACES

The combined effects as discussed above suggest that the real hazard may be more significant than is supposed without reference to the combined effects. Therefore, it is not a realistic idea, because of the economic reasons, to simply construct more powerful disaster prevention facilities. In this situation, relocation of human habitation to safer places is often discussed. The recent gigantic earthquake and the associating tsunami disaster in Japan are demonstrating an interesting problem concerning the relocation.

After the previous big tsunami disaster in 1933, relocation program was conducted extensively in the affected coastal area and people started to live at higher elevations. Fig. 13 shows one of the examples of this type. Later on, further safety efforts were made to construct a high sea wall (Fig. 14) so that the highest ever-known tsunami in 1896 would be stopped. Consequently, the local people felt safer than before and started to live at low places behind the wall. This situation led to a tragedy again in 2011 because the tsunami height exceeded the height of the wall. Houses at low elevation were totally washed away, while those at high places survived the disaster (Figure 15).

The fundamental problem here was that people had been wishing to live near the sea because the main industry in this locality was fishing. Obviously, low places are much more convenient for daily life than high places. Hence, the construction of the high seawall gave people a good reason to move to the low places. People in 2011 did not take the earthquake and tsunami alert seriously because they fully trusted the “high” sea wall. Unfortunately, the tsunami evacuation drills and education in the local community were not very helpful. Probably similar situation occurred at many other places and increased the number of victims.

Another problem in the discussion on relocation is the lack of concern with industries. The fish industries have to be situated near the tsunami-prone coastal area. Because the industries were completely destroyed in 2011 (Figure 16) and the future direction of the tsunami disaster mitigation is not decided, those industries cannot be reconstructed soon. This situation leads to the lack of employment and the local communities cannot be easily reconstructed. Thus, it is very important to take into account not only the relocation and the life safety but also protection of local main industries that the life of survived families would rely on.

Figure 13 Village at tsunami-free high place (Karani-Hongo, Iwate)

Figure 14 High sea wall against tsunami attack (Karani-Hongo)

Figure 15 Tsunami disaster behind the sea wall of Karani-Hongo (houses at higher elevations in the top right survived the tsunami)

Figure 16 Destroyed fish industry in Kesen-numa

6. RISK MITIGATION

The difficulty in mitigation of combined disasters lies in the fact that the extent of danger is increased by the first event of disasters. Since the increased problem is not accounted for during the original design stage, the risk is unexpectedly high. Thus, the construction of disaster prevention structures such as river levees, retaining walls, and slope reinforcement becomes more expensive. This is particularly true for the recent combination of earthquake and tsunami in Japan of which the recurrence period is possibly one thousand years and the huge monetary expenditure for disaster prevention appears too big. To avoid this problem, it is often mentioned that the disaster mitigation should employ such soft and less expensive measures as relocation and emergency actions. However, this "reasonable" idea still has problems. In this regard, this chapter attempts to investigate some details about relocation and emergency evacuation on the basis of information collected by visits and interviews with local officers and people.

In March, 2012, the author visited the City of Legazpi and the localities around the Mayon Volcano in the Albay Province in the Luzon Island of the Philippines. The Mayon Volcano has produced many lahar disasters in the recent times (Figure 8). The major principles for disaster mitigation are relocation and evacuation (Delos Reyes et al., 2006). The public sectors such as Albay Public Safety and Emergency Management Office (APSEMO) in Legazpi have been doing significant efforts to push forward this principle; in particular after the lahar disaster in 2006 that claimed 1266 casualties (Paguican et al., 2009). For example, the evacuation order is issued on the basis of precipitation intensity and people are forced to follow this order. In contrast, relocation program, by which people change the place to live, may not be easy to implement, although the program is assisted by economic dislocation compensation by which food and sleeping place are supplied by the government. As will be stated later, people prefer to live in their home places where business and working are easier.

The author visited several villages prone to the lahar disaster and talked with people. In the Padang Village in Fig. 8, a male person who was able to survive the 2006 disaster made the following remarks:

- Because his residence was destroyed, he is living in a temporary house in a safer place.
- He is allowed to come back to and work in the original home only in the day time, although some people stay overnight.
- Although the risk of lahar is understood widely, people still prefer their home place to live.
- His ancestors taught him a lesson to evacuate in high places during heavy rain.
- Around himself, senior people and children could not evacuate and were killed during the 2006 lahar.
- Because the local school, which was a designated evacuation center, had been attacked by flooding in the same year, evacuation order to the same place was difficult to issue.

One of the reasons for people to prefer their home place is the job and income. Many families live on collecting aggregates from lahar-filled river channels. Therefore, they need to live near the channels. Thus the risk and income are closely related with each other. This situation is similar to the problem caused by the destroyed fish industry in Fig. 16. Another important point is that people fully understand the problem of lahar and, as indicated by the ancestors' lesson, they are willing to evacuate during heavy rains. This makes the governmental evacuation order easy to be accepted.

In the village of Salvacion (Figure 17), people made the following remarks;

- Ancestors taught the danger of lahar as well as importance of evacuation.
- People do not feel 100% safe even if they live in a relocation place.
- When an official evacuation order is issued, they go to a designated place by a group; transportation is supplied by the government.
- People understand that the time lag between the evacuation order and the onset of lahar is a few hours.
- The main job of the people is collecting aggregates from the river channel.
- Relocation may reduce their income.

Figure 17 Salvacion village that is situated upon a relatively high place

Figure 18 Block manufacturing in lahar-prone area

Figure 19 River channel in San Rafael

A local block manufacturer in lahar-prone Barangay Bunot (Fig. 18) said that he wished to live in his home place because the place is next to a local main road where many customers come. Again, income is more important than relocation.

In San Rafael, a house wife in her 30s mentioned as what follows:

- Her family cannot move to a safer place because there is no money to employ a carpenter and build a new house, although land and building material are supplied by the government.

- The family collects aggregates from a river channel (Fig.19) behind her house.
- Children's school is close to the present place.

To summarize the interview, there are two important points that are;

1) People understand the importance of evacuation because they experienced a real lahar only a few ago (2006).
2) For many people, convenience for business and working is more important than relocation to a safer but less convenient place. In other words, daily income is essentially important.

If these points are generalized for disaster management for people,

1) emphasis should be placed on early warning and evacuation, while relocation may not be preferred by people,
2) disaster management experts should not forget the importance of earning income and making a living,
3) in other words, local main industries deserve special protection,
4) education and evacuation drill are essential because otherwise people would soon forget the risk of natural disasters, and
5) engineers should help local governments and people foresee the incipient risk and initiate evacuation by supplying such appropriate technologies as early warning and construction of an evacuation shelter (Figure 20).

Figure 20 Cyclone shelter in Myanmar

7. CONCLUSIONS

A combination of different disaster mechanisms worsens the situation and makes the damage mitigation more costly and difficult. The combined effects of several disasters are being considered more important than before because people desire more extent of safety today than before. However, the combined action is more significant than what is supposed in the current design principles, and achievement of the desired safety appears difficult or very expensive. To shed light on this problem, the present paper described the recent experiences and thoughts of the author who visited tsunami-hit areas in Japan and lahar-prone areas in the Philippines. Because the recent discussion on disaster mitigation often focuses the importance of "soft" measures in place of the traditional construction of "hard" measures, the author intended to study more details of the "soft" measures as seen from the people's side. The major findings and conclusions drawn are as what follows.

1) Relocation of habitation and evacuation in an emergency situation are absolutely important.
2) A construction of a protection structure made people misunderstand that they became absolutely safe.
3) Evacuation drill and education are necessary so that people understand the importance of efficient evacuation upon emergency.
4) In contrast, people may not want to relocate their homes to elsewhere because job and daily income at the original place are very important for their living.
5) Disaster management should not forget the importance of protecting local major industries even from very severe natural disasters because income is important for people and, after an extreme disaster, reconstruction of a damaged community relies on the people's activities.

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9. REFERENCES

Delos Reyes, P. J., Bornas, M. A. V., Arpa, M. C. B., Daag, A. S., Maximo, R. P. R., Mirabueno, M.H.T., Perez, J.S., Aquino, A.T., Laguerta, E.P., and Solidum Jr., R.U. (2006) Lahar and flood hazards mapping and assessment after super typhoon Reming and Typhoon Seniang, Report of investigation, PHIVOLCS (Philippine Institute of Volcanology and Seismology).

Hsu, P. S. T. (2012) Tsengwen reservoir siltation problem and remedial strategy, Personal communication.

Ma, D. T. (2010) Some suggestions on controlling catastrophic debris flows on Aug. 8th, 2010 in Zhouqu, Gansu, Journal of Mountain Science, ISSN 1-008-2786, 28(5), pp. 635-640.

Paguican, E. M. R., Lagmay, A. M. F., Rodolfo, K. S., Rodolfo, R. S., Tengonciang, A. M. P., Lapus, M. R., Baliatan, E. G., and Obillem, E. C. (2009) Extreme rainfall-induced lahars and dike breaching, 30 November 2006, Mayon Volcano, Philippines, Bulletin of Volcanology, 71(8), pp. 845-857.