TECHNICAL ARTICLE
ON COMBINED EFFECTS IN NATURAL DISASTERS AND THEIR MITIGATION

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Recently, the first author had a chance to submit a technical note to some journal. The content of that manuscript addressed recent experiences and findings during many technical visits at natural disaster areas. The first author hereby use one part of the article for readers' information concerning what is called the combined effect.

The combined effect stands for a situation in which two or more disasters occur simultaneously or sequentially and aggravate the results. In one situation, the first disaster 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. Because the former situation appears to be very rare, this article addresses the second type. Because of the nature of this bulletin, the content mainly concerns slope problems.

The author made a technical investigation in 2005 immediately after the Kashmir earthquake. Among many slope failures in weathered surface materials, the situation in Fig. 1 was impressive in that the crack apparently provided a water channel into the subsoil. During a rainy season, the surface run-off water would easily flow into the slope and increase the weight of soil, reduce the effective stress, and possibly deteriorate the mechanical properties of the submerged soils. Thus, the negative effects of a heavy rain fall were made worse by the preceding strong earthquake shaking, which is herein called the combined effect.


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

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

It was peculiar that the same earthquake triggered a long-term slope failure in a mountain behind a local capital of Muzaffarabad City (Fig. 2). Possibly the mechanical properties of the rock was disturbed by strong shaking and minor cracks were created. Consequently, the continuous failure of the slope and falling of debris especially during heavy rains have been a significant threat to the local community. These cases described above illustrate a combined effect of earthquake and rainfall.

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There are more examples, similar to the aforementioned ones, where a preceding strong earthquake impact induced a long-lasting slope instability problem during rains. Fig. 3 illustrates the Ohya slope in Japan (Imaizumi et al., 2005; Shizuoka Prefecture at about 100 km to the west of Tokyo) that was most probably destroyed by the 1707 Ho-ei earthquake of Mw=8.7. Since then, slope instability and debris flow upon every heavy rain have continued for 300 years, and slope stabilization works are going on intensely even now. This situation will continue further as suggested by the current slope surface that is still covered by unstable stones and debris (Fig. 4).

Fig. 3 Unstable Ohya slope.

Fig. 4 Surface of Ohya slope covered by debris.

Fig. 5 Slope failure that occurred during the 2008 Wenchuan earthquake.

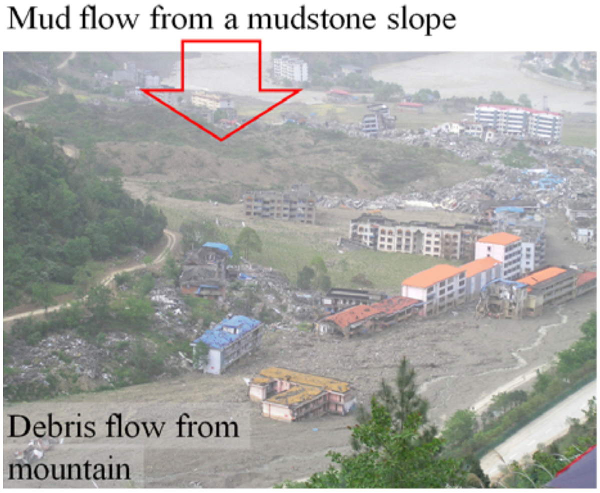

Fig. 6 Continued slope disasters in Beichuan after the earthquake on May 12th, 2008 (photograph taken on April 20th, 2009).

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Similarly, the Sichuan Province of China has suffered from many slope failures and debris flows after the 2008 Wenchuan earthquake of Mw=7.9. During the earthquake, first, many slope failures occurred; see Fig. 5. It seems that the many mountain slopes were disturbed significantly by the strong shaking, even if they did not fall down, and produced instability problems during the following years. One of the examples of this type of disaster is found in the local capital city of Beichuan. Fig. 6 illustrates two slope problems in this city. The upper one is a failure of a mudstone slope that started after the earthquake and the slope has been falling down repeatedly upon heavy rains. Another one seen near the bottom of the photograph is a debris flow that came down along a valley. The channel of this debris flow is extremely unstable (Fig. 7) and therefore the problem will continue for many years from now on. Both problems started after the earthquake. Because this dangerous situation could not be overcome by emergency works, the local capital was moved from Beichuan to a safer place.

Fig. 7 Debris channel behind Beichuan City.

Fig. 8 Debris flow in front of Yinxiu City.

The epicenter of the Wenchuan earthquake was near Yinxiu City. In 2008, an expressway was under construction to connect this city as well as Wenchuan City, both being situated in a mountainous area, with the main part of the Sichuan Basin. Although the construction was stopped for some time because of the earthquake, it was resumed and became nearly completed in the part near Yinxiu. In 2010, however, a heavy rain induced debris flow and destroyed the expressway (Fig. 8). Probably because of this unstable slope conditions along this part of the expressway, the expressway is now situated in the center of the valley; away from the slope and hence above river water.

Fig. 9 Huge volume of debris deposits in the valley bottom at Wenjiagou.

A similar but much more significant disaster occurred in August, 2010, in Zhouqu County that is located to the north of the Wenchuan earthquake area. Heavy rain triggered a huge amount of debris flow that attacked a township and claimed one thousand and four hundred lives. Ma (2010) stated that the debris came from valley deposits that were produced by an earthquake in the 19th Century. This is a kind of combined effect of an earthquake and rain fall.

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Fig. 10 Township located at the exit of a valley prone to debris flow.

The tragedy in Zhoqu was a good lesson to local officials. One week later, another heavy rain occurred in a mountain area of the nearby Sichuan Province. Because the valleys in the area had a significant amount of debris deposits because of slope failures during the Wenchuan earthquake, an evacuation order was issued immediately. Fig. 9 illustrates a situation in Wenjiagou valley in November of 2010 where a huge debris deposit was washed by heavy rain. This case implies a long-term hazard of debris flow after a strong earthquake induced falling of slope material into the valley. Although human life was thus saved, more fundamental care is needed of land use and development design. Fig. 10 shows that there is a town at the exit of the hazardous valley. Safety planning should relocate human habitations away from this dangerous place.

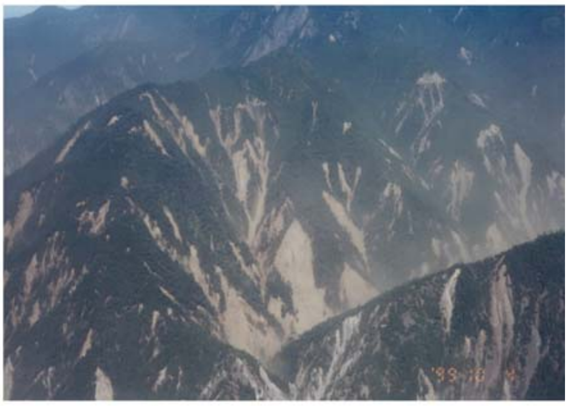

Fig. 11 Slope failures caused by the 1999 Chi Chi earthquake in Taiwan.

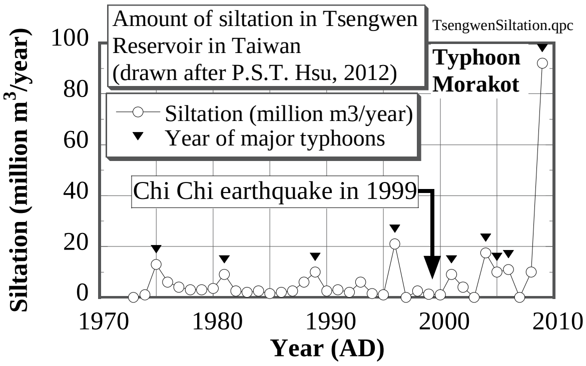

Fig. 12 Siltation rate in Tsengwen Dam Reservoir (drawn after Hsu, 2012).

The 1999 Chi Chi earthquake in Taiwan probably affects today the stability of mountain slopes; see Fig. 11. Fig. 12 illustrates the rate of siltation (soil flux per year) at the Tsengwen Dam Reservoir that is situated in the downstream area in south Taiwan. Generally, the extent of siltation has increased in the years when strong typhoons, particularly the Typhoon Morakot (Lee and Towhata, 2010), hit the upstream area. From a long-term viewpoint, however, it is further interesting that siltation increased around the year of

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1999, possibly suggesting that the mountain slope was disturbed by the Chi Chi earthquake and more amounts of soils are eroded afterwards during heavy rain falls.

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 disaster combination.

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.

ON RELOACTION AND EVACUATION FOR DISASTER MITIGATION

Combined disasters are more powerful than an individual event whether they occur simultaneously or sequentially. To manage this extreme condition, it is often stated that relocation to safer places and/or evacuation in advance are essential. The case of Fig. 9 is one of the successful examples of this idea. It seems, however, that there are still points to be noted. In this regard, the authors visited the Mayon Volcano area in the Philippines and interviewed local people about the ongoing disaster mitigation efforts against lahar. Lahar is a flow of volcanic debris that is induced by heavy rain. Because the ash deposit was made by a preceding volcanic eruption, lahar is a combined disaster caused by eruption and rain.

The Mayon Volcano (Fig. 13) is a very active volcano in the Albay Province, Luzon Island, the Philippines and measures 2,463 m in altitude. It erupts very often and deposits ash in its slope. The disaster mitigation program has been conducted by a public sector named Albay Public Safety and Emergency Management Office (APSEMO) in Legazpi City. Its basic activities are relocation and evacuation (Delos Reyes et al., 2006). The ongoing program is accepted and supported by local people because they remember a very bad lahar disaster in 2006. The information obtained from interviews in several villages is introduced in what follows.

Fig. 13 Mayon in Albay Province of the Philippines.

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Fig. 14 Lahar channel in Padang Village.

In the Padang Village that was devastated by lahar in 2006 (Fig. 14), a male resident 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 and work in the original home only in the day time, although some people stay overnight on their own risk.
- Although the risk of lahar is understood widely, people still prefer their home place to live.
- His ancestors taught him a lesson to evacuate at high places during heavy rain.
- Around himself, senior people and children could not evacuate 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.

In spite of the lahar risk, people still prefer to come back to their home place because of the job and income. Many families wish to live near lahar-filled channels because their main income comes from collecting aggregates from river beds. Therefore, the risk and income are closely related with each other. 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 Salvacion Village (Fig. 15), 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 onset of lahar is a few hours.
- The main industry is collecting aggregates from the river channel.
- Relocation may reduce their income.

Noteworthy is that the current risk of lahar is low because Mayon has not made big ash eruption since 2006 and hence there is not much ash deposit in the mountain slope. Accordingly, people use river channel for small agriculture (Fig. 16). This implies that people are keen to work in order to make their living even along slopes within the 6-km Permanent Disaster Zone (PDZ).

A local block manufacturer in lahar-prone Bunot Village (Fig. 17) said that he wished to live in his home place because the home was next to a local main road where many customers come. Again, income is more important than relocation.

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Fig. 15 Salvacion village that is situated upon relatively high place.

Fig. 16 Small agriculture in lahar-prone river channel.

Fig. 17 Block production in lahar-prone village of Bunot.

Fig. 18 River channel in San Rafael.

In San Rafael, a house wife in her 30s mentioned 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. 18) behind her house.
- Children's school is close to the present place.

In summary, people understand the importance of evacuation because they experienced a devastating lahar only a few years ago (2006) and a minor one in 2011. At the same time, however, 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. Accordingly, the following points have to be borne in mind by disaster mitigation managers and engineers so that the mitigation programs would be successfully accepted by people;

1) Emphasis should be placed on early warning and evacuation, while relocation may not be fully preferred by people.
2) Hence, disaster management experts should not forget the importance of earning income and making a living.

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4) In other words, local main industries deserve special protection.
5) Education and evacuation drill are essential because otherwise people would soon forget the risk of natural disasters.
6) 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.

PEOPLE'S EMPIRICAL KNOWLEDGE OF SAFETY

Nature is complicated and there are many things that we do not know yet. In particular, modern engineering relies on stress-strain-strength issues and often misses what cannot be accounted for by analytical-numerical approaches. In contrast, many animals are able to sense risk in advance and avoid it. As one of the animals, human beings should have a similar sense but probably have lost such a sense significantly. It is, however, still possible to find non-engineering wisdom for disaster mitigation at different places. One of the aims of a damage reconnaissance after natural disasters is to find such wisdom.

Figure 19 indicates a situation in an alluvial fan near the capital (Timpu) of Bhutan. An alluvial fan is subject to flooding and other slope disasters. In contrast to old and abandoned houses that are situated behind a protection of forest, newer houses are located in the center of the fan which is more convenient for working. This may imply that recent people are forgetting old wisdom and put more emphasis on daily conveniences. Fig. 20 indicates that houses are located on parts of a slope that did not fail during the 2004 Niigata-Chuetsu earthquake in Japan. The first author was impressed after that earthquake to find that people's residents were not much affected by slope failures, while public buildings that came only recently were situated on less stable parts of slopes and were affected by the earthquake-induced slope failures. Probably the long (nearly 1000 years) history of the local community has taught people which parts of slopes are safer.

Fig. 19 Location of old and new houses in an alluvial fan near Thimphu of Bhutan.

Fig. 20 Houses located on safer parts of seismically affected slope (Yamakoshi Village, after 2004 Niigata-Chuetsu earthquake, Japan).

Relocation of human habitation to safer places is often discussed. The recent gigantic earthquake and the associating tsunami disaster in Japan are demonstrating a significant problem concerning the relocation. After the previous big tsunami disaster in 1933, a relocation program was conducted extensively in the affected coastal area and people started to live at high elevations. Fig. 21 shows one of the examples of this type. Later on, further safety efforts were made to construct a high sea wall (Fig. 22) so that the highest ever-known tsunami in 1896 would be stopped. Consequently, the local people felt safer than

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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 (Fig. 23).

Fig. 21 Village at tsunami-free high place (Karani-Hongo, Iwate).

Fig. 22 High sea wall against tsunami attack (Karani-Hongo).

Fig. 23 Tsunami disaster behind the sea wall of Karani-Hongo (houses at higher elevations in the top right survived the tsunami).

Fig. 24 Tsunami water level well above the sea wall and close to the entrance gate of a local shrine.

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 were 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. Fig. 24 indicates that the tsunami reached an elevation much higher than the wall and close to the entrance gate of a local religious shrine.

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An interesting wisdom of people reasonably suggests the ever-greatest height of tsunami. This height is now very important for design of the local communities subjected to extremely high but rare tsunami. In the affected region, the record of tsunami in the modern sense dates back only to 1896. Height of older tsunamis may be found only by excavation of soil for deposits of tsunami sand. In addition to this way of study, another approach to the ever-highest tsunami is supplied by the location of holy gates of shrines (Fig. 24). Since the gate and shrine are holy, local people have been reconstructing shrines at higher and safer places after every tsunami disaster. Hence, today, it is possible that the elevation of the gate indicates the highest level of past tsunami; probably a record in the past 1000 years or so. This time length is much longer than modern written records and therefore is very useful. Recent trips of authors to the tsunami-hit area found many holy gates that are located immediately above the tsunami run-up height (Figs. 25 - 28). This probably means that the tsunami in 2011 was one of the highest in the past 1000 years or so.

Fig. 25 Shrine in Onagawa.

Fig. 26 Shrine gate in Rikuzen-Tokura.

Fig. 27 Shrine gate in Ohtsuchi.

Fig. 28 Shrine in Taro.

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CONCLUSIONS

This article intends to demonstrate an idea of combined effects of two or more natural disasters that occur sequentially and worsen the consequence. Several cases indicate that the combined effects in slope instability during heavy rainfall are induced by preceding earthquakes in terms of material deterioration and/or cracks that affect the mechanical properties of rocks or allow more surface water to come into the depth. The worsened situation requires the increased effort for safety in spite of the increased cost. To accommodate this cost, “soft” approaches such as relocation and evacuation are often discussed. It is noteworthy therein that people considers the way of daily income as important as or more important than the life safety during an emergency situation. Finally, discussion was addressed to non-engineering wisdom for safety that local communities acquire after a long time of life under critical conditions.

ACKNOWLEDGEMENT

The authors’ visit and interview in the area of Mayon Volcano was made possible through the collaboration with the University of the Philippines (UP), Philippine Institute of Volcanology and Seismology (PHIVOLCS) as well as the Albay Public Safety and Emergency Management Office (APSEMO). In particular, the assistances supplied by Dr. A. A. Acacio of UP, Dr. R, U. Solidun, Jr. and Dr. A. S. Daag of PHIVOLCS, and Dr. C. D. Daep of APSEMO are deeply appreciated. Moreover, another technical visit at the Tsengwen Reservoir in Taiwan was arranged by Prof. A. B. Huang of National Chiao Tung University in Taiwan. Their contribution and kindness are sincerely appreciated by the authors.

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.

Imaizumi, F., Tsuchiya, S., and Ohsaka, O. (2005) Behaviour of debris flows located in a mountainous torrent on the Ohya landslide, Japan, Canadian Geotechnical Journal, 42, 919-931.

Lee, W. F. and Towhata, I. (2010) Geotechnical structure damages during the 2009 Typhoon Morakot, Bulletin of ISSMGE, March, pp. 25-35.

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), 635-640.