Coseismic and Post-Seismic Slope Instability along Existing Faults

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Abstract. The world in the 21st Century faces increased hazards of gigantic earthquakes and heavy rains as compared with the previous century. Under this circumstances, coseismic landslide is one of the important topics in geotechnical earthquake engineering and is promoted by the increased precipitation both before and after the gigantic earthquakes. This paper shed light on this topic, paying attention not only to the effects of strong shaking but also to the important role played by faults, which are either active or inactive. The fault action consists of the rock fissures along the fault and possible water ejection from the fault plane. The rock fissures made by the fault dislocation causes the long-term instability of mountains slopes for years or for centuries after strong shaking.

Keywords: earthquake-induced landslides, slope instability, rock rupture, fault.

1 Introduction

The traditional concept on coseismic landslides has been that the shear stress induced by the seismic inertial effects in conjunction with the gravity exceeds the material shear strength of the mountain body and that the hazard extent has to be assessed without detailed subsurface investigation. The second issue is simply due to the financial limitation that cannot take care of the vast vulnerable mountain areas in which the topography and material properties as well as geo-hydraulic conditions are highly variable. Because of this limitation, there is always a possibility of unexpected coseismic landslide disaster during real earthquakes. In the recent times, we are aware that the types of coseismic landslide disaster is not limited to the fall of materials during shaking. The newly recognized problems, although they did occur and were problems in the past, are the landslide dams, the compound effects of seismic shaking and heavy rains and the long-term slope instability and sediment disasters that last for years or for decades after the causative earthquakes. Moreover, the fault rupture is now recognized as a threat to the human community nowadays, in contrast to the past when the fault rupture was just a target of scientific/geological studies. This situation is a consequence of the spreading human activities in mountainous and hilly terrains where human did not live. With these changing situations in mind, the author summarized the latest situations of coseismic landslides in [1]. Because the content of this publication is vast, the present paper attempts to pick up what is related with fault and show details.

2 Effects of rainfall on coseismic landslides

Science and technology achieved profound development from 1970s to the end of the 20th Century when people started to demand more safety under natural disasters and the public sectors are more supportive of improved safety. It appears that many important principles and design codes were made in those decades and are still used widely at the present time. We have to know, however, that the situations in those great decades and today may not be identical and that the previous way of thinking may not be valid today. The difference from the past is not limited to the growth of human population and spreading of human habitations into difficult natural conditions. The natural conditions are changing in the meantime as well.

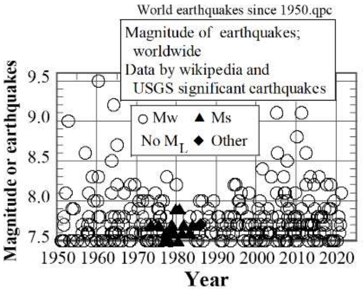


Fig. 1. History of major earthquakes in the world.

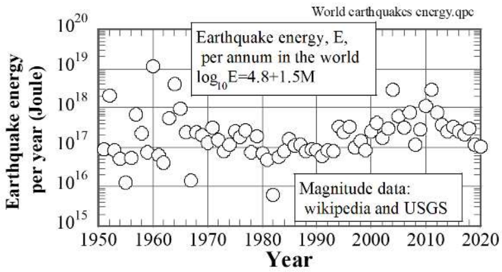
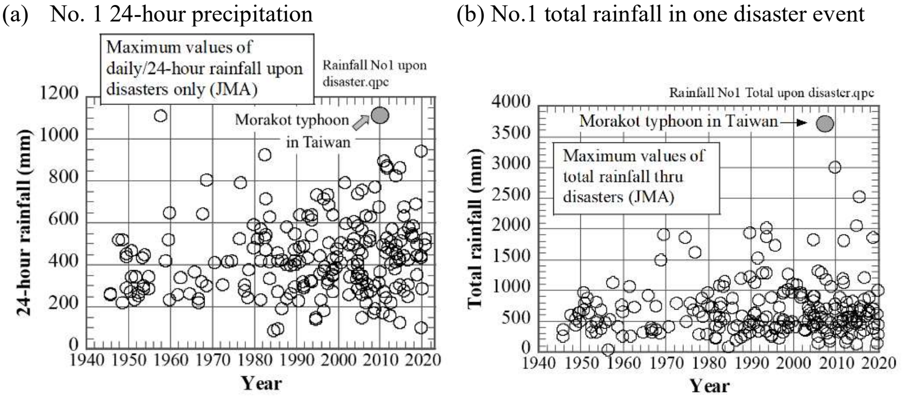


Fig. 2. History of annual earthquake energy in the world.


(a) No. 1 24-hour precipitation

(b) No.1 total rainfall in one disaster event

Fig. 3. History of rainfall records in Japan that triggered disasters since 1945.

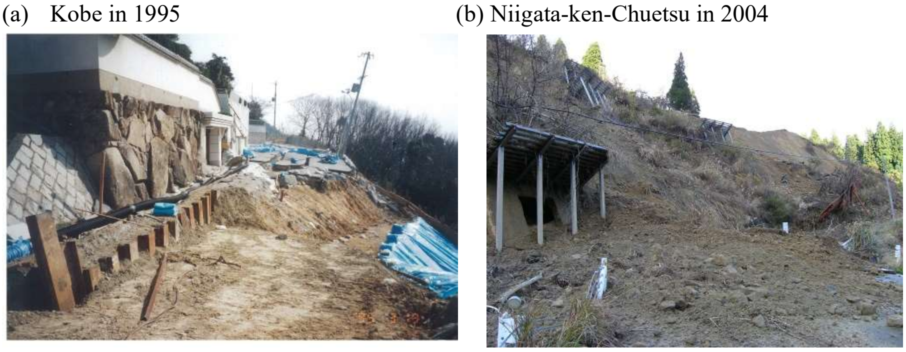
Fig. 1 plots the seismic magnitude of major earthquakes in the world that happened since 1950s. For most events, the moment magnitude was plotted in this diagram, while, for some events, the moment magnitude value is not available and other types are used here. It is evident in this figure that gigantic earthquakes with their moment greater than 8.5 did not occur from the aforementioned decades (1970s, 80s and 90s) of technology development in contrast to the years in the 21st Century. Fig. 2 employed the same dataset and indicates the change of annual earthquake energy release all over the world. The earthquake magnitude was converted to the energy by using the equation by [2], which is shown in this figure. It is evident again that the earth was relatively quiet in those decades of technology development, while getting more active since the beginning of the 21st Century. This increasing trend is stressed by the two gigantic earthquakes in 2004 (in Indian Ocean) and 2011 (Tohoku, Japan) but, even without them, the increasing trend in the first 10 years of the Century is evident. Although it is difficult to say further about this trend, it is reasonable that we may not be able to fully rely on the safety frameworks that were developed during the relatively quiet years of the earth and to expect more safety than before. In other words, the experiences in the 20th Century should be reviewed and, if necessary, revised in the 21st Century.

This situation is worsened by the recent increasing trend of precipitation that is a very important cause of flood and landslide disasters. The recent increase of rainfall is possibly a consequence of the global climate change but I cannot make any definite remark on this issue. Only what I can do is to present data recorded and reported by established institutions. While many institutions have been publishing the annual or extreme daily rainfall records that are increasing, I collected the only precipitation records that induced flood and sedimentary disasters in Japan since 1945 [3]. Because a heavy but short rainfall event does not trigger disaster, Fig. 3 indicates the nation's No. 1 rainfall record of one-day (or recently 24-hour) precipitation as well as the total rainfall during one disaster event. It is shown here that the upper bound of the disastrous rainfall have been increasing since 1990s, implying that the risk of significant rainfalls has been aggravating for the past 30 years. By combining the views on earthquakes and rainfalls, it can be said that the risk of the compound disasters as induced by earthquakes followed by heavy rain or, conversely, the antecedent rainfall followed by earthquakes is becoming significant nowadays.

The effects of the antecedent rainfall are captured by looking at Figs. 4 and 5 that illustrate the less important occurrence of coseismic landslide during the 1995 Kobe earthquake (Mw=6.9) together with the rainfall history together with the similar information of the 2004 Niigata-ken-Chuetsu earthquake (Mw=6.6) (for their locations, see Fig. 6) which was preceded by a heavy rainfall and was associated with many coseismic landslides.

An interesting phenomenon was reported by Oike [4] who investigated the correlation between the onsets of small but many earthquakes (tremors) and rainfalls along the Yamazaki Fault in Japan. It was demonstrated that more tremors occurred after heavy rainfalls and high level of ground water. This implies that the pore water pressure in the ground increased after infiltration of rain water, leading to reduced effective stress and shear strength in the earth crust. Accordingly, the shear strength in the underlying faults decreased and the earthquakes were made easier to occur.

The knowledge obtained from the reality show that water effect is significant in stability of earth crust and most probably the mountains slopes. It deserves attention that local rainfall may trigger minor earthquake along an existing fault.


(a) Kobe in 1995

(b) Niigata-ken-Chuetsu in 2004

Fig. 4. Coseismic landslides induced by two different earthquakes with similar magnitudes.

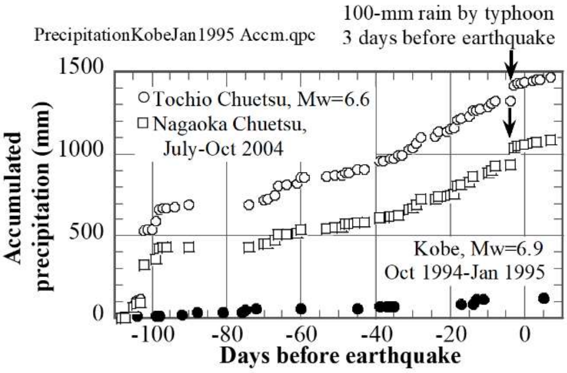


Fig. 5. Antecedent rainfall records prior to the 1995 Kobe and the 2004 Niigata-ken-Chuetsu earthquakes.

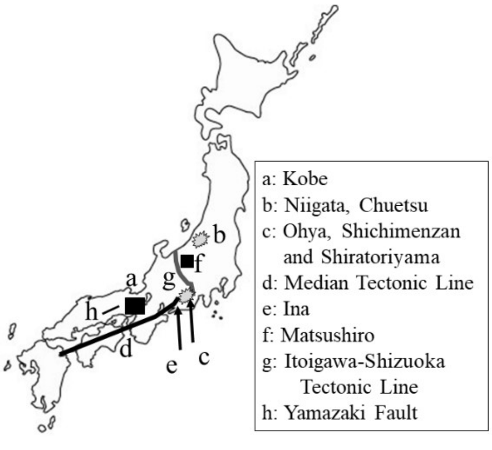


Fig. 6. Location of the sites prone coseismic slope instability.

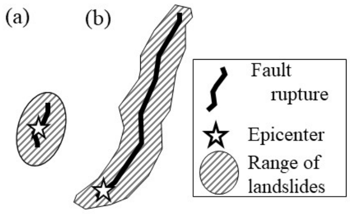


Fig. 7. Schematical illustration of the effects of fault length on landslides distribution.

3 Distribution of coseismic landslides along existing faults

3.1 General issue

Discussion in this section begins with the distribution of coseismic landslides along the causative faults that generate the seismic shaking. In the past, the studies on earthquake-induced landslides were interested in the effects of epicentral distance on the extent of landslides [5, 6, 7 and 8]. In contrast, the gigantic earthquakes in the 21st century (the 2005 Kashmir earthquake of Mw=7.6 and the 2008 Wenchuan earthquake of Mw=7.9) demonstrated that many coseismic landslides were distributed along the fault rupture. This difference is probably because the studies in the 20th Century collected data from earthquakes of smaller magnitude and shorter fault length, while the events in the 21st Century had greater seismic magnitude and longer fault length; see Fig. 7. Although the intensity of shaking varies with the distance from the fault rupture plane, the greater fault length situates the landslides geometrically along the fault rupture. Fig. 8 shows the coseismic landslides during the 2005 Kashmir earthquake. Noteworthy is that the 2016 Kaikoura earthquake of Mw=7.8 triggered a number of coseismic landslides along the fault rupture, while the epicenter at the southernmost part of the rupture was out of the landslides area [9]. Therefore, the “distance” is unlikely the only major factor that controls the likelihood of coseismic landslides.

Fig. 8. Landslides along the fault valley caused by the 2005 Kashmir earthquake (south of Balakot).

3.2 Ohya and Shichimenzan Landslides in Central Japan

The present paper calls attention upon the effects of existing fault, which is not necessarily the causative fault, on the landslides induced by an earthquake. Figs. 9 and 10 show the landslides at Ohya and Shichimenzan in central Japan (Fig. 6). Both sites have been unstable for many centuries. Legends say that the Ohya landslide was triggered by the 1707 Hoei earthquake of Mw=8.7-9.3 with the volume of the failed sediment = 94 million m^3 [10]. The other one at Shichimenzan is old as well, having been unstable at the latest since the 13th Century as historical documents in AD 1278 refers to it [11].

What is interesting is that both landslide sites are located close to the Itoigawa-Shizuoka Tectonic Line (Fig. 6) that transversally crosses the Honshu Island of Japan in N-S direction and is associated with many local faults in the parallel direction (Fig. 11 as well as [12]), which implies a complicated history of tectonic stress in this region. Consequently, the rock mass has been undergoing the effects of both the movement of the nearby faults and the regional tectonic stress, and are fractured profoundly. The unstable situation in these landslides sites can be captured in Figs. 9 and 10. The disrupted rock (Fig. 12) and the rock mass folding (Fig. 13) imply the highly unstable condition of the rock mass at Ohya site. This material property is most probably related with the creep deformation of the mountain body at both sites (Figs. 14 and 15). Because of the unstable condition, the slopes of Ohya and Shichimenzan sites have been undergoing continuous instability and landslides over centuries

Fig. 9. Landslide at Ohya, Shizuoka, Japan.

Fig. 10. Landslide at Shichimenzan, Shizuoka, Japan.

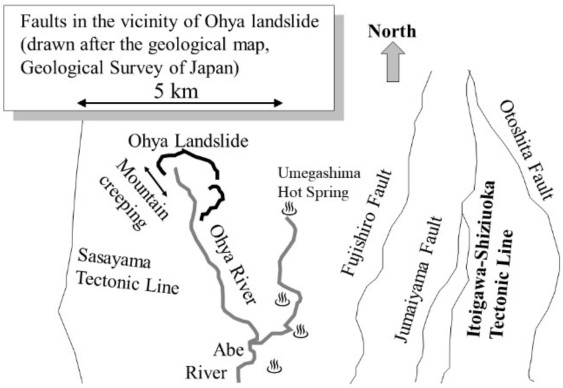


Fig. 11. Location of local faults around the Ohya landslide site (drawn after a geological map, Geological Survey of Japan).

Fig. 12. Fractured rock of Ohya landslide site.

Fig. 13. Folded rock mass of Ohya.

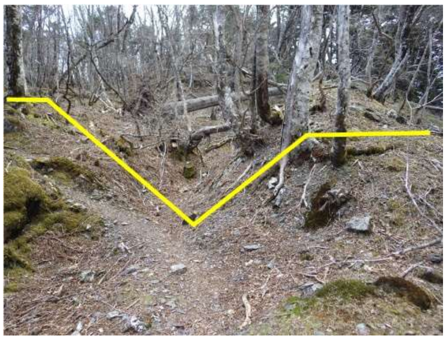


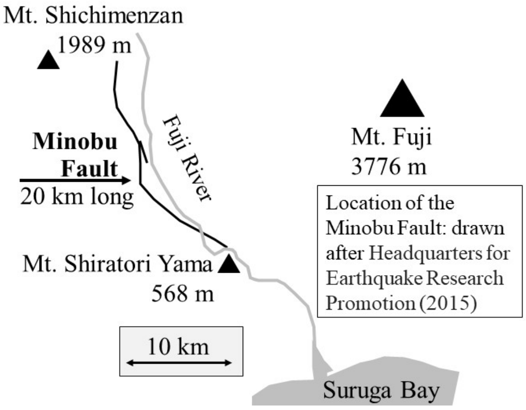
Fig. 14. Creep deformation at Ohya..

Fig. 15. Small lake formed by creep deformation/depression of Shichimenzan Mountain.

3.3 Shiratori Yama, Japan

To the south of Shichimenzan (Fig. 6), there is another unstable mountain body that is called Shiratoriyama Mountain (Fig. 16). Although low (568 m in altitude), this mountain caused coseismic landslide disasters twice in the recent history; in 1707 upon the Hoei earthquake of Mw=8.7-9.3 and in 1854 upon the Ansei Tokai earthquake of Mw=8.4-8.6. During both events, the landslide mass blocked the Fuji River channel at the bottom (Fig. 17) and, most probably, the dam breaching caused further disasters. It is thought that the 1707 landslide left a substantial amount of material at the top which partially fell down in 1854 [13]. Still there is a big mass of earth at the top.

Shiratoriyama mountain appears very fragile, comprising fractured or broken pieces of rock: Fig. 18 illustrates the mountain surface near the headscarp where there are many cobbles that are said to be a product of geological procedure. It is noteworthy in Fig. 16 that this mountain is located near the southern tip of Minobu Fault that has recently been registered as an active fault [14]. There are possibly the effects of fault movement on the quality of the rock mass of the mountain. It should be stressed that rock fracturing effect of a fault can remain for a long time even if the fault has ceased its activity and is not considered active anymore.



Location of the Minobu Fault: drawn after Headquarters for Earthquake Research Promotion (2015)

Fig. 16. Location of Shiratoriyama Mountain and Minobu Fault [14].

Fig. 17. Shiratoriyama slope that failed in 1707.

Fig. 18. Cobbles on the flank of Shiratoriyama near the headscarp of the failure in 1707.

3.4 Landslides along the Longmenshan Fault after the 2008 Wenchuan earthquake, China

The long-term instability of mountain slopes was a serious problem in Sichuan Province of China after the Wenchuan earthquake [15]. In addition to the coseismic landslides in May, 2008, the heavy rainfall in September triggered additional landslides in the fault-affected area. Fig. 19 illustrates one of the examples of the post-seismic disasters in which the debris came from the coseismically disrupted mountain slope behind the town (Fig. 20). Fig. 21 shows another landslide caused by the post-seismic heavy rain. This landslide occurred in a slope made of mud stone that had been most probably prone to deterioration by infiltration of rain water (or slaking) and could not remain stable. Obviously, there are two kinds of post-earthquake instability caused by 1) mountain slopes disrupted by strong shaking (generation of cracks and fissures) as shown in Fig. 20, and 2) rainfall erosion of soil deposits on slopes and in valley bottoms. The former case implies the vulnerability of mountain slopes along faults under strong shaking. It took 5-7 years for the mountain slopes to be stabilized and recover vegetation cover (Fig. 22).

Fig. 19. Buildings in Yinchanggou Gully destroyed by debris flow during post-seismic rainfall.

Fig. 20. Disrupted mountain slope as the source of debris flow.

Fig. 21. Landslide to the west of Qushan Zhen induced by post-seismic rain.

Fig. 22. Recovery of vegetation on slopes that was failed in 2008 (picture taken on May 15 2018).

3.5 Landslides along the Ina part of the Median Tectonic Line, Japan

The Median Tectonic Line (MTL) is a long and old fault that runs in the approximately E-W direction in the western part of Japan (“d” and “e” in Fig. 6). It started its activity in the Cretaceous Period [16] and the dislocation to date has accumulated to 60 km [17] or more. Fig. 23 shows one of the MTL outcrops in the Ina region. It is hence reasonable to expect the fault-induced fracture of rocks along it. While very little is known about the activity of MTL (causing earthquakes) during the historic times (in the past 1500 years or so), its Ina section triggered two damaging earthquakes in 8th Century (probably in AD 715) and then in 1718. Fig. 24 illustrates one of the sites of the historical coseismic landslides in Tohyama Village of Ina. The more serious problem along MTL is the instability of mountain slopes undergoing heavy rainfalls. Fig. 25 shows the site of Ohnishi Yama landslide (1961) and Fig. 26 indicates the ongoing instability at Tobigasu.

Fig. 23. Exposed fault dislocation at Itayama within the Ina section of MTL.

Fig. 24. Site of historical landslide triggered by Tohyama earthquake of Magnitude = 7 in 1718.

Fig. 25. Ohnishi Yama landslide site Immediately upon MTL.

Fig. 26. Tobigasu slope failure along MTL

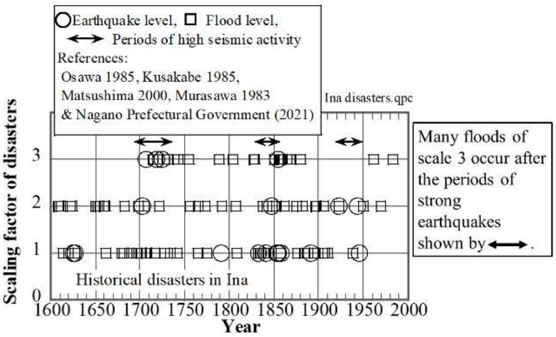


Fig. 27. Possible correlation between severe seismic effects and landslide disasters during their aftermath (data by [18-21]).

In line with the previously-described sites, it is likely that the MTL dislocation in the past affected the mechanical property of the mountain slopes in the Ina region. This idea seems supported to a certain extent by the landslide disasters as shown in Figs. 24 and 25. In this perspective, Matsushima [18] assembled the historical data on earthquakes and landslides in Ina, which are both coseismic and non-seismic. The

Author added a few more data to his study and plotted the results in Fig. 27. Although the severity of earthquakes and landslides in this figure is prone to the subjective judgment of researchers, it appears that floods and landslides were more frequent after the strong seismic shakings in early 18th and middle 19th Centuries.

3.6 Landslide induced by water ejection and seismic tremors in Matsushiro, Japan

Matsushiro in Central Japan (Fig. 6) was affected by seismic tremors in middle 1960s (Fig. 28). This event was characterized by substantial water ejection and induced landslides. JMA [23] presents photographs of significant water ejection from hot springs in the area. Eventually, a huge landslide was triggered by water ejection. The mechanism of water ejection-induced landslide is simple and understandable from the soil-mechanic viewpoints; pressurized water came up from the deep elevation and increased the pore water pressure in the slope, while the total stress was unchanged, thus reducing the effective stress and shear strength in the slopes. Later, water injection tests were conducted in Matsushiro [24] in order to verify that the increased water pressure triggered the fault rupture at depths by reducing the effective stress. The landslide site remains vacant today due to the possible risk of reactivation of water ejection and landslide (Fig. 29).

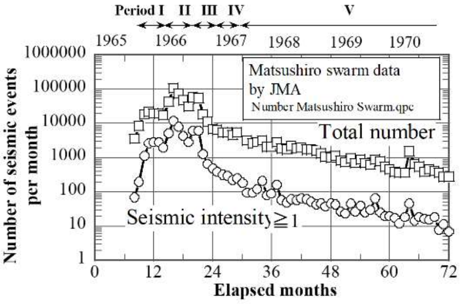


Fig. 28. History of tremors in Matsushiro.

Fig. 29. Present view of the Makiuchi landslide site.

4 Long-term instability of slopes after big earthquakes

Section 3.4 addressed the slope instability that started after the earthquake and lasted for many years. Similar problem occurred after the 1999 Chi-chi earthquake in Taiwan (Mw=7.6) and Pakistan in 2005 (Mw=7.6). Fig. 30 shows the extent of slope instabilities within a selected area along the East-West Crossing Highway in the mountainous area of Taiwan Island. It appears that the size of slopes affected by typhoons and rainfalls after the Chi-chi earthquake increased drastically but then decreased slowly towards the original level. This decreasing process took twenty years. During this process, however, there was a positive correlation between the amount of rainfall and the increment of landslide area (%) (Fig. 31), suggesting that the decreasing landslide size in Fig. 30 was possibly the consequence of less amount of rainfall during the post-earthquake years. To investigate the rainfall effect quantitatively and illustrate the vulnerability, the vulnerability index was defined by

Vulnerability index = [*Areal increment ratio (%) in Fig. 31*] / [*Total rainfall (mm)*] (1)

and plotted in Fig. 32. It is now evident that the vulnerability decreased with the elapsed time after the earthquake, implying that the stabilization of the mountain slopes took twenty years after the Chi-chi earthquake. Noteworthy is that the mountains slopes in Sichuan Province, China, took shorter time for recovery (Fig. 22). This is probably because of the rainfall difference between two regions as well as the geology; Taiwan Island is prone to heavier rainfall and geological weak rocks are subject to more weathering. Moreover, the island is more or less 30 million years old "only" and rock is not so lithified yet.

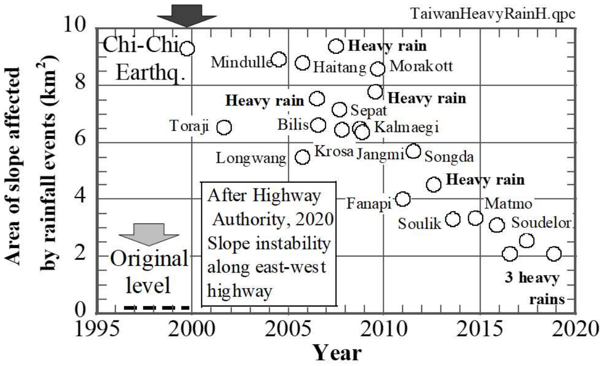


Fig. 30. Summary of slope instability in Central Mountain of Taiwan drawn after data of Highway Office of Taiwan [25].

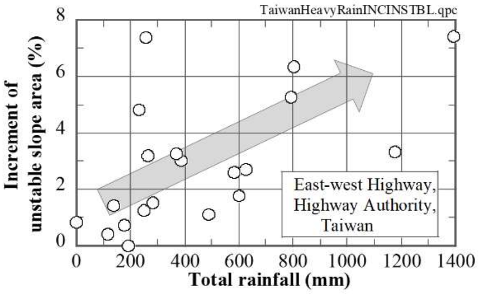


Fig. 31. Relationship between ratio of rainfall-induced increment of landslide area and total rainfall during disasters in Central Taiwan [25].

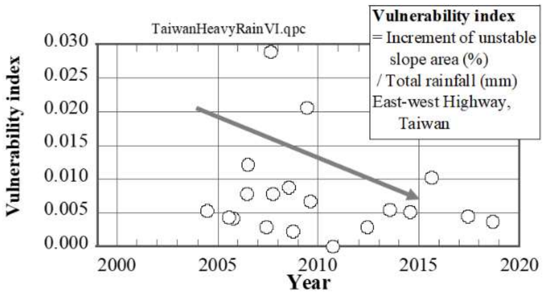


Fig. 32. Temporal change of rainfall vulnerability of slopes in Taiwan [25].

In clear contrast, the Ohya and Shichimenzan slopes (Figs. 8 and 9) have been unstable for centuries. One possible reason for this is many and frequent strong seismic events caused by the 1707 (Mw = 8.7-9.3) and 1854 (Mw = 8.4-8.6) earthquakes as well as many events in the past. The other reason is the weak geology as indicated by the fractured rock mass (Fig. 12) as a consequence of the accumulated damaging effects of the fault action.

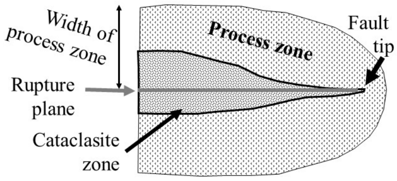


Fig. 33. Definition of rock damage around the fault plane (drawn after [25]).

The fault effect mentioned above is otherwise called the process zone and its width (Fig. 33) was originally supposed to be 1% of the fault length on the basis of field inspection [26]. Fig. 34 illustrates this 1% correlation together with the results of more literature information collected by the author. This figure shows that “1%” is a good value for the upper bound of the process zone width while there are narrower width at several places. Note that the judgement of the process zone is subject to personal judgment and difference.

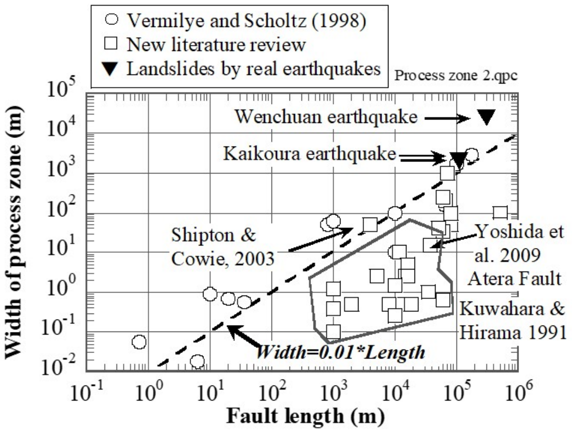


Fig. 34. Empirical relation between the width of process zone and the length of the causative fault [26-29].

5 Slope instability along pull-apart mechanism of strike-slip faults

The pull-apart mechanism of a strike-slip fault produces a basin where a unique geotechnical problem occurs. Fig. 35 illustrates schematically the mechanism of a pull-apart basin where the lateral extension of the earth crust results in vertical compression and depression. One of the examples of this type of geomorphology is the Izmit Bay of Turkey whose southern coast line was affected by subsidence (Fig. 36) and submarine landslides [30].

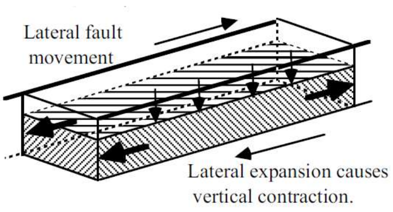


Fig. 35. Basin formation by pull-apart mechanism.

Fig. 36. Subsidence of the coast line of the Izmit Bay.

In a more striking manner, many landslides occurred on September 28th, 2018, in the pull-apart basin of Palu, Central Sulawesi of Indonesia, after an earthquake of Mw=7.5 (Fig. 37). This basin is the product of highly active Palu-Koro Fault with the mean rate of dislocation being 30 mm/year or more [31]. The following section discuss briefly the causative mechanism of the landslides.

Fig. 38 shows one off the four big landslides that occurred in the Balaroa area in the southwestern suburb of Palu City. The size of this landslide was 0.85 km in length and 0.58 km in width, making the area 0.39 km^2, while the ground gradient was merely 2 % on average. Similar to the other three landslides of this type, the surface soil of about 3-5 m in thickness suffered from liquefaction and the slope instability was induced. The induced soil displacement in the horizontal direction was 500 m or more, which was notably greater than those of other liquefaction-induced displacement in gentle slopes (typically 1-2% gradient) that were merely several meters [32]. The similar extent of displacement occurred in other three big landslides in Palu Basin as well. The notably long distance of displacement implies that the disaster in Palu Basin had something special in its mechanism.

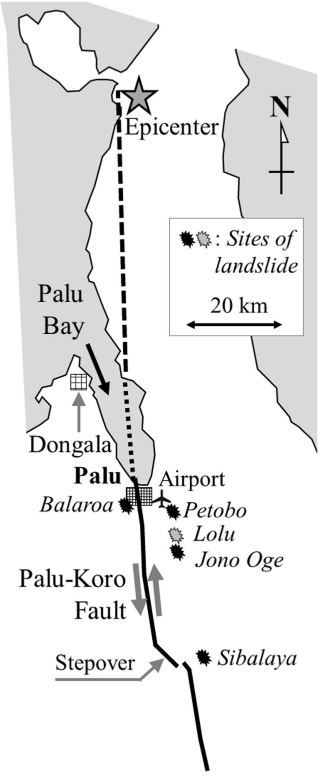


Fig. 37. Sites of liquefaction-affected landslides around Palu City in 2018.

The second special feature of the landslides was the existence of substantial ground water ejection as evidenced by the water springs recorded five weeks after the disaster in the exposed slip plane (Fig. 39). Springs were found in other landslide sites as well. It should be recalled that the ample ejection of ground water during the Matsushiro swarm that triggered landslides as mentioned before. The source of this ample ground water is not necessarily the irrigation channel or leakage from local sewage system because the Balaroa site does not have either such a channel or evidence of leakage (Figs. 40 and 41). Accordingly, there seems to be very special feature in the local geology, geohydrology and soil conditions in the four landslide sites. They are special because occurrence of similar landslide is not known elsewhere in the world.

Fig. 38. Landslide at Balaroa.

Fig. 39. Water spring observed at the bottom of Balaroa landslide on November 2nd, 2018.

Fig. 40. Lack of irrigation channel above the headscarp of Balaroa landslide.

Fig. 41. Dry headscarp of Balaroa landslide.

Extensive study has been made of the causative mechanism of these landslides. Among several ideas, the undrained softening of loose sand (Fig. 42) was declined first because the laboratory tests on undisturbed specimens did not exhibit it. The second mechanism to be studied was the formation of water films at the interface between less pervious silty layer and the underlying liquefied sand (Fig. 43). When the excess pore water pressure dissipates after liquefaction, the drained pore water remains below the layer interface and forms a “film” with null shear resistance, thus making large shear deformation easy [33-36]. This mechanism is possible in Sulawesi [37] but a question arises why the same disaster has not been known elsewhere despite that the interbedding of more and less pervious layers is not uncommon in alluvial fans over the world. Another issue is that the water film mechanism requires a continuous and smooth film of water over the entire landslide area, which may not be very likely.

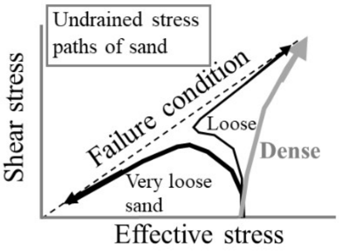


Fig. 42. Schematic illustration of undrained stress paths of sand.

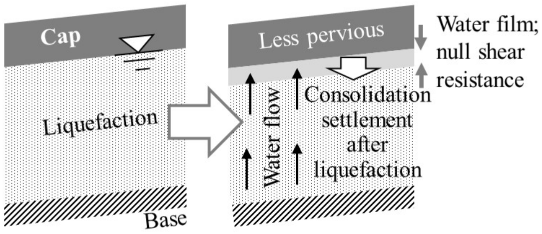


Fig. 43. Mechanism of water film formation during pore pressure dissipation after liquefaction.

The Author pays attention to the two features that are special to the Palu Basin. First, the four big landslides associated with liquefaction occurred in slightly low spaces between bigger alluvial fans (Fig. 44). This suggests that the long-distance mass movement was a process of new fan formation by which the existing fans were produced long time ago. It is speculated that the pressurized water aquifers as suggested by many local springs were destroyed by the earthquake and the out-blow of water uplifted the surface soil crust, enabling its long-distance flow. Because the alluvial funs are several km long, the induced flow displacement was long as well.

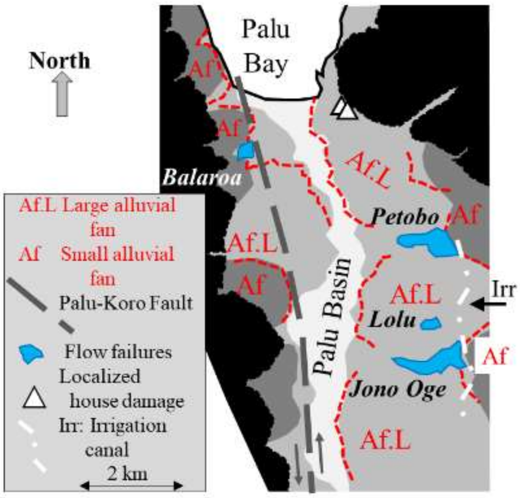


Fig. 44. Location of landslides between existing alluvial fans abbreviated as “Af”.

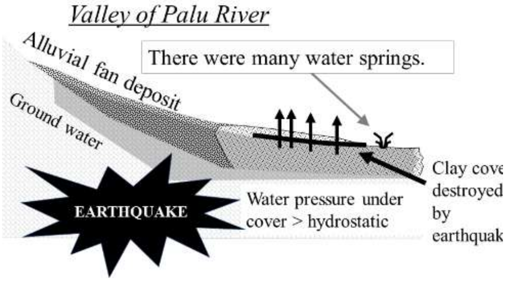


Fig. 45. Mechanism of water out-blow from underground pressurized aquifer.

The second possible mechanism [38] is related with the underground fault plane [39]. Because of the pull-apart depression, there are many normal faults parallel to the edge of the basin. There are many springs and hot springs in the basin as well, some of which are under artesian pressure. All in all, it is supposed that a substantial amount of water blew out through the normal fault planes at the time of the earthquake, making the entire landslide mass slip immediately. In other words, it might be possible that the high pore water pressure in the fault plane induced the earthquake, similar to the Matsushiro swarm.

To date, no conclusion has been achieved yet and discussion is going on. The difficulty is that there is no other example of such a landslide in clean sand both internationally and in the past in Sulawesi.

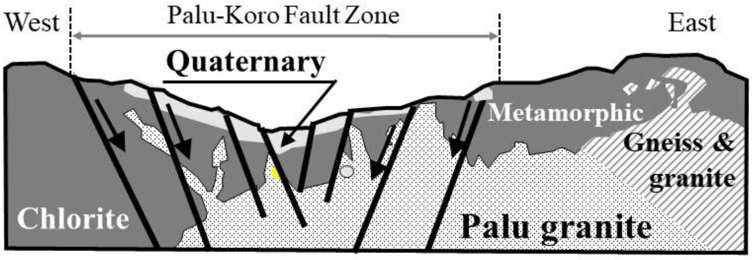


Fig. 46. East-west geological cross section of Palu Basin (drawn after [39]).

Conclusion

The magnitude of earthquakes and rainfalls are greater in the 21st century than in the late 20th century when the current practice of disaster-mitigation engineering was developed. It is therefore important to attempt a new and different perspective on natural disasters in the new century. In the traditional approach of soil mechanics to coseismic landslide problems, the effect of ground water was considered just in terms of the formula of “total stress – pore water pressure = effective stress.” However, the recent experiences of real coseismic landslides suggest that the ground water is producing the pore pressure effect through many dynamic or mysterious mechanisms. Such a mechanism seems more intensified along faults, whether active or inactive, where rocks are fractured by the continuous fault dislocation. The author attempted to introduce the examples of such a situation to the readers and invite them to further studies.

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