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Characteristics and mechanisms of earthquake-induced landslides according to recent events and studies

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ABSTRACT: According to events and studies on landslides of rock slopes due to recent earthquakes mainly in Japan, the author remarks some differences of the characteristics and mechanisms among landslide phenomena. Rockfalls occur by the seismic inertia force on steeper reverse-dip slopes as topples and falls, which consist of loosen rock or jointed rock material in shallow portions. On the other hand, rockslides occur on gentler dip slopes as translational or rotational slide, which develop surface gravitational deformation, consist of mainly bed rock and intercalate sandy, silty or clayey strata of slip plane. Furthermore, rockslides are caused not by the seismic inertia force but by the cyclic shear load which results in both decrease of shear strength and liquefaction with excess pore water pressure of slip plane in earthquake duration.

1 INTRODUCTION

Many earthquake-induced landslides have occurred on rock slopes in the seismically active areas of the world. In Japan, earthquake-induced landslides have caused hundreds of deaths and billions of dollars in economic losses in recent years. Since Japan situates on the subduction of both the oceanic Pacific plate and the oceanic Philippines plate beneath both North American plate and Eurasian plate.

Characteristics and mechanisms of earthquake-induced landslide have been discussed based on their numerous historical records induced by seismic ground motions. For example, Voight & Pariseau (1978) introduced the distance at which earthquakes can trigger landslides is subject to the following: the stability of the potential slide mass, the orientation of the earthquake in relation to the slide mass, earthquake magnitude, focal depth, seismic attenuation, and aftershock distribution.

Wyllie & Mah (2004) introduced the performance of rock slopes during earthquakes by Keefer (1984, 1992) that the following five slope parameters have the greatest influence on stability during earthquakes:

- *Slope angle* Rock falls and slides rarely occur on slopes with angles less than about 25°;
- *Weathering* Highly weathered rock comprising core stones in a fine soil matrix, and residual soil are more likely to fail than fresh rock;
- *Induration* Poorly indurated rock in which the particles are weakly bounded is more likely to fail than stronger and well-indurated rock;
- *Discontinuity characteristics* Rock containing closely spaced or open discontinuities are more susceptible to failure than massive rock in which the discontinuities are closed and healed; and
- *Water* Slopes in which the water table is high, or where there has been recent rainfall, are susceptible to failure.

However, these discussions are mainly about effects of shaking acceleration on the site. There were few discussions about the slope instability in earthquake duration except, for example, Newmark (1965) and Gucwa & Kehle (1978).

Newmark (1965) proposed that in the case the displacement on slip plane increases, the slope should be unstable with decrease of slip plane, because the repeated inertia of the sliding mass by downward acceleration pulse results in residual strength of slip planes during earthquake motions.

Gucwa & Kehle (1978) mentioned that earthquake loading is suggested as a cause of elevated pore fluid pressure or an equivalent loss of strength during earthquake duration, and catastrophic slope failures accompanying earthquakes are the result of soil liquefaction caused by the cyclic loading of the soil; this load occurs with the upward passage of seismic shear waves.

Previous discussions above are almost proved by recent events. However, according to events and studies on recent earthquake-induced landslides of rock slopes mainly in Japan, the author remarks that there are several differences in performance between types of earthquake-induced landslides: rockfall and rockslide, and some rockslides occur on the slopes with angles less than about 25°. We have investigated their mechanisms concerning topography, geology, groundwater condition and soil strength under dynamic stress, and discussed particularly rockslide occurrence during cyclic shaking duration of earthquake. As a result, we suggest that rockslides occur owing to both excess pore water pressure by liquefaction and decrease of shear strength by particle breakage of slip plane.

In this paper, earthquake-induced landslides of rock slopes are classified into rockfalls and rock-slides based on the principles and terminology of Varnes (1978). Rockfalls are defined as rock descending of individual boulders or disrupted masses on slopes by bounding, rolling, free fall or toppling. Whereas rockslides are defined as rock mass movements by rotational slump, translational slide including deep-seated block slide, and lateral spread.

2 EARTHQUAKE GROUND MOTION RELATING TO ROCKFALLS OR ROCKSLIDES

Recently, many landslides have occurred in Japan and its adjacent area as follows: East Nagano Earthquake (Eq. ; 1984, M6.8), Hokkaido south-western offshore Eq. (1993, M7.8), South Hyogo Eq. (1995, M7.2), Taiwan-Chi chi Eq. (1999, M7.6), Chuetsu Eq. (2004, M6.8), Noto peninsula Eq. (2007, M6.9), Chuetsu offshore Eq. (2007, M6.8), Iwate/Miyagi inland Eq. (2008, M7.2), China-Bunsen Eq. (2008, M7.9), East Japan Eq. (2011, M9.0), Kumamoto Eq. (2016, M7.3), and East Iburi of Hokkaido Eq. (2018, M6.7).

According to studies of both these events and earthquake-induced landslides and to previous discussions above, the author remarks the performance of earthquake-induced landslides as follows:

2.1 *Moment magnitude and intensity of earthquakes relating to landslide occurrence*

The intensity of earthquake at specific location depends on several factors in recent events of Japan: (1) the total amount of energy released, (2) the distance

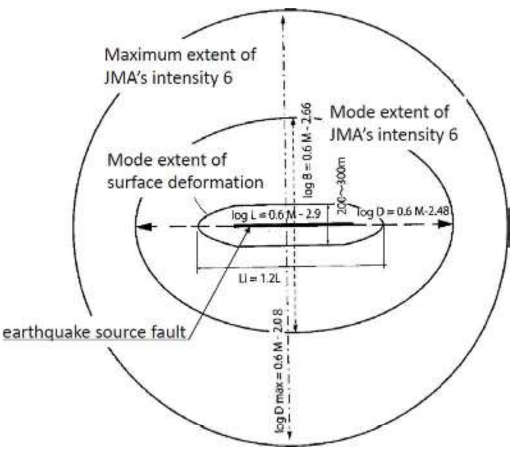


Figure 1. Assumed extents of JMA's intensity 6 and surface deformation from earthquake source fault (Kuwahara, 2008)

M: Moment Magnitude, L: length of earthquake source fault, Li: extent of surface deformation in the direction of fault strike, B & D: Mode extent of JMA's intensity 6 from earthquake source fault, and D max: Maximum extent of JMA's intensity 6 from earthquake source fault from the epicenter, (3) the site topography, and (4) the type of rock and degree of consolidation (seismic velocity of materials).

1. *The total amounts of energy released* (moment magnitudes), which concerned almost all earthquake-induced landslides, are more than M6.1 of offshore (inland) earthquakes, and more than M7.9 of onshore (submarine trench) earthquakes.

Similarly, ground motions relating to earthquake-induced landslides are that minimum earthquake intensity is 5 minus of Japan Meteorological Agency scale (JMAs) almost same as IV of Modified Mercalli Intensity scale (MMIs). Furthermore, the number of landslide occurrence increases more than 6 plus of JMAs almost same as IX of MMIs.

Maximum accelerations of earthquake ground motion concerning landslide occurrence range from 200 gal to 1000 gal. Especially, rockfalls are likely to occur with more than 200 gal, and larger rock-slides with more than 500 gal.

2. *The distance from the epicenter* is that the longer the distance is, the weaker the intensity is due to seismic attenuation. For example, Figure 1 shows the correlation between moment magnitude of earthquake and extent of intensity more than 6 of JMAs from earthquake source fault in Japan (Kuwahara, 2008); the intensity is likely to trigger landslides.
3. *The site topography* of convex landforms causes amplification of seismic waves as shown in Figure 2a.

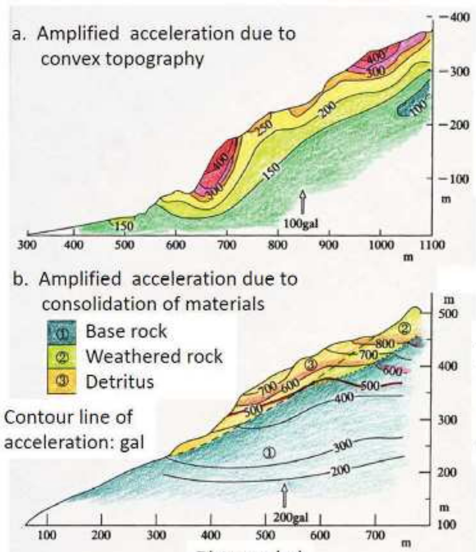


Figure 2. Amplified acceleration of seismic wave by response analysis in mountain area (Yamaguchi, 1998)

a: amplified acceleration of seismic wave on convex topography, and b: amplified acceleration of seismic wave in weak consolidated materials

4. *The type of rock and degree of consolidation* (seismic velocity of materials) causes amplification of seismic waves as shown in Figure 2b. The lower the seismic velocity of materials (less consolidated materials) is, the lager the amplification of seismic waves becomes.

2.2 *Landslide distribution from earthquake source faults*

The correlation between maximum distance of disrupted slides or falls from epicenter and earthquake magnitude has been discussed by Keefer (1984). In addition to this, we remark on the distribution of landslides from recent events in Japan as follows:

1. Landslides by offshore(inland) earthquakes on reverse fault (thrust) are concentrated on the slopes of hanging wall by so-called "hanging wall effect" within about 15 km far from earthquake source faults (Fig. 3);
2. Landslides by offshore(inland) earthquakes on normal fault occur on the slopes of hanging wall, however they are distributed less than about 2 km near earthquake source faults (Inagaki, 2015); and
3. Landslides in extension of the earthquake source faults occur owing to so-called "Doppler effect" by accumulation of seismic waves to the direction of fault rapture.

3 TYPES OF EARTHQUAKE-INDUSED LANDSLIDES CORRELATING WITH TOPOGRAPHY AND GOELOGY

Earthquake-induced landslides of rock slopes are classified into rockfalls and rockslides according to types of movement. Table 1 shows the diagram of these types combining slope gradients and materials.

Rockfalls are relatively free falling of newly detached segments of bed rock especially on steep slopes (Table 1-1, 2a, 2b, 2c, 3) or on reverse-dip slopes (Table 1-5, 6, 8); these types are shallow slides, topples and falls, and are likely to result in debris flows or sediments on the foot of cliff after collapse.

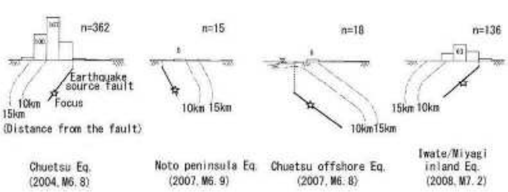
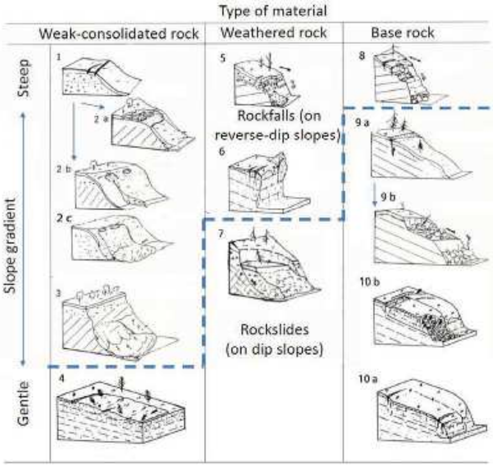


Figure 3. Distribution of earthquake-induced landslides on the section parallel to the dip of the reverse earthquake source faults

Table 1. Types of earthquake-induced landslides (Komata, 2015)



: Maximum extents of landslides are almost all within 15 km from the faults.

: Rockfalls are defined as rock descending of individual boulders or disrupted masses on slopes by bounding, rolling, free fall or toppling, and rockslides also as rotational slump, translational slide including deep-seated block slides, and lateral spreads.

Rockslides of larger rock mass occur on slopes with convex ridge in topography or on gentle slopes behind the shoulder of cliff eroded by river, sea or man-made so-called "knick point" (Table 1-9a, 9b).

Furthermore, rockslide slopes have developed gravitational deformations in head portion of the sliding mass under tensional stress, such as steps, trenches or double ridges before earthquake (Table 1-9a). They also consist of downward-dipping bedding strata: dip slope (Table 1-9a, 9b, 10a, 10b).

In fractured rock slope, rotational slides occur owing to earthquake (Table 1-7). In the case of slopes of soft rock, for example, newly volcanic sediment, translational slides occur owing to earthquake (Table 1-4).

4 MECHANISM OF EARTHQUAKE-INDUSED ROCKFALLS

Ground motion (an earthquake tremor) increases extremely on cliff shoulders, and the amplified tremor exists decreasing backwards of the cliff shoulder within the distance of two times of the cliff height shown in Figure 4. The ground motion is greater in perpendicular to the cliff face (towards the free cliff face) than in parallel to it. Therefore, rockfalls occur easily from cliff shoulders so-called "knick point" and its adjacent potions.

Rockfalls of small mass are caused by the inertia force and the amplified tremor with repeating (cyclic) ground motion of earthquake depending on site

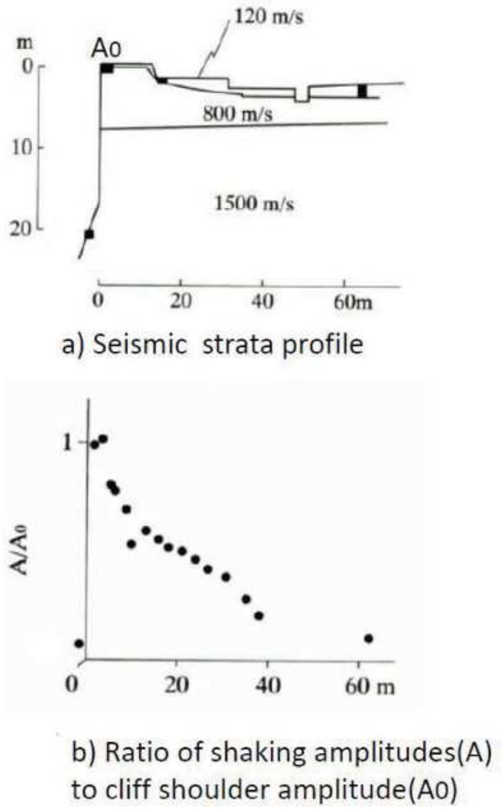


Figure 4. Measurement of ground motion amplification on cliff shoulder (Komaki & Toida, 1980)

: Ground motion: an earthquake tremor increases extremely on cliff shoulders, and the amplified tremor exists decreasing backwards of the cliff shoulder within the distance of two times of the cliff height.

conditions. They are convex portion or "knick point" of topographical condition, which consists of jointed or loosen rock material with lower seismic velocity than fresh bed rocks. Yagi *et al.* (2007) mentioned that 80 % of rockfalls triggered by Chuetsu Eq. were distributed on steep reverse-dip slopes of more than 35°gradient and its mode were between 45°and 50°gradient.

The amplified tremor causes shear or tensile stress along joints to increase and rock materials to loosen. In the case that the shear or tensile stress becomes larger than joint strengths, rockfalls such as strip type rockfall or wedge failure occur. The ground motion which triggers rockfalls almost has the intensity of more than 5 minus of JMAs and the duration of about 10 seconds.

In general, the natural shaking period of the slopes around cliff shoulders is from 0.1 to 0.3 seconds about 10m below the surface. If the period of the slope resonates with the period of input earthquake ground motion, which is in the case of short period and large amplification of the input earthquake, then rock-falls and rock failures may occur easily by the earthquake ground motion.

5 MECHANISM OF EARTHQUAKE-INDUCED ROCKSLIDES

5.1 *Effect of the inertia force to rockslide mass*

Rockslides of large rock mass could not be unstable only by the earthquake ground motion. Since the motion of earthquake is the cyclic shaking of frequency with about 10 to 0.1 Hz, the downward acceleration pulse does not work to the whole sliding mass at the same time during earthquake motions. Consequently, it is unlikely to move the large rock mass by only the inertia force. Furthermore, the dynamic shear strength is larger than the static one by the effect of shear velocity especially in the case of cohesion soil; the effect is that the soil strength become stronger as the shear velocity rise during earthquake with high frequency.

In addition, the deeper the depth of slip plane is, the larger the confined pressure on slip plane becomes. For example, the confined pressure in the case of a rockslide of 50m deep is assumed about 1MPa. Landslide mass could not move easily under high confined pressure, because the slip plane strength is unlikely to decrease owing to the small displacement by earthquake inertia force. Relating to this, Kokusho (1980) experimented on the confined pressure effect concerning the relation between shear strain rise and shear strength fall; the experiment suggests that the decrease of slip plane during earthquake under high confined pressure of deep rockslides needs more strain than under low confined pressure of shallow rockslides.

5.2 *Liquefaction of slip plane materials*

The slip planes of earthquake-induced landslides of Chuetsu Eq. consist of saturated sandy or silty soil. Sasa et al. (2007) have experimented with these materials of slip plane by dynamic and cyclic ring shear test shown as Figure 5, which continued the vibration of shear stress raise by a sine wave of 1 Hz of frequency until 15 second (15 cycles), then stopped the vibration. It was found that the shear resistance increases with the dynamic effect until 10 second and decreases after 10 second as the pore-water pressure rising. Pore-water pressure rises to almost same as normal stress at 20 second and after, consequently the shear displacement increases after stopping the vibration; the liquefaction of slip plane occurs at 20 second and after.

In Japan, many large rockslides have recently occurred after rainfall or in snow melting season, when the water table of landslide slopes becomes higher and the materials of slip plane are saturated. Therefore, earthquake-induced rockslides are suggested to occur by liquefaction of slip plane.

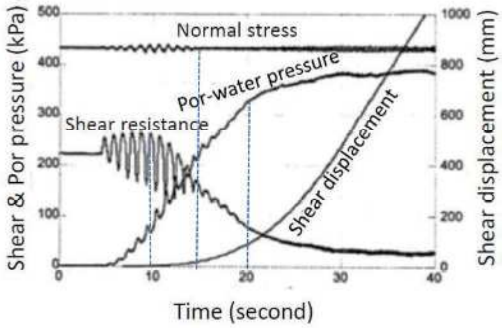


Figure 5. Undrained cycle shear test of sandy material (Sasa et al., 2007)

: vibration of shear stress is continued until 15 second (15 cycles) by a sine wave of 1 Hz of frequency. Then stopped the vibration. Shear resistance increases until 10 second, then it was decreasing as the Pore-water pressure rising after 10 second. Pore-water pressure rose to almost same as normal stress at 20 second, consequently the shear displacement increases after stopping the vibration.

5.3 *Particle breakage of slip surface materials*

In addition to the liquefaction, the particle breakage of slip plane materials occurs owing to earthquake ground motion. Figure 6 shows the decrease of slip plane material strength by cyclic shear loading test.

The strength of test piece decreases slightly in shear velocity (rate of displacement) of 50mm/min (0.8 mm/s) and is reduced rapidly to about 1/3 of the peak strength in 500mm/min (8mm/s). The reduction may occur not only on the slip plane but also in the side boundary materials of the slide mass, therefore the friction on these portions decreases and results in occurrence of landslide.

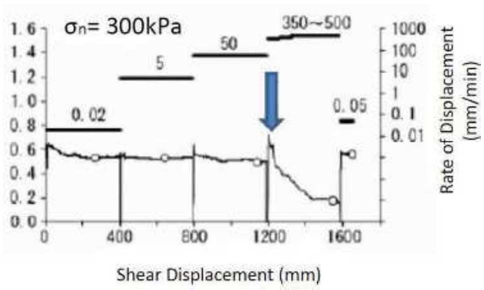


Figure 6. Shear strength decrease of fractured sample relating to shear velocity increase (Kinoshita et al. 2009)

: Slip plane material decreased by cyclic shear loading test with normal stress σ_n of 300 kPa. The strength of the test piece decreases slightly in 50mm/min of shear velocity (rate of displacement) and are reduced rapidly to about 1/3 of the peak strength in 500mm/min (8mm/s).

Furthermore, in the case that slip plane materials are saturated, the particle breakage occurs and results in the reduction of void volume so that excess pore water pressure rise and landslides are more likely to occur.

6 DISCUSSION

It is said that rockfalls occur owing to earthquake of lightening acceleration type with high frequency and in short duration, while rockslides occur on dip down- ward slopes (dip slope) owing to earthquake of energy type (of greater wave amplitudes than rockfall slopes) with low frequency and in long duration (Keefer, 1984).

The author discussed earthquake-induced landslides of recent events and previous discussions above and remarked the performance of them as follows (Fig. 7):

Rockfalls occur on steep reverse-dip slopes as toppling and fall, which consist of loosen rock material of sheeting, columnar joint or gravitational deformation in shallow portions. Since earthquake acceleration of ground motion (the intensity of an earthquake) can be magnified on the slopes both with topography such as convex slopes, shoulder of cliff ("knick line": erosion front) in upper slopes and along ridges, and with unconsolidated materials such as talus deposits, detritus and loosen rock structure. It is said that rockfalls occur on these portions by the seismic inertia force.

Whereas rockslides occur on gentle dip slopes as translational or rotational slide, which develop surface deformation structure such as cracks,

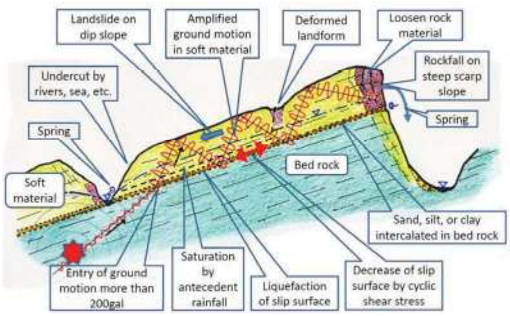


Figure 7. Mechanism of earthquake-induced landslides

: Rockfalls occur on steep reverse-dip slopes as toppling and fall, which consist of loosen rock material in shallow portions result from sheeting, columnar joint or gravitational deformation. Rockslides occur on gentle dip slopes as translational or rotational slide, where develop surface deformation structure such as cracks, depression, uphill-facing scarp and double ridges, and consist of mainly bedrock and intercalate a thin saturated sandy, silty or clayey bed.

depression, uphill-facing scarp and double ridges. The slopes consist of mainly bedrock and intercalate a thin saturated sandy, silty or clayey bed. If rivers, sea or man-made undercut into those unstable slopes, large rockslides might occur owing to earthquake.

Furthermore, in the case there are springs or antecedent rainfall add to saturating slope body, rockslides are more likely to occur than unsaturated condition.

When earthquake wave locally reaches these slopes in more than about 200 gal, the intensity of earthquake is magnified with greater wave amplitudes and longer durations than that in solid bedrock. Shear resistance of slip plane (layer of rupture) decreases by shear repeating and by liquefaction with excess porewater pressure, resulting in the rockslide occurrence. Under these conditions, rockslides are likely occur even on gentle slopes of lower than 25°.

Deep rockslides on gentle gradient portions are unlikely to occur only by the seismic repeating inertia force. They result from slope instability caused by factors of increasing shear stress or lowering shear resistance on rupture of slip plane in earthquake duration.

Furthermore, these rockslides may occur in distance less than about 15km from earthquake fault of shallow direct hit; especially they occur on slopes to overlie the fault (hanging wall of the fault) or to extend in the fault direction.

7 CONCLUSIONS

The author reviewed previous discussions about performances of earthquake-induced landslides, and then studied events and investigations of recent earthquake-induced landslides on rock slopes mainly in Japan. We have recognized that there are several differences in performance between the types of earthquake-induced landslides: rockfall and rockslide. Some rockslides occur on the gentler slopes with angles less than about 25°. The suggestions from studies are as follows:

Rockfalls occur by the seismic inertia force, to say the primary effect of earthquake, on adjacent portion of so-called "knick line (cliff shoulders)" in steeper reverse-dip slopes, which consist of loosen rock or jointed rock materials and are likely to amplify ground motion. They rupture in shallow portions as topples and falls.

Rockslides occur on gentler dip slopes, which develop the surface gravitational deformation, consist of mainly bed rock and intercalate a saturated sandy, silty or clayey strata of slip plane. On these slopes, rockslides occur as translational or rotational slide on slip planes owing to both excess pore water pressure with liquefaction and shear strength decrease by particle breakage of slip planes during earthquake cyclic shaking; that is the secondary effects of earthquake.

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