EARTHQUAKE-INDUCED-LANDSLIDES: DISTRIBUTION, MOTION AND MECHANISMS

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ABSTRACT

Landslides triggered by the 1995 Hyogoken-Nambu earthquake were reviewed based on air photo interpretation for their distribution. Landslides were almost linearly distributed along the line of aftershocks. Most landslides showed limited motion probably affected by less saturated soil condition due to the very dry season. The Osaka group layer, however, retained the ground water and rapid landslides took place there. The Nikawa landslide and the Takarazuka landslide were investigated as case histories. The undrained cyclic loading ring shear test suggested that this landslide showed a rapid motion due to the high pore pressure generation caused by grain crushing along the sliding surface. It can be called "sliding-surface liquefaction".

The trench investigation for the Takarazuka landslide and the previous undrained loading ring shear test for the Sale landslide suggested that the high mobility of the Takarazuka landslide was caused by the undrained loading onto the saturated layer. The sliding surface was formed inside the saturated layer below the ground surface, and the landslide mass moved scraping the surface soil layer above the saturated layer.

Key words: angle of internal friction, direct shear test, earthquake, earthquake damage, landslide, pore pressure, (ring shear test), shear strength (IGC: E6/E8/D6)

INTRODUCTION

The 1995 Hyogoken-Nambu earthquake occurred in a very dry season following the most dry summer of 1994 in Japan. Compared to the tremendous damage of artificial building structures, landslides in natural slopes occurred infrequently. Most of them were small, and also landslides in granitic layers showed a very limited motion with cracks. However, some landslides in the Osaka group layers (limnic and marine deposits of granitic sands and clays in Pliocene to Middle Pleistocene) indicated long run-out motion, because the low permeability retained the ground water during the dry season.

The authors present initially the general view of landslides triggered by this earthquake, then the Nikawa rapid landslide which killed 34 persons, finally the Takarazuka long run-out landslide, which took place in a golf course and was very well investigated with borings, penetration tests and trenches without disturbance.

Figure 1 shows the landslide distribution based on air-photo interpretation with field investigation for not clear

landslides by Scarascia-Mugnozza, and also the landslide distribution in an urban area investigated by T. Kamai 1995 in which most of them could not be distinguished by air photos because the landslide motion was very limited and damaged houses were still standing. The landslide distribution is clearly overlapped by the distribution of aftershocks (Ito, 1995). They were not proportional to the distance from the epicenter, but rather distributed linearly along active faults. Most of the landslides took place during the 17 January earthquake, though some landslides were reported to have moved gradually in a few days after the landslide. This linear landslide distribution, therefore, was not due to the aftershocks. The solid lines in Fig. 1(B) show the distribution of active faults which are also located in non-landslide areas. Those landslides are probably very much affected by the slopes formed by the fault movements, but they also seem to have been affected by the behavior of those active faults which caused this earthquake.

Many slope failures and rock falls took place in granitic slopes on Mt. Rokko. However, their size was not

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Fig. 1. (A) Distribution of landslides and (B) distribution of aftershocks (K. Ito, 1995)

large probably due to the most dry season of the year. Photograph 1 shows one of the largest example of slope failures in the Rokko mountains. In addition to slope failures in steep slopes in the mountains, the earthquake caused many landslides in very flat urban and residential

areas. Many of them were embankments in previous small valleys or paddy fields. Photograph 2 shows an example. Those houses are still standing, but can not be used for dwelling. This damage was also a serious problem in costly residential areas.

Photo. 1. A landslide in mountain areas (Arima, Hyogo Prefecture)

Photo. 2. A landslide in urban area (Hourakucho, Nishinomiya city)
 (A) A series of houses constructed along the filled in valley moved and houses were deformed while still the standing (taken by T. Kamai)
 (B) A garage extensively deformed due to compression (taken by K. Sassa)

THE NIKAWA LANDSLIDE

One of the largest disasters from this earthquake was the Nikawa landslide, which destroyed 11 houses and buried 34 persons. The landslide volume was 110,000–120,000 m³. All of the people buried by the landslide mass were not rescued. Photograph 3 (JGS, 1996) shows an aerial view of the source area of the Nikawa landslide

taken by K. Sassa on 21 January 1995. The plan of the slope before the landslide and the landslide area are shown in Fig. 2. Locations of borings and excavation pits for observation and sampling points are plotted. The white arrow in Photo. 3 shows standing ground water on a secondarily moved debris. The period was very dry, but the Osaka group layer (limnic and marine deposits of granitic sands and clays in Pliocene to Middle Pleistocene) retained the ground water. The level of the ground water table was re-confirmed later by monitoring the level in borings. Figure 3 is A-A' section of the Nikawa landslide. The section was drawn based on the ground surface survey, borings and the ground water level monitoring inside the borings. Trees, buildings are shown only schematically. The slope was about 20 degrees, but the energy line connecting the top of the source area for the landslide and the toe of the deposited landslide mass shows 11.4 degrees for section A-A' as the mobilized apparent friction angle during motion, 9.6 degrees along the section from the top of the landslide to the toe along the Nikawa river (right side of Fig. 2). The characteristics of this landslide are a low value of the apparent friction angle mobilized during motion, and the resulting high velocity. The main cause of the 34 fatalities was insufficient time for evacuation.

Two pits located at P1 and P2 were excavated to investigate subsurface condition, and the rescue team excavated the buried house area along the river. Of these three points, S1 in the buried house area provided the best sample, because the clear interface between the displaced landslide mass and the original ground was exposed to a great extent. The bottom of the landslide mass was blue granitic sands including clays from the Osaka group. This material was the most major unit in this slope. The blue clays and dark gray clays from the Osaka group were also found inside the landslide mass and in the excavation pits. However, their distribution was very limited, and the clays generally (and also in the Osaka group) caused a very slow landslide. This landslide behavior was apparently different. The blue granitic sands including clays were therefore taken as the main sample. The grain distribution is $D_{10}=0.005$ mm, $D_{30}=0.05$ mm, $D_{50}=0.28$ mm, $D_{60}=0.60$ mm, $D_{80}=1.7$ mm, and the uniformity coefficient $U_c=120$.

Sassa developed a high-speed ring shear apparatus in 1984 (Sassa, 1988) to study the motion of landslide where the maximum shear speed was 100 cm/sec at the center of the sample. Based on this apparatus, the cyclic loading ring shear apparatus was developed to study the initiation of earthquake induced landslides (Sassa, 1995). In this apparatus both torque-control Shearing and speed control Shearing is possible with a maximum shear speed of 30 cm/sec. This apparatus was recently improved for the undrained testing and pore pressure measurements during shearing using circular porous metals along the whole circumference of the edge of the upper shear box (Sassa, 1994a). The apparatus was applied to the Sale landslide (Sassa, 1993), the Lishan landslide (Sassa, 1994b and Sassa et al., 1994).

Photo. 3. The Nikawa landslide in Nishinomiya city, Japan (taken by K. Sassa on 21 January 1995)

Photo. 4. Aerial view of the Takarazuka landslide

Fig. 2. Plan of the slope before the Nikawa landslide and the outline of the landslide area

Fig. 3. The central section A-A' of the Nikawa landslide

Fig. 4. Stress path of the undrained cyclic loading ring shear test on the sample taken from the sliding zone of the Nikawa landslide

(A) Stress path for the test of OCR=1.0, Pore pressure coefficient $\Delta u/\Delta\sigma=0.35$

(B) Stress path and shear velocity & displacement for the test of OCR=1.9, Pore pressure coefficient $\Delta u/\Delta\sigma=0.35$

L : Shear displacement at the center of sample

ϕ_m : Effective friction angle during motion

ϕ_a : Apparent friction angle during motion

This undrained cyclic loading ring shear apparatus was applied for the sample taken from the bottom of the moved landslide mass in the Nikawa landslide (Sassa et al., 1995). The test procedure was as follows;

1) Sample soils in the slurry state were set into the shear box. 2) The soils were consolidated in $OCR=1.0-2.0$, because the landslide mass was estimated to be the secondary deposit likely due to old not-compacted artificial fill from the cone penetration tests, the observation of boring cores and the historical records. The OCR in the secondary deposit will be $1.0-2.0$ because the ground water fluctuation is the only cause of consolidation. 3) Shear stress corresponding to the initial stress due to the self-weight of the soil layer was loaded in the drained state. The shear box was switched into the undrained state after the consolidation was completed. 4) Cyclic shear stress was loaded with an increasing amplitude in the undrained state while the total normal stress was maintained constant. Shear resistance, pore pressure and shear displacement were monitored before and after shear failure.

Figure 4(A) shows the stress path for the case of $OCR=1.0$ and the pore pressure coefficient after consolidation $\Delta u/\Delta\sigma=0.35$. No special procedure to increase the pore pressure coefficient was taken in these tests because the purpose of the tests was to reproduce the natural condition. When cyclic shear stress loading began, pore pressure was built up and the shear failure took place in the fourth cycle, at a shear displacement of 4 mm. After the shear failure, much pore pressure was generated and the stress path moved downward along the failure line and reached a constant shear resistance during motion (τ_m). The apparent friction angle mobilized during motion was 8.5 degrees. Figure 4(B) shows the stress path for the case of $OCR=1.9$ and the pore pressure coefficient $\Delta u/\Delta\sigma=0.35$. When the cyclic shear stress loading began, a negative pore pressure was generated, and the stress path before failure moved right-upward. Shear failure took place in the seventh cycle. After the failure, a high pore water pressure was generated and the shear resistance decreased greatly to a certain constant value. The apparent friction angle during motion was also 8.5 degrees. The reason why the stress path after failure deviated from the failure line in Test B was due to the delay of pore pressure measurement and possibly a smaller permeability. The shear displacement and the shear speed during Test B was shown in the same figure. Shear speed rapidly increased to the maximum value (30 cm/sec) for this apparatus after the failure. This test result gave the experimental interpretation for the rapid motion of the Nikawa landslide.

The reason for the rapid motion was due to a low apparent friction angle after failure. The stress path of Fig. 4 may appear to be similar to liquefaction. However, it is different from liquefaction in the conventional sense. Firstly, liquefaction normally takes place in very loose saturated soils because it is caused by the destruction of soil structure. The soil for Fig. 4(A) may be loose because

the pore pressure was generated before failure, but the soil for Fig. 4(B) is not loose because negative pore pressure was generated at increasing shear stress before failure. Secondly, pore pressure generation takes place instantaneously in liquefaction. The pore pressure in these tests however seemed to be gradually generated with the progress of shear displacement over 1 meter. Thirdly, the sample state was observed during tests through the transparent acrylic wall and also by removing the upper and outer shear box after the test, but a phenomenon suggesting liquefaction of the whole sample was not observed. The pore pressure generation after failure was likely caused by grain crushing along the sliding surface (Sassa, 1995; Sassa, 1994a).

Figure 5 is the result of long distance shearing of the dry state of grains of weathered granite (Shirakawa sands in Kyoto) using the high-speed ring shear apparatus under the conditions of constant normal stress, shear speed-control and the drained state (Fukuoka, 1991; Sassa, 1995). The volume is shrinking with the progress of shearing and converged to a certain level which is likely due to grain crushing. After the tests, the shear zone was observed, grains in the shear zone were apparently crushed. The lower graph shows the grains size distribution of the original sands before tests and those taken from the shear zone after the tests of 1.0 kgf/cm^2 and 3.0 kgf/cm^2

Fig. 5. Grain crushing during long distance shearing by high-speed ring shear test (Fukuoka 1991, Sassa 1995)
(A) Variation of sample height and friction angle for the test of $\sigma=3.0 \text{ kgf/cm}^2$
(B) Grain size distribution of the sample before the test and those obtained from the shear zones after tests of $\sigma=1.0 \text{ kgf/cm}^2$ and $\sigma=3.0 \text{ kgf/cm}^2$

A. (Mass) Liquefaction

B. Sliding-Surface Liquefaction

Fig. 6. Stress path and illustration of (mass) liquefaction and the sliding-surface liquefaction
R.F.L.: Residual failure line; P.F.L.: Peak failure line

cm². Grain crushing in the shear zone is quite clear.

The soil sample (Osaka group) taken from the Nikawa landslide was limnic or marine deposits of granitic grains, and it is crushable as well as the Shirakawa sands. It is reasonable to estimate the following process; 1) un-drained shearing of the sample caused grain crushing, 2) grain crushing caused negative dilatancy and the resulting pore pressure generation, 3) it continued until the effective normal stress decreased to a certain value under which grain crushing did not proceed anymore.

The difference of liquefaction and sliding-surface liquefaction is illustrated in Fig. 6. Liquefaction is normally caused by destruction of the meta-stable soil structure. Grain crushing is not necessary, and it is caused for loose soil mass. Then, it can be called (mass) liquefaction. Usually the stress path fails before reaching the failure line in the case of liquefaction. On the contrary, the sliding-surface liquefaction takes place only along the sliding-surface, the destruction of structure is not necessary. It can take place even in medium or dense soil structure so long as grains are crushed along the sliding surface and grain crushing causes negative dilatancy. The stress path in the sliding-surface liquefaction necessarily reaches the failure line, then it moves downward.

THE TAKARAZUKA LANDSLIDE

The Hyogoken-Nambu earthquake triggered a very interesting long run-out landslide at the Takarazuka Golf Club. Photograph 4 shows an aerial view of the landslide. The landslide mass transported a standing forest on it. This landslide did not kill any person, and it was well preserved in the original state for some months, so we could investigate this landslide with the cooperation of the Takarazuka Golf Club. Figure 7 is a plan of the landslide, 1/1000 map was made by the Golf Club before and after the landslide. We did survey the location of the identified objects using a Laser Electronic Distance Meter (EDM), and the movements are shown in the figure. The maximum movement identified was 85.2 meter. Figure 8 shows the central section of the Takarazuka landslide. We conducted the portable cone penetration tests at points marked as filled circles in Fig. 7 and P 2—P 20 in Fig. 8. The landslide seemed to have moved scraping the surface soil layer as observed from the section. The toe of the initial landslide is not very clear, however it will be between P11 and P13. The length of the initial landslide is 50–70 m, the total length of landslide from the top of the source area to the toe of the deposit is 185 m. Some soil

Fig. 7. Plan of the Takarazuka landslide area and location of investigation points

Fig. 8. Longitudinal section A-A' of the Takarazuka landslide

mass was therefore added to the moving landslide mass.

Sassa (1988) proposed a new mechanism of undrained loading onto the saturated deposits by a moving landslide mass for long travel distances in the 1984 Ontake debris avalanche and the 1985 Jizukiyama landslide, Japan. The pore pressure generation inside the saturated soil layer due to the undrained loading by the landslide mass caused a low apparent friction angle and enabled the high mobility. This concept gave a theoretical interpretation for the empirical relationship between the landslide volume and the average apparent friction (equivalent coefficient of friction) in long run-out landslides in the world (Sassa, 1992), and it was experimentally supported by the undrained loading ring shear test simulating the real situation (Sassa and Lee 1993; Sassa et al., 1994).

Figure 9(A) is an illustration of long run-out landslide due to undrained loading onto a saturated alluvial deposit (Sassa and Lee, 1993), and Fig. 9(B) shows the result to reproduce the situation of upper figure using the sample taken from the alluvial deposit in the 1993 Sale landslide in China. The test procedure is as follows; 1) soil sample in the slurry state was consolidated in the shear box corresponding to the stress at point P (Fig. 9(A)) before the landslide mass (point P in Fig. 9(B)). Pore pressure coefficient after consolidation was measured. In this test, the value was 0.97. And the shear strength was measured in the drained state (point A). In order to reproduce the undrained loading by the landslide mass, normal stress was increased to the maximum capacity of the apparatus for 50 sec in the undrained state. During this normal stress loading, shear rotation was continued at 8.8 cm/sec, and shear resistance and pore pressure was monitored. The total stress reached point B and the effective stress reached point B'. After undrained loading, the shear box was changed to the drained state and rotation was continued at 0.014 cm/sec. Pore pressure dissipated, and both the total stress path and the effective one moved upward and converged at point C. From this test result, the effective friction angle during motion was determined to be 30.1 degrees, however the apparent friction angle mobilized during undrained loading was 5.2 degrees. This value explained

Fig. 9. Illustration of undrained loading onto a saturated soil layer (A) and the stress path of undrained loading ring shear test on the sample taken from the alluvial deposit in the Sale landslide (B)
 ϕ_m : Effective friction angle during motion
 ϕ_a : Apparent friction angle mobilized during undrained loading

very well the long run-out motion in the Sale landslide.

The Takarazuka landslide could be the best example of long run-out landslide due to the undrained loading mechanism. To check this assumed undrained loading mechanism, a trench investigation was carried out at points of T1 and T2. Figure 10 is the sketch of cross section of this trench T1. The sliding surface was observed to be 2.7 m below the original ground surface. The side wall was very steep and almost vertical. Lawn covering the golf course was observed at some places as shown in this figure. In order to investigate the front of the landslide and obtain a longitudinal section, trench T2 was excavated. Figure 11 illustrates the longitudinal central section based on the observations in Trench T2 and Trench

Fig. 10. Sketch of the cross section of the Takarazuka landslide in trench T1

T1 and also data from Figs. 7 and 8. Because of the difference of displacements between the sandbunker and forests, the forest overrode above the lawn. The same situation was found at the toe of the cliff and at the front tip of the landslide mass as shown in the upward shear surfaces in Fig. 11.

The Takarazuka landslide had a high degree of mobility of 10.8 degrees as the apparent friction angle. The major material in the source landslide was the blue sands including clays from the Osaka group which is similar to the Nikawa landslide. Hence, the mobilized apparent friction angle in the source area is estimated to be low similar to that observed for the Nikawa landslide (Fig. 4). The apparent friction angle in the flat area must be low due to the undrained loading mechanism (Fig. 9). These were estimated to be the causes of high mobility of this landslide.

CONCLUSIONS

- 1) The 1995 Hyogoken-Nambu earthquake caused landslides along the zone of the aftershocks, which is also the zone of active faults related to this seismic activity. It was determined that the landslide distribution area was not circular around the epicenter, but was rather linear.
- 2) Due to the dry season, most landslides in the mountain areas seemed to have taken place in unsaturated layers. But the Osaka group layer retained the ground water. Rapid landslides due to high pore water pressure were therefore triggered in the layer.
- 3) Undrained cyclic loading ring shear tests showed that high pore pressure was generated due to grain crushing along the sliding surface. It may be classified as the sliding-surface liquefaction. This is different from the conventional "liquefaction", which is the destruction of meta-stable soil structure in a mass of saturated loose soils.
- 4) The Takarazuka landslide was found to be a typical case of undrained loading landslide based on the trench investigation. The failed mass from a steep slope should have imposed undrained loading onto a saturated soil layer a few meters beneath the ground surface. The moving landslide mass scraped the surface soil layer above the sliding surface which was formed inside the saturated layer. The result of an undrained loading ring shear test to reproduce this situation for the Sale landslide, China indicated only 5.2 degrees for the soils with 30.1 degrees for the effective friction angle during motion.

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Fig. 11. Illustration of the longitudinal central section for the front part of the Takarazuka landslide estimated from trench T1, T2 and surveying

also presentation of general information and photos of landslides in the Prefecture. Our gratitude also to the Asia Kousoku Company and the Takarazuka Golf Club for their generous cooperation for chartered flights, surveying, trenches and borings for investigation of the landslide. Field investigation and laboratory testing of both landslides was executed by collaboration and discussion with colleagues in the Landslide Section, Disaster Prevention Research Institute, Kyoto University.

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