Rainstorm-induced landslides in Kisawa village, Tokushima Prefecture, Japan

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Abstract: From the end of July to the beginning of August 2004, a typhoon (called Typhoon No. 10 in Japan) attacked Shikoku Island and the Tyugoku area of Japan before moving towards the eastern part of the Korean Peninsula. Due to this typhoon, rain fell very heavily on Shikoku Island. From July 30 to August 2, the accumulated precipitation reached 2000 mm, and a daily precipitation of 1,317 mm was recorded, which was greater than the Japanese historical daily rainfall record of 1,114 mm. During this period, a huge number of landslides was triggered on Tokushima Prefecture, among which some catastrophic landslides on Kisawa village caused the loss of two lives and severed roads. Field investigations showed that the displaced soil mass from the source areas of these landslides travelled long distances with low apparent friction angle, showing the characteristics of high mobility. Because the main rocks of the displaced landslide masses are weathered greenstone and serpentinite, which are usually not liquefiable, questions were then raised as to why these landslides were of such high mobility. Samples were collected from the source areas and then drained/undrained ring shear tests were performed on them. The failure process due to the rainfall was firstly geotechnically simulated using a newly developed ring shear apparatus: the initial stresses on the sliding surface were reproduced in the apparatus; then, the pore-water pressure was gradually increased simulating the rise of ground-water level during rainfall until the shear failure was triggered. The test results showed that a great reduction in the shear strength resulted after the shear failure with very low apparent friction angle. Undrained ring shear test results also showed that high pore-water pressures could be generated within these samples when they suffered large displacements of shearing. This paper presents the field and laboratory investigation results, as a case study.

Résumé: De fin juillet au début d'août 2004, un ouragan (appelé le numéro 10 d'Typhoon au Japon) a attaqué l'île de Shikoku et la région de Tyugoku du Japon avant de se déplacer vers la partie orientale de la péninsule coréenne. En raison de cet ouragan, pluie est tombé très fortement sur l'île de Shikoku. Juillet de 30 août à 2, la précipitation accumulée a atteint 2000 millimètres, et une précipitation quotidienne de 1.317 millimètres a été enregistrée, qui était plus grande que le disque quotidien historique japonais de précipitations de 1.114 millimètres. Pendant cette période, un nombre énorme d'éboulements a été déclenché sur la préfecture de Tokushima, parmi laquelle quelques éboulements catastrophiques sur le village de Kisawa ont causé la perte des deux vies et de routes divisées. Les investigations de champ ont prouvé que la masse déplacée de sol des secteurs de source de ces éboulements a voyagé de longues distances avec le bas angle apparent de frottement, montrant les caractéristiques de la mobilité élevée. Puisque les roches principales des masses déplacées d'éboulement sont diorite survécue à et serpentinite, qui n'est habituellement pas liquéfiable, des questions ont été alors soulevées quant à pourquoi ces éboulements étaient d'une telle mobilité élevée. Des échantillons ont été rassemblés des secteurs de source et alors des essais de cisaillement d'anneau de drained/undrained ont été réalisés sur eux. Le procédé d'échec dû aux précipitations premièrement a été geotechnically simulé à l'aide d'un appareillage nouvellement développé de cisaillement d'anneau : les efforts initiaux sur la surface de glissement ont été reproduits dans l'appareil ; puis, la pression de l'pore-eau a été graduellement augmentée simulant l'élévation du niveau de ground-water pendant les précipitations jusqu'à ce que l'échec de cisaillement ait été déclenché. Les résultats d'essai ont prouvé qu'une grande réduction de la résistance au cisaillement a résulté après l'échec de cisaillement avec l'angle apparent très bas de frottement. Les résultats d'essai de cisaillement d'anneau d'Undrained ont également prouvé que des pressions élevées de l'pore-eau pourraient être produites dans ces échantillons quand elles ont souffert de grands déplacements du cisaillement. Cet article présente les résultats de champ et de recherche de laboratoire, comme étude de cas.

Keywords: Landslides, case studies, laboratory tests, liquefaction, mechanical properties.

INTRODUCTION

Typhoon Namtheun (the 10th tropical storm in the western Pacific in 2004) originated west of Minamitorishima Island of Japan on July 25, 2004. It made landfall on Shikoku Island on July 31, then passed through the Seto Inland Sea and Hiroshima Prefecture, and moved toward the eastern part of the Korean Peninsula, losing energy to become a tropical depression (Figure 1a). Accompanying this typhoon, heavy rain fell on the Shikoku area of Japan (Figure 1b), especially in the Nakagawa District (on the southwest part) of Tokushima Prefecture, setting a new Japanese daily precipitation record (Figure 2).

Many landslides were triggered by the storm; the most catastrophic among them were five giant landsides occurring on Kisawa village of Nakagawa District, Tokushima Prefecture. These were at the Oyochi, Kashu, Azue, Kamagatani, and Shiraishi areas of Kisawa village, and we call them the Oyochi, Kashu, Azue, Kamagatani, and Shiraishi landslides, respectively (Figure 3). The Oyochi, Kashu, Azue, and Shiraishi landslides are within a small area; the Kamagatani landslide is little further from the others. These landslides destroyed houses, forests and farms and severed roads. Two people were caught in Oyochi landslide, and their bodies were never recovered. This report gives a brief, preliminary account of these landslides in Kisawa village.

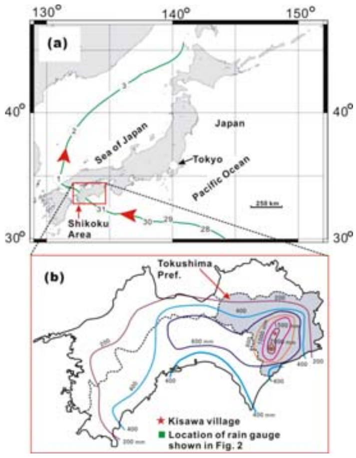

Figure 1. (a) Path of Typhoon Namtheun from July 28 to August 3, 2004 (after National Institute of Informatics, 2004). (b) Rainfall distribution in the Shikoku area from July 30 to August 2 during the typhoon (after Nakagawa River Office, Shikoku Development Bureau, Ministry of Land, Infrastructure and Transport, Japan, 2004)

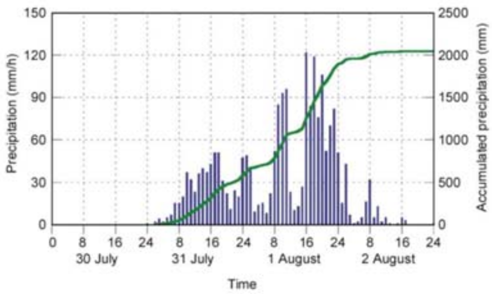

Figure 2. Hyetograph of the heavy rainfall (data courtesy of Shikoku Electric Power Co., Inc.)

Figure 3. Location of Oyochi, Kashu, Azue, Kamagatani, and Shiraishi landslides

RAINFALL CHARACTERISTICS

Torrential rain in Tokushima and Kochi Prefectures accompanied the slow approach and passing of Typhoon Namtheun. At Kaminaka town (about 10 km far away from these four landslides) of Nakawaga District, Tokushima Prefecture, the total precipitation from July 30 to August 2 was more than 2,000 mm (Figure 2). This is several times the normal precipitation for the months of July and August in this area. Hourly precipitation reached more than 120 mm (Figure 2). The highest daily precipitation of 1,317 mm was recorded on 1 August; this value exceeds the previous Japanese daily precipitation record of 1,114 mm, recorded at Kito village (about 16 km southwest of Kisawa village) on September 11, 1976 accompanying Typhoon Fran.

The area where precipitation exceeded 1,500mm for the storm was centered on Kisawa village and Kaminaka town, as a very narrow area of 5-6 km in the east-west direction, and 10-20 km in the south-north direction (Figure 1b). Within this area, many landslides were triggered.

GEOLOGICAL BACKGROUND

The area where the landslides occurred is characterized by deep river valleys with steep slopes, and many of the mountain slopes have steep chutes. Most of the settlements are located on gentle slopes formed by past landslides, or on narrow streamside terraces. According to the subsurface geological map of Tokushima Prefecture (Tokushima Prefecture, 1983), the area is mainly underlain by Paleozoic greenstone, Paleozoic and Mesozoic pelite and greywacke, and serpentinite of the Mesozoic Kurosegawa terrane, as well as limestone and chert.

LANDSLIDES IN KISAWA VILLAGE

Oyochi Landslide and Kashu Landslide

The Oyochi and Kashu landslides occurred on the same ridge and side of a mountain (Figure 4). Oyochi landslide was triggered mid-slope on the mountainside, about 1 km from the Oyochi settlement (Figure 5) at approximately 20:30 hr, August 1. Two people were caught up in this landslide, and their bodies have not been found. The displaced materials of about $0.5\sim1\times10^6$ m^3 from the cover and weathered bedrock moved downslope to the river, and hit the opposite side of the channel. A part of the displaced mass crossed a ridge on the opposite slope (area I in Figure 5), and transformed into a large debris flow, traveling a further 2 km along the valley (area II in Figure 5). In this area, the bedrock is mainly composed of greenstone and serpentinite with visible cracks. Immediately below the source area, the displaced landslide mass is meters thick, and contains some huge boulders. The deposited mass could be liquefied by stamping feet, indicating the highly liquefiable character of the landslide materials.

Kashu landslide (Figure 6) occurred on the same slope near the Oyochi landslide, and almost at the same time as the Oyochi event. According to a local resident, Kashu landslide started on the lower valley slope near Kashu settlement (below A-A' in Figure 6), and was followed by another two failures, finally retrogressing almost to the ridgeline of the mountain on August 2.

Figure 4. Oblique aerial view of the Oyochi, Kashu, and Azue landslides (photo by Shikoku Regional Development Bureau, Ministry of Land, Infrastructure and Transport, Japan)

Figure 5. Oblique aerial view of Oyochi landslide (photo by Shikoku Regional Development Bureau, Ministry of Land, Infrastructure and Transport, Japan). The head scarp is situated at an altitude of about 1000 m, while the join of the slope to the Oyochi valley is about 560 m. The slope angle averaged 34 degrees

Azue Landslide

Azue landslide is located on the left side of Sakashu-Kito River, in front of the Kashu landslide (Figure 7). A remarkable scar indicating an ancient landslide is also visible at the same site (Figure 7 outlined approximately by a broken line). We also found a small-scale linear depression on the mountain top during our survey. The new landslide occurred near the southern boundary of the old landslide scar, and the sliding surface was in the weathered bedrock layer. Azue landslide has a width of about 130 m, a horizontal length of about 1 km, and a depth ranging from 10 to 20 m. The volume of the displaced material was estimated to be about $1\sim2\times10^6$ m^3. The displaced material slid down the slope, crossed Sakashu-Kito River, and rose up the opposite mountain slope to a height of about 30 m (immediately below the Fudono area), destroying and carrying away the Fudono bridge, which was built on the national road (Figure 8).

Figure 6. Oblique aerial view of Kashu landslide (photo by Shikoku Regional Development Bureau, Ministry of Land, Infrastructure and Transport, Japan). The head scarp is situated at an altitude of about 910 m, while the altitude of river floor is about 300 m. The slope angle averaged 27 degrees

Figure 7. Oblique aerial view of Azue landslide and the unstable blocks after the August 1, 2004 event (photo by Nakanihon Sky Service Station, Japan). The area below F-F' was displaced in 1994 during a rainfall. The broken brown line outlines the area of the ancient landslide. The white broken line marks cracks from reactivation of the old landslide

Figure 8. Oblique aerial view of the Fudono area after the landslide (photo by Shikoku Regional Development Bureau, Ministry of Land, Infrastructure and Transport, Japan)

A longitudinal section of the landslide (Figure 9), was plotted using data from an airborne laser scanner after the failure (performed by Aero Asahi Corporation), and the pre-failure topography was obtained from a forest map with 2-m contour. The landslide originated on a slope of approximate 23.5 degrees with an apparent friction angle of about 17.8 degrees. From the travel distance and the height reached on the opposite slope, the speed of the displaced landslide material was estimated to be very fast (>20 m/s, Hiura, et al, 2004).

The main failure of Azue landslide occurred at approximately 23:00 hr on August 1, a little later than the Oyochi and Kashu landslides. Afterwards, loud crashing noises continued for several hours, probably due to retrogressive failures. On the upper parts of the slope near the scarp, landsliding of the unstable regions of the displaced mass on a small scale is still continuing, and some places have been covered by thick displaced material. Light green and light red/purple bedrock (green stone) is exposed on the right hand side of the landslide.

We were told that a landslide occurred 5 years ago on the area below the red curve (F-F') shown in Figure 7, also during heavy rain. We noticed that a smooth surface of relatively hard bedrock crops out (below F-F' on Figure 7), which strikes N45ºE and dips north. We infer that this surface formed an impermeable or less permeable layer, which facilitated a rapid rise in the local ground-water table during the storm, which in turn triggered the slope failure.

Above the main scarp of Azue landslide, another huge block moved slightly. After the landslide, numerous cracks with significant displacements were found on the slope above the main scarp (and along the scarp of the old landslide). The white dashed lines that were drawn basing on the observed cracks outline the boundary of each sliding sub-block. The road on the left hand side of the old landslide scar was severed by a crack, where there was subsidence of about 2.0 m (Figure 10). The subsidence increased to 2.5m over about two weeks. It exposed a well-consolidated sliding surface of the old landslide, which originated in the bedrocks and strikes N44ºW and dips 48ºW. The deformation observed from the ground surface indicates that the deforming landslide shows translational movement in general.

Preliminary bore-hole data indicate that the unstable block ranges from 20–50 m in thickness. Therefore, the unstable landslide mass was estimated to be in the order of 10^6 m^3. This landslide mass is still deforming, and measured displacements by the installed extensometers show that its movement is very sensitive to rainfall. This can be seen from Figure 11, where the displacements that were monitored on the place shown in Figure 7 from September 22, 2004 to September 26, 2005, are plotted. During this period, two typhoons came. At present, 10 extensometers are installed on the unstable block to monitor the displacements of different places. Detailed account on the deformation of this landslide mass is beyond the scope of this report and will be presented elsewhere.

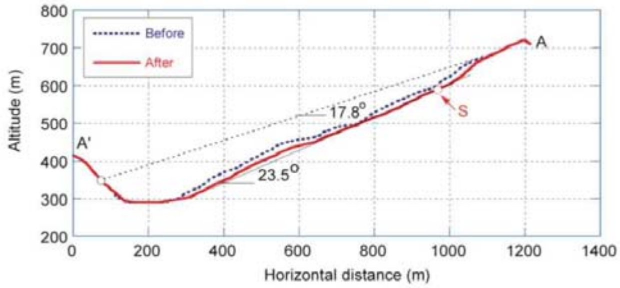

Figure 9. Longitudinal section of the Azue landslide (A-A' in Figure 7; S is sample point)

Figure 10. Exposure of the sliding surface beneath the old landslide. The materials above/below the sliding surface are weathered green stone

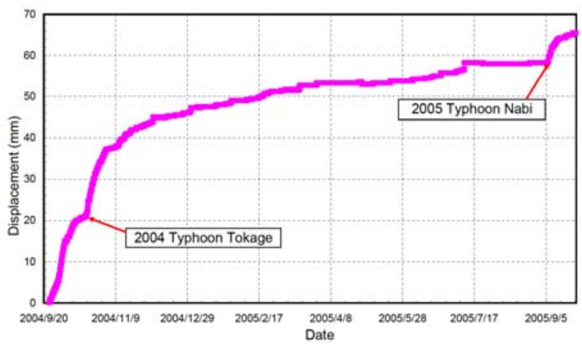

Figure 11. Monitored displacement from Sept. 22, 2004 to Sept. 26, 2005 on the back crack

Kamagatani Landslide

Kamagatani landslide (Figure 12) is located on the true right slope of the valley of Kamagatani River, the upper tributary of Sakashu-Kito River. This landslide is about 7 km north of the three landslides discussed above.

The landslide originated on a slope of about 33 degrees. It has a width of 120 m, a length of 200 m, and a depth of 10–15 m. The displaced landslide mass was estimated to be about 2×10^5 m^3. The source area consists of mudstone, which is overlain by sandstone and ancient colluvial deposits. The failure occurred within the outer layers of these strata. In the middle part of the source area, a ridge-shaped roll existed, suggesting the presence of hard rock. A large amount of groundwater discharges near the mudstone-sandstone boundary. The landslide carried away a soil-conservation (Check) dam that previously stood on the toe of the slope. A large block of concrete from the dam is now on the top of the slope ridge on the opposite slope across the valley (Figure 13). This is where we placed the total-station measurement system to measure the landslide's longitudinal profile (point C' on Figure 14). The displaced soil mass reached and dammed Kamagatani River. The landslide dam had been eroded by the river before our investigation, but we have inferred from the deposit profile remaining on the river banks that the displaced material was deposited with a final slope angle of about 9 degrees. From the height of the concrete block and elevation of deposits on the slope opposite to the landslide, the displaced landslide material was estimated to have had a speed greater than 17 m/s when it reached the valley bottom.

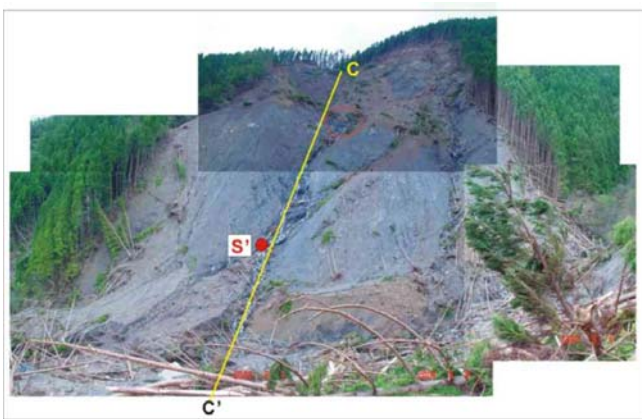

Figure 12. A general view of Kamagatani landslide. S' marks the sample site

Figure 13. A displaced concrete block from the soil-conservation (Check) dam on the slope opposite the landslide source (Black area outlined by the broken white line: former location of the block; Red arrow: the flow direction of the valley water; White curved arrow: the move direction of the block)

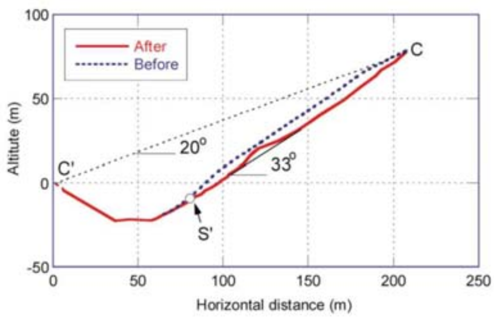

Figure 14. Longitude section of the Kamagatani landslide (S' is sample point; the pre-failure topography was obtained from neighbouring slope)

Shiraishi Landslide

Shiraishi area was designated as the landslide prevention area on 1962, basing on the Japanese Landslide Preventive means, and the mountain stream was also designated as the debris-flow-risk-rich stream. Shiraishi landslide was also trigged around 20:00 hr on 1 August. The landslide on the source area sized 70 m in length, 35 m in width, and 2-3 m in depth, and was originated on a slope of about 29 degrees (Hiura et al 2004). The scarp of this landslide was at the elevation of 540 m, and toe was at the elevation of 290 m reaching the national road, and the horizontal travel distance was about 550 m. The displaced landslide mass was approximately 5,000-7,000 m^3. The landslide transformed to debris flow when came to the lower slope part. Many houses were destroyed or damaged by this event (Figure 15). Fortunately, the residents of this area noticed some unusual phenomena, such as the ground water flowing out from the middle par of the mountain slope and unusual sound by moving rocks. They recognized these landslide precursors, and started to evacuate by themselves from 15:00, and then there was neither fatality nor injury. This is a good case coupling the precaution of disaster precursor with evacuation successfully. It is noted that after this event, an unstable block on the upper part of the source area formed and was keeping moving. Three extensometers were installed to monitor the movement (Figure 16). The monitored displacement and rain precipitation are presented in Figure 17. It is seen that great displacements were observed in these three extensometers. Due to the continuous deformation of this unstable block and the great possible damage area in case that the unstable block slides and transforms into debris flow, an evacuation order had been issued for months and, countermeasures have been performed now. It is interesting to note that the displacement of landslide on crystalline schist area is usually not so great, however, a displacement of even greater than 4m was observed, as shown in Figure 17. Concerning on the possible reason for this phenomenon, further investigation is necessary, and planed

Figure 15. Traveling path of Shiraishi landslide as well as the predicted damage area if the unstable block become debris flow

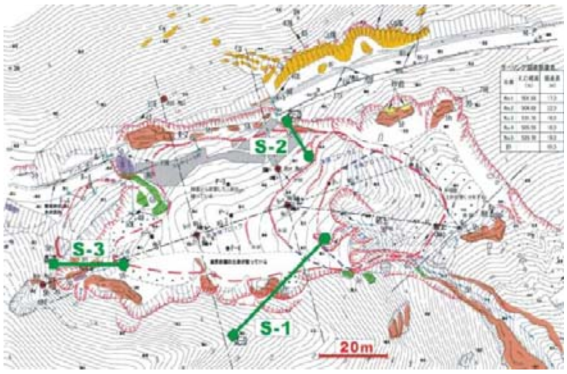

Figure 16. Plan of the source area of Shiraishi landslide, and the unstable block after the landslide event as well as the locations of extensometers

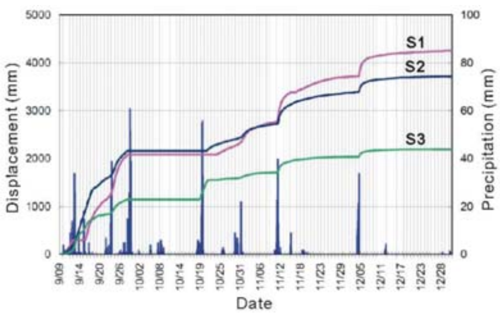

Figure 17. Monitored rain precipitation and displacement

POSSIBLE MECHANISMS FOR THESE LANDSLIDES

As mentioned previously, the Oyochi, Kashu, and Azue landslides have very similar geological backgrounds, while the Kamagatani landslide is different. Nevertheless, they all were rapid to some extent. To understand the triggering, as well as the possible movement mechanism, it is important to understand the shear behaviour of these materials before and after the failure, and how these are affected by rainfall. Therefore, samples were take from the source area of Azue landslide (S in Figure 7) and from the Kamagatani landslide (S' in Figure 12), for laboratory examination, and testing in a ring-shear apparatus described in Sassa et al. (2004a). The grain size distribution for these samples is presented in Figure 16. Note that due to a size limitation imposed by the shear box, gravels greater than 2 mm were removed by sieving before testing, assuming that the undrained shear behaviour of these samples be mainly controlled by the grains less than 2 mm when the gravel content is less than a certain percentage, say 40 % (Kuenza et al 2004).

The landslides were obviously triggered by heavy rain, and so to simulate the rising ground-water table due to rainfall, shear tests were performed with slowly increasing pore-water pressure. During the test, the oven-dried sample was first dropped into the shear box by means of dry deposition method, and then was saturated by means of CO_2 and de-aired water to ensure high saturation. Saturation degree was verified by computing B_D value, a pore pressure coefficient in direct shear state, which was proposed by Sassa (1985), and denoted as:

$$B_D = \Delta u / \Delta\sigma \qquad (1)$$

where Δu and $\Delta\sigma$ are increments of pore pressure and normal stress respectively. If $B_D \geq 0.95$, it indicates an approximately full saturation. After the checking of B_D value, normal stress and then shear stress were loaded slowly to the target initial values, respectively. After the consolidation, pore-water pressure was increased slowly until shear failure was triggered.

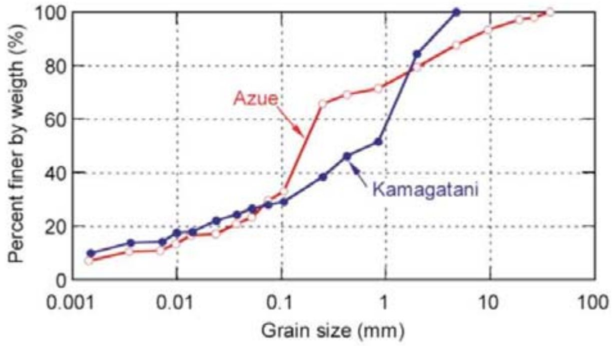

Figure 18. Grain-size distributions of samples from the Azue and Kamagatani landslides (after removal of the >2 mm size fraction)

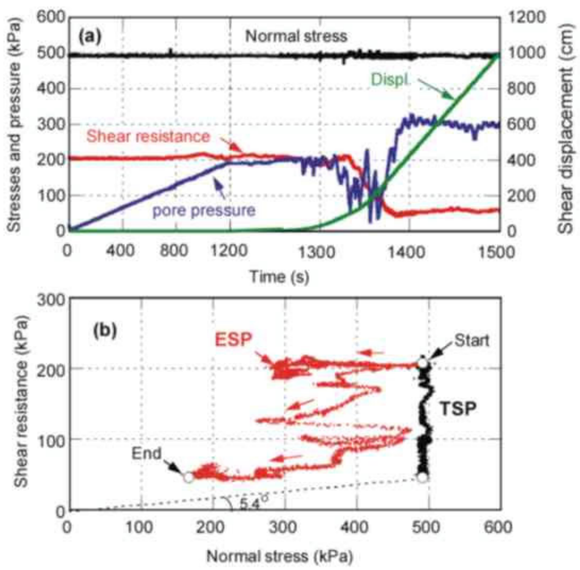

Figure 19. Results of a ring-shear test on a sample from the Azue landslide source area. (a) Time-series data for normal stress, shear resistance, pore-water pressure and shear displacement; (b) stress path (ESP: Effective Stress Path; TSP: Total Stress Path) (B_D= 0.96, e = 0.425)

For Azue landslide, the sample had a specific gravity of 2.94 in the field, and dry density of 2.08 g/cm^3. Because the test aim was to examine the shear behaviour of the landslide material before and after failure, a soil element was selected from the sliding surface where the overlying soil was 25-m thick. The initial normal stress and shear stress acting on the soil element were calculated to have been 488 kPa and 212 kPa, respectively. The test results are presented in the form of time-series data (Figure. 19a) and effective stress path (Figure. 19b). Shear failure was triggered when the pore-water pressure was increased to a certain value (Figure 19a). The monitored pore-water pressure after failure showed a brief reduction and thereafter increased with further shearing. During this period, shear resistance was greatly reduced. The effective stress path fluctuated widely (Figure 19b), probably due to problems in measuring pore pressure (as detailed in Sassa et al 2004b). The final apparent friction angle was very small, about 5.4 degrees.

A similar test was performed on a sample from the Kamagatani landslide. Time-series data (Figure 20) show that shear failure was triggered when the pore-water pressure was increased to point “P”. After failure, pore-water pressure showed a sharp increase and then decreased. To measure the pore-water pressure within the shear zone, the shear box was switched to an undrained condition after point "SUD". The pore-water pressure increased with progress of shearing. The shear resistance showed almost no change in the final shear stage, indicating no further build up in excess pore-water pressure within the shear zone. The apparent friction angle was about 8.3 degrees (Figure 20b). Although the final shear resistance shown in Figure 20 is smaller than that in Figure 19; the greater apparent friction angle in Figure 19b is due to the smaller initial normal stress. The initial consolidated normal stress usually does not affect the shear resistance at steady state when a sample is subjected to undrained shearing, if other test conditions were the same (Castro & Poulos 1977; Kramer 1988).

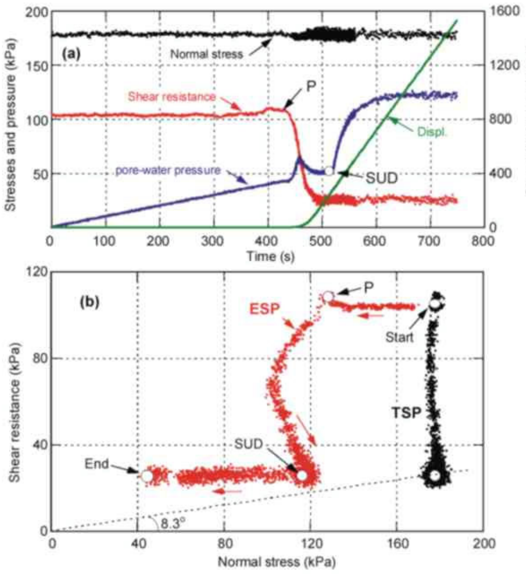

Figure 20. Results of a ring shear test on a sample from the Kamagatani landslide source area. (a) Time-series data for normal stress, shear resistance, pore-water pressure and shear displacement; (b) stress path (ESP: Effective Stress Path; TSP: Total Stress Path) ($B_D = 0.97$, e = 0.513)

CONCLUDING REMARKS

A field investigation was made of the larger landslides triggered at Kisawa village by an unprecedented rainstorm accompanying typhoon Namtheun in 2004. Basic characteristics of these landslides were described and some laboratory ring-shear experiments were performed to examine possible triggering and movement mechanisms.

(1) The Oyochi, Azue, Kamagatani, and Shiraishi landslides moved rapidly over long distances, although no evidence was found from which to determine the speed of the Kashu landslide. The Oyochi, Azue, and Shiraishi landslides were triggered almost at the same time.

(2) The Azue landslide originated on the gentle slope on an ancient landslide. Due to the occurrence of the new landslide, the old landslide was reactivated and continues to move.

(3) Impermeable hard bedrock (or a layer of lower permeability) enabled the ground-water table to rise, which caused an increase in pore-water pressure within the overlying soil, and triggered the landslides.

(4) Shiraishi landslide originated from a landslide preventive area. The precursor of the landsliding was recognized and coupling with evacuation successfully. After the landsliding, an unstable block was formed on the source area and kept deforming with a displacement even greater than 4 m.

(5) Results of ring-shear tests on samples from the Azue and Kamagatani landslides showed that build-up of high excess pore-water pressure could greatly reduce shear resistance in both samples, indicating that both samples are highly liquefiable.

Further studies of the relationship between rainfall characteristic and the timing of the landslides, and of the sliding characteristics of the unstable landslide blocks above Azue landslide during rainfall, as well as the shear behaviour of the landslide mass on the source area of Shiraishi landslide subjected to large shear displacement, are needed and are being performed.

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