京都大学防災研究所年報 第43号 B-1 平成12年4月
Annuals of Disas. Prev. Res. Inst., Kyoto Univ., No. 43 B-1, 2000

A Preliminary Report on the Landslides and Other Ground Surface Movements Induced by 1999 Chichi Earthquake, Taiwan

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Synopsis

Preliminary discussion on the geomorphological conditions of characteristic ground surface movements induced by the 1999 Chichi Earthquake is presented on the basis of the field reconnaissance study in December, 1999. The displacement of the soft ground by the earthquake-inducing fault was dominated by the horizontal movement and induced damage of structures. Two gigantic landslides visited in this study suggest that the dip of the intercalated mudstone and sandstone of the Neogene and the groundwater conditions determined the occurrence of large-scale landslides. Extensive occurrence of surficial landslides suggests the importance of the weathering characteristics of coarse sedimentary formation of weak cohesion.

Keywords: landslide, Chichi Earthquake, geomorphology, surface movement, Taiwan, earthquake

1. Introduction

The Chichi Earthquake of a Richter scale magnitude of 7.6 on 21 September, 1999 induced a variety of ground surface movement including large-scale landslides. In comparison with recent earthquake hazards in Japan (e.g., Okunishi et al., 1999), it is marked that hazardous ground motion took place along a long distance of the outcrop of the fault, and that a number of large-scale landslides including several gigantic landslides caused a catastrophic disaster in a wide area (Lin, 2000). Here is reported the result of our reconnaissance study between 6 and 12 December 1999. The route map of the field investigation is shown in Fig. 1.

2. The ground surface movement associated with the outcrop of the earthquake fault

Destruction of rigid structure spanning the outcrop of the earthquake fault (bridges and the Shigang Dam) was marked. Destruction of bridges at the outcrop of the earthquake fault was largely due to its horizontal displacement, which caused the tilting of the piers through the horizontal movement of the girder. The outcrop of the earthquake fault was at high angle when it crossed the bedrock (Photo 1) and at low angle when it crossed a soft stratum, presumably reflecting the difference in friction angle. An anticlinal uplift was observed on a soft and cohesive stratum (Photo 2).

3. Gigantic landslides

Two gigantic landslides of an order of magnitude of 10^8 m^3 in volume, visited in this reconnaissance study, were thought to have slid along the bedding plane, and a layer of sandstone moved on the surface of siltstone. In the case of Tsaolin Landslide, the dip of the bedding plane coincides with the slope aspect, although the dip angle was a little smaller than the slope angle. In the case of Chiufengershan Landslide, on the other hand, the slope aspect was different from the direction of the dip of the bedding plane, although the gradient of the slip surface was similar to the component of the gradient of the bedding plane in the direction of the slope aspect. It was suggested that the slip surface had been saturated with groundwater in the both cases.

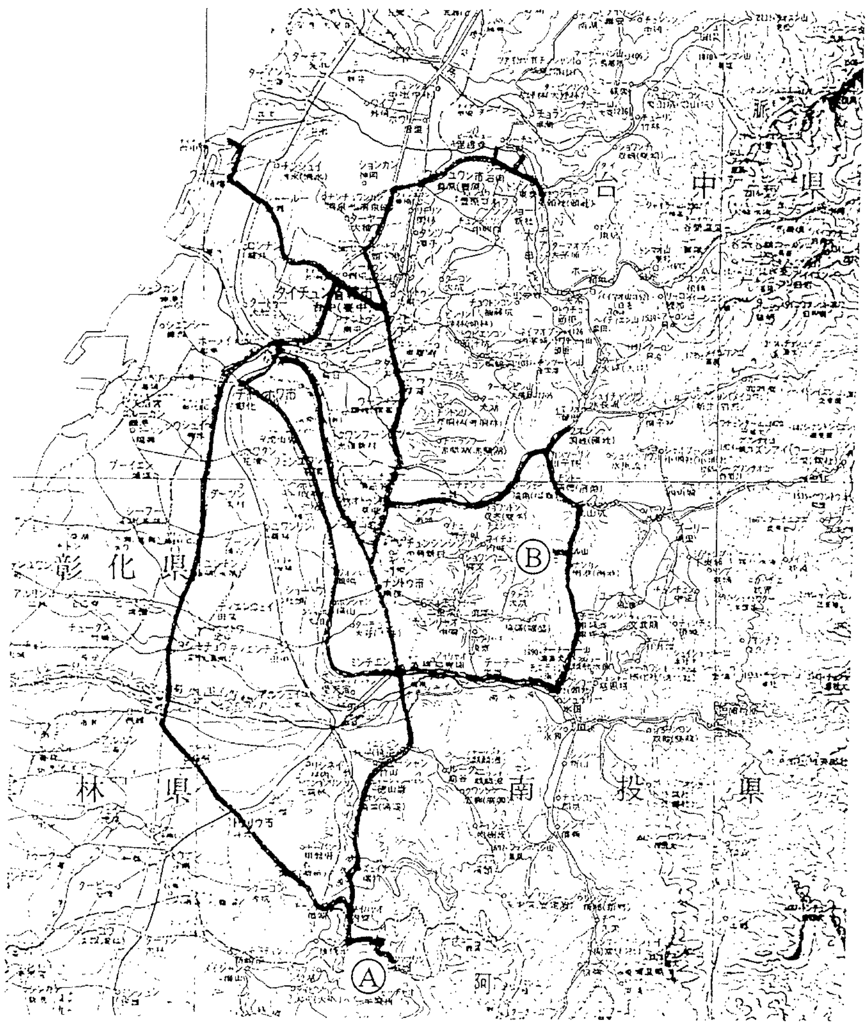

Fig. 1 A route map of the ground survey by car. A: Tsaolin, B: Chiufengershan.

Photo 1 A water-fall created by the earthquake fault in the Dachia-shi River near Fengyuan. Crushed rock is left on the high-water bench beyond the river. Erosion by running water is already in progress in the central part of the river.

Photo 2 A building in Fengyuan tilting towards the uplifted side of the fault due to an anticlinal ground deformation. The river on this side also suffered from this deformation.

3.1 Tsaolin Landslide

This landslide is located in the headwaters of the Qingshui-shi River which is a tributary of the Zhuoshui-shi River. According to the estimation based on the topographic map of a contour interval of 5 m prepared by National Taiwan University, the

Photo 3 Aerial photograph of the Tsaolin landslide (from the home-page of National Cheng Kung University)

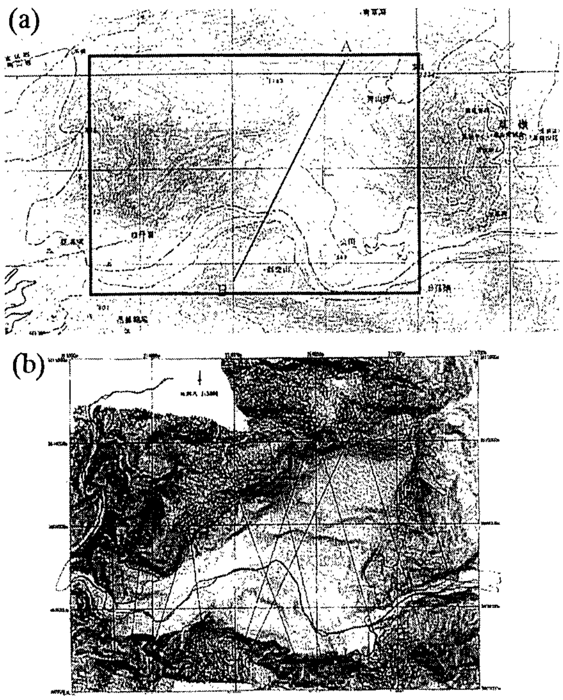

Fig. 2 Topographic map of the Tsaolin Landslide Area before the earthquake (a) and after it (b), after Lin (2000). Grid interval is 1 km.

landslide mass was 120,000,000 m^3 and the affected area is 698 ha with a distance of about 4 km between the top of the slip surface and the snout of the debris avalanche. There were only small casualties because the landslide area was off the village center of Tsaolin. The aerial photograph and the topographic map of this landslide area are shown in Photo 3 and Fig. 2, respectively.

This area had experienced landslides: in 1862 due to an earthquake (unknown volume), in 1941 due to the Chiayi Earthquake (> 10^8 m^3), in 1942 due to a heavy rainfall (> $1.5\text{x}10^8$ m^3) and in 1979 due to a heavy rainfall (> $1.5\text{x}10^8$ m^3). The Qingshui-shi River was dammed up by the 1941 landslide and a lake was formed upstream. It became larger due to the blockage of the 1999 landslide and the risk of flood due to the breach was worried. At the time of the field reconnaissance, the countermeasure work was in progress. It is planned to withdraw the channel eventually to the original level, by excavating a shallow tentative channel and by leaving it partly lined with large stones. This policy seems appropriate under the condition that the drainage area is not so large and the downstream reaches of about 10 km are not inhabited.

As usual in gigantic landslides, this landslide has a compound structure (Okunishi, 1982). It is composed of the main block and two side blocks. These blocks are briefly described in the following.

Photo 4 The denudational area and the area of former channel of the Qingshui-shi river of the Tsaolin Landslide.

(1) Main block

There is a main scarp of horseshoe type at the center of the top part. It was accompanied by two shallow landslides on its right and left side at a little higher position (Photo 4). The main block extends to southwest from the main scarp and there are two steps of the secondary scarp. Viewed from the bottom, the upper one represents a cross section of layered strata and the other does not present obvious lamination (Photo 5). Such structure is characteristic of the sliding along the bedding plane of a gentler angle. The denudation area and the transport area were not easily distinguished, since many landslides had been repeated here. The depositional area was beyond the original channel of the Qingshui-shi River. The sliding was inferred to be caused by the intercalation of permeable sandstone and impermeable siltstone, which store perched groundwater lubricating the interface, as demonstrated at the eastern edge of the lower step (Photo 6). There, water was found to seep out of the interface between sandstone and siltstone and flow on the planar surface of the latter. The discharge was thought to have decreased from that at the time of landsliding, since the white powder (main constituent is Na_2SO_4) was seen covering the rock pieces and debris besides the watercourse. It suggests the leaching of Na_2SO_4 associated with the hydration of clay minerals (Sato and Aoki, 1990).

The depositional area of the main block is composed of a obvious heap of the sliding mass on the southern side of the original channel of the Qingshui-shi River. There are secondary scarps towards the rear side of the depositional area suggesting the back-slip according to the inverse gradient of the ground surface. A wide and shallow valley had been left along the original channel, not by the channel erosion but by the high-speed transit of the sliding mass. The snout of the depositional area is formed by sheets of debris with a shape like a tongue (Photo 7). It suggests the liquefaction by the water which was squeezed out of the sliding mass (Suwa et al., 1985). A schematic illustration of the main block in its moving state is shown in Fig. 3 according to the above consideration.

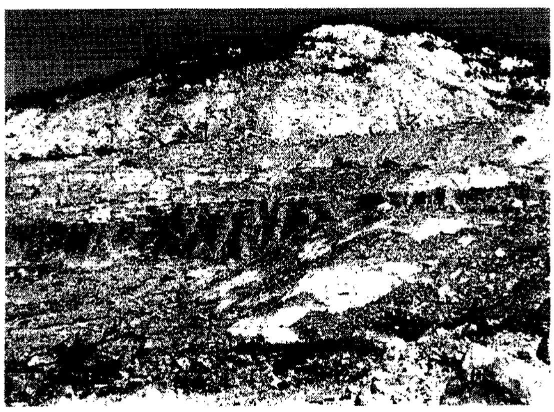

Photo 5 Outcrop of the bedding plane at the secondary landslide scar of the Tsaolin Landslide.

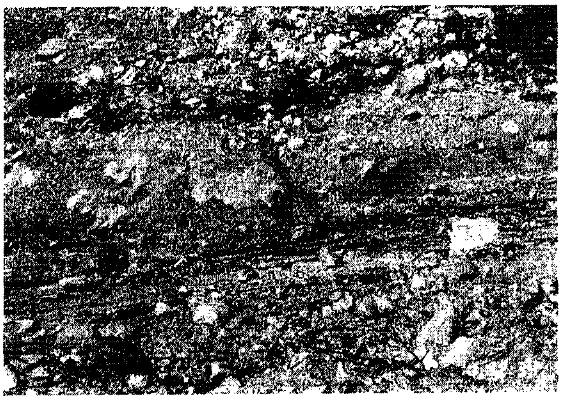

Photo 6 Water running out of spring on the bedding surface of siltstone.

Photo 7 Depositional mound of the main block of the Tsaolin Landslide. Tong-like snout is visible at its head and slip-back scars are at its tail facing the site of the original channel.

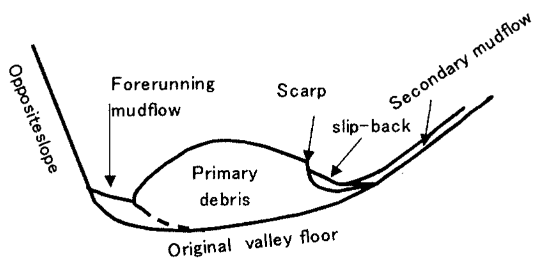

Fig. 3 Schematic illustration of the depositional features of the main block of Tsaolin Landslide

(2) Western side block

The western boundary of the upper part of the landslide area is a rocky cliff. The debris falls on it is obviously independent of the gigantic landslide. The part of the gigantic landslide that is adjacent to the border is distinguished from the main block by its color suggesting a high mobility. A group of flow mounds form hummocky zone between this part and the main block. This zone is interpreted as the transitional zone between the main block where the sliding mass was essentially rigid, and the fluidized part. Thus these two parts should be lumped as a side block. Photo 8 shows the central part of the western side block viewed from the helicopter. Corresponding to the main block expanding its width towards the lower end, the side block moved towards west-southwest and after reaching the channel of the Qingshui-shi River, it flowed along the channel for about 500 m (Photo 9).

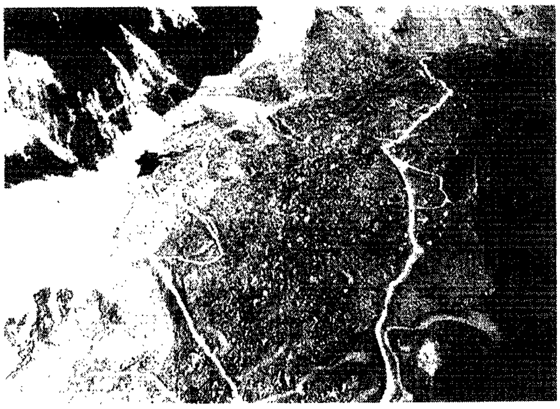

Photo 8 An overview of the western side block. It consists of two zones of different color. The black object a little at the upper left of the center is a pond.

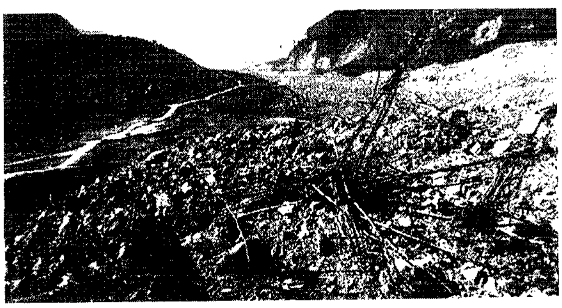

Photo 9 The debris that flowed downstream along the Qingshui-shi River (photograph was taken from the main block).

The snout of this side block that hit the opposite (southern) side of the Qingshui-shi River was bifurcated into several parts suggesting greater mobility in comparison of that of the main block. The part that moved downstream along the Qingshui-shi River can be regarded as a branch of the bifurcation.

(3) Eastern side block

The side block on the eastern side has more complicate in structure. There is a block at the northeast corner of the landslide area where trees are left with enlarged interval with one another (Photo 3 and Photo 10). It is interpreted that a block of shallow transitional slide of highly weathered soil was divided into many zones by cracks expanding towards the downslope direction as suggested by Photo 11. The mobility of the lower part of this block seems to have been larger than the upper parts since the arrangement of the left trees was more irregular. To the lower-left of Photo 11 (Photo 12) is a hummocky zone similar to that in the western side block. It is associated with two small slumps at its upslope part (see Photo 3).

Photo 10 The upper part of the eastern side block (at the left edge of this photo).

Photo 11 A close-up of the lower part of Photo 10.

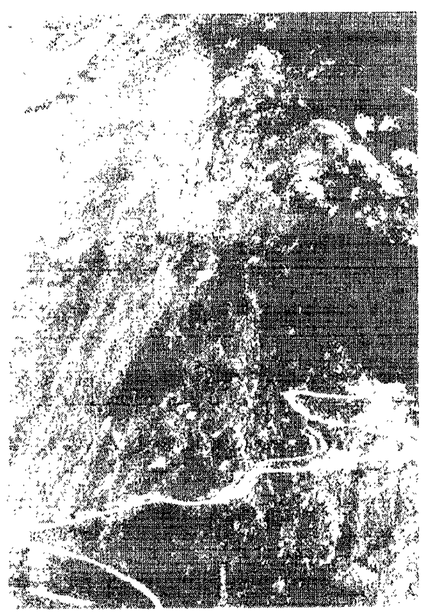

Photo 12 The hummocks in the eastern side block located at the lower left of Photo 11.

This hummocky zone continues to the original channel of the Qingshui-shi River, and beyond it, the sliding mass is bifurcated similarly to the western side block. While the western side block can be regarded as a variant of the main block due to a high mobility, the eastern side block seems to be an assembly of the regions of different dynamic properties. It includes transitional slide of highly weathered soil and slumping of the laminar formation, as well as the hummocky zone. However, these regions should be regarded as a block as a whole, since they are commonly associated with deep weathering along the eastern edge of the landslide area.

3.2 Chiufengershan Landslide

This landslide occurred on the eastern slope of a ridge stretching in the north-south direction and dividing the drainage basins on the both sides (Fig. 1 and Photo 13). This ridge is accompanied by a peneplain with farmlands and 30 houses, among which 21 houses were demolished causing 39 victims due to the landslide. A house was found standing at a place about 1 km apart from the original place, presumably because its base was appropriately soft so as to avoid crushing, still maintaining its consistency (Photo 14). Another house was found about 100 m apart from the original place, standing on a base of a cubic rock mass of about 1,000 m^3. As shown in Photo 13, the landslide scar of the denudational area is planar suggesting the slide along the bedding plane. It should be, however, noted that, immediately after the landsliding, this plane had not been so flat as shown in Photo 13. The longitudinal colored stripes on the exposed slip surface suggest that the bedding plane was oblique to the slip surface and that its dip is a little greater than the gradient of the latter. It is, however, inferred that the sliding was essentially along the bedding plane. The horizontal linear object across the landslide area is a tentatively restored road. A part of weathered mantle that had been left intact is found at the upper edge of the denudational area.

Photo 13 An overview of the Chiufengershan Landslide (the natural dam is not visible).

Below the denudation area is a hummocky depositional are. It is steeper on its upper part and gentler on the lower part. The lower part is underlain by the main channel of a small river and one of its tributaries, and also by a small ridge between them. The river was blocked along a distance of about 1 km (Photo 15). A small lake has been formed at the upstream side. A large construction work was in progress and the ground surface of the depositional area had been partly disturbed at the time of the field reconnaissance study.

Photo 14 A house that had been near the ridge of Mt. Chiufengershan was moved along a distance of about 1 km by the landslide.

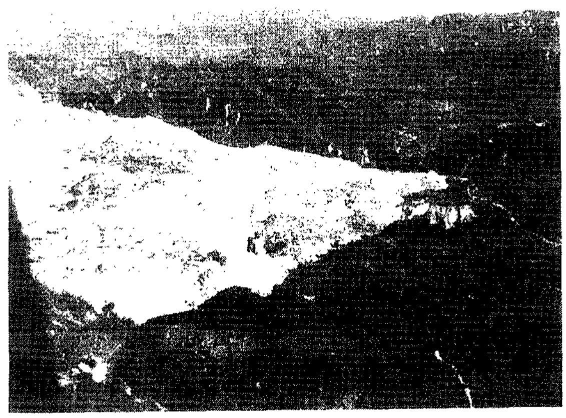

Photo 15 The lowest part of the landslide deposit that blocked a small river around its confluence with a tributary. A part of the deposit has been modified by the restoration works.

Different from the case of the Tsaolin Landslide, the landslide area of the Chiufengershan cannot be clearly divided into the main block and the side blocks.

4. The other large-scale landslides

Although Taiwanese researchers have recognized some other gigantic landslides, we have visited only two gigantic landslides described above. The other large-scale landslides observed from a distance and from the helicopter are briefly described below. They are transitional slides along the lamination, slumpings of weathered rock or debris, and the slide-fall of weathered rock, loosened boulders and weathered soil mantle (particularly laterite). Since the depth of the sliding was unknown, the magnitudes of them have been estimated only according to the observation by the eyes.

4.1 Sliding along the bedding plane

Except for the Quaternary formations, the geology of Taiwan is zonal in the direction of the north to the south with monoclinal structure steeply dipping toward the east (although a syncline is found in the vicinity of Tsaolin where the strata dip gently toward the south on the axis of the syncline). Therefore, the geological susceptibility to the landslides along the bedding plane shows a regular geographical distribution according to the slope aspect. Hence, if a group of landslides occur collectively on the slopes of the same aspect, they can be recognized as of this type. This tendency was obvious in the mountains on the left side of the Dachia-shi River. Similar tendency was also recognized in the mountains on the both sides of the Qingshui-shi River, where larger number of landslides occurred on the south facing slopes and seemed deep-seated. Photo 16 shows an example of the landslides that seemed to have slid along the bedding plane.

Photo 16 An example of the landslide presumably along the bedding plane (in the mountains to the east of the Qingshui-shi River).

4.2 Sliding along the joint surface or other geological discontinuity

In the cases of the landsliding along the bedding plane of the bedrock, the sliding mass was frequently observed to have been fractured into rock pieces by the joints perpendicular to the bedding plane. Therefore, the landslides on the steep slopes with the aspect against the direction of the dip of the geological strata are thought to have been caused by the joints or other geological discontinuity crossing the bedding plane. An example of the relatively deep-seated landslide apparently belonging to this category is shown in Photo 17.

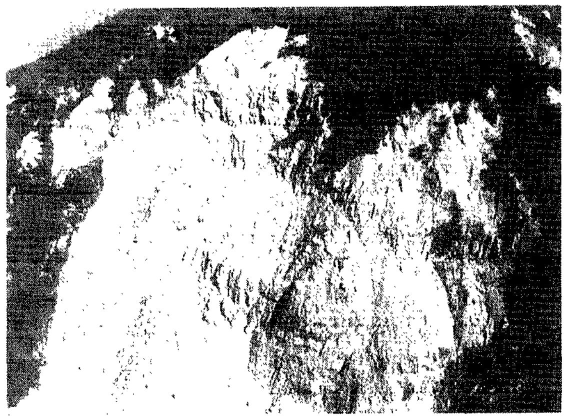

Photo 17 An example of the landslide presumably along the joint surface (in the mountains to the east of the Qingshui-shi River).

4.3 Sliding and fall of highly weathered mantle

In humid areas under active crustal movement, sliding and fall of highly weathered material frequently occur at the time of heavy rainfalls, particularly in the hollow on the slopes (Iida and Okunishi, 1981). At the times of the earthquakes of great magnitude the return period of which is much greater than that of heavy rainfall, it is frequently observed that more landslides occur on steep convex slopes (e.g., Okunishi et al., 1999). This was the case in 1999 Chichi Earthquake.

Although this type of landslides are of small volumes, they can occur at many parts of a slope, and the total debris produced by them may constitute debris avalanches or debris flows of a large scale, running down a long distance and inundating into wide areas and causing heavy damage. In the case of the Chichi Earthquake, a swarm of such landslides were found here and there (Photo 18), although no severe discharge of debris to the fluvial system was

Photo 18 An example of a swarm of surficial landslides (in the mountains to the east of the Qingshui-shi River).

observed. In several areas, this type of landslides were connected with one another to produce a wide landslide area. An extreme example of such cases was observed on the Mt. Chiushichiu-feng (the naming came from "ninety-nine peaks") where almost all parts of the mountain slopes of conglomerate had became denuded of vegetation (Photo 19). A series of marked geomorphic changes (Okunishi et al., 1987) are anticipated in the future.

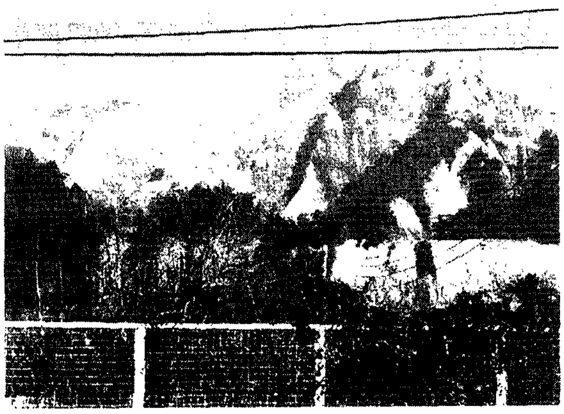

Photo 19 A view of Mt. Chiushichiu-feng denuded of vegetation due to extensive and intensive surficial landslides.

4.4 Slumping

Although many slumpings have been reported, we did not find the landslides that can be obviously decided to be slumpings. It is, presumably, because we did not visit the places of slumping by car or by helicopter.

4.5 Reactivation of dormant landslides

Reactivation of dormant landslides has been reported in many places. However, we photographed only a few slopes suspicious to be dormant landslides, presumably due to the condition similar to section 4.4.

Acknowledgments

Our field reconnaissance study was carried out with Dr. Okimura, Dr. Yoshida and Dr. Torii (Kobe Univ.), Dr. Kawabe (Mie Univ.), Dr. Ishikawa (Chuo Kaihatsu Corporation), and Dr. Yamamoto (Obayashi Corporation). This report is partly based on the discussion with them. Prof. Lin Jiun-Chuan (National Taiwan Univ.) and his students, and Dr. Zhang Xian-Qing (Central Geological Survey) kindly guided us to the field as well as giving valuable information. The investigation was supported by the Grant-in-Aid for Scientific Research of the Japanese Ministry of Education, Science, Sports and Culture (No. 11800012 for Prof. Iemura, Kyoto University). The Helicopter was chartered in expense of Kobe University.

References

Iida, T. and Okunishi, K. (1981) Evolution of hillslopes including landslides, *Trans. Jap. Geomorph. Union*, Vol. 2, No. 2, pp. 131-150.

Lin, S. C. (2000) The primary study of landslide triggered by Chi-chi Earthquake, *Sino-Japan Second Workshop on Seismic Hazard and Mitigation*, National Taiwan Univ., 110p.

Okunishi, K. (1982) Kinematics of large-scale landslides -A case study in Fukuchi, Hyogo Prefecture-, *Trans. Jap. Geomorph. Union*, Vol. 3, No. 1, pp. 41-56.

Okunishi, K. Okuda, S., Suwa, H. (1987) A large-scale debris avalanche as an episode in slope-channel processes, *IAHS Publication*, No. 165, pp. 225-232.

Okunishi, K., Sonoda, M. and Yokoyama, K. (1999) Geomorphic and environmental controls of Earthquake-induced landslides, *Trans. Jap. Geomorph. Union*, Vol. 20, No. 3, pp. 351-368.

Sato, O and Aoki, S. (1990) Groundwaters from fresh and old landslides in the Tertiary landslide area in Niigata Prefecture, J. Japan Landslide Society, Vol, 27, No. 1, pp. 27-33 (in Japanese).