Relationship Between Geological Structure and Landslides Triggered by the 2007 Mid-Niigata Offshore Earthquake

14

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Abstract

Compared with the case of the 2004 Mid-Niigata Earthquake, by which so many large and middle-scale landslides were triggered, only a few middle-scale ones occurred with many small-scale ones by the 2007 Mid-Niigata Offshore Earthquake in spite of their similar geology and topography [landslide-scale with apparent volume (the Japan Landslide Society, 2004); small-scale: 10^2–10^4 m^3, middle-scale: 10^4–10^6 m^3, large-scale: 10^6–$10^8 m^3$]. Some of them, however, caused serious damage to the infrastructures. Around the Hijirigahana cape in Yoneyama town located at about 30 km south of the epicenter, some middle to small-scale landslides occurred as a group. Geology of the study area is composed of sedimentary rocks simply dipping to the sea. An open anticline gently plunges to north, and the study area is just located on and around its axial part. Due to the topography 'cuesta', both of translational and rotational slides occurred on the cataclinal and orthoclinal slope, respectively. It had been thought that mechanism of those landslides was not so complicated because of the simple structure. During the excavation for the countermeasure of those landslides, however, a vertical fault, which looked like a tectonic one, with some others including bedding faults were found behind the affected area. Although the most hazardous slide occurred on the cataclinal slope was a simple translational one, rotational slide occurred on the orothoclinal slope was a little complicated, and non-tectonic structure due to the pre-historical event was found behind the new slide.

1 Introduction

This paper is one of our case-studies on the landslides triggered by large earthquakes which occurred within the last decade in Niigata Prefecture.

Activities in WG 8 of JLS-ELRP.

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K. Ugai et al. (eds.), *Earthquake-Induced Landslides*,
DOI: 10.1007/978-3-642-32238-9_14, © Springer-Verlag Berlin Heidelberg 2013

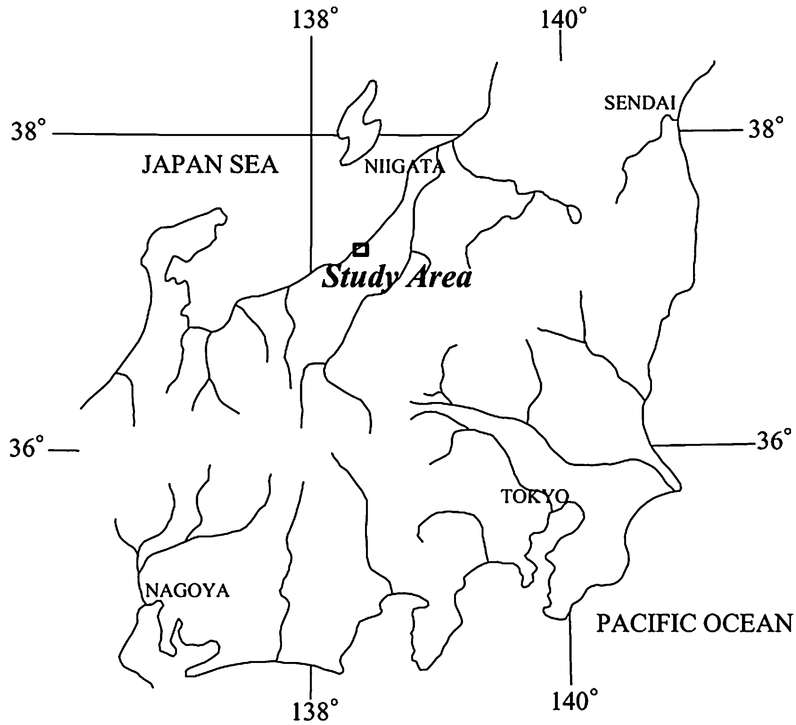

Fig. 14.1 Location map

Tragically, on July 16, 2007 only 3 years after the Mid-Niigata Earthquake (Mj = 6.8) in 2004, the Mid-Niigata Offshore Earthquake (Mj = 6.8) occurred. Both of the ravaged areas were partly overlapped, because both the epicenters were only 25 km away, and many residents in the affected area of the preceded earthquake, who had just rebuilt or were the halfway to repair their houses, were miserably suffered with liquefaction and slope movement again (Fig. 14.1).

Compared with the case of the 2004 Earthquake, by which so many large and middle-scale landslides were triggered, only a few middle-scale ones occurred with many small-scale ones by the 2007 Earthquake in spite of their similar geological and topographical conditions. Some of them, however, caused serious damage to the highways and the railroad lines. Around the Hijirigahana cape in Yoneyama town located at about 30 km south of the epicenter, some middle to small-scale landslides occurred as a group (see Fig. 14.2). These landslides blocked a local road at two places, and accidentally a car passing along was trapped between them (see Photo. 14.1), fortunately the driver and his car were safe. Geology of the study area is composed of sedimentary rocks simply dipping to the sea. An open anticline gently plunges to north, and the study area is just located on and around its axis. Due to the topography ‘cuesta’, both of translational and rotational slides occurred on the cataclinal and orthoclinal slope, respectively. It had been thought that mechanism of those landslides was not so complicated because of the simple homoclinal structure. During the excavation for the counter measure of those landslides, however, a vertical fault, which looked like a tectonic one, with some others including bedding faults were found behind the new slides. In this paper, we described the hazard of landslides, and discussed the mechanism of the new and old rockslides with the issue of non-tectonic geological structure.

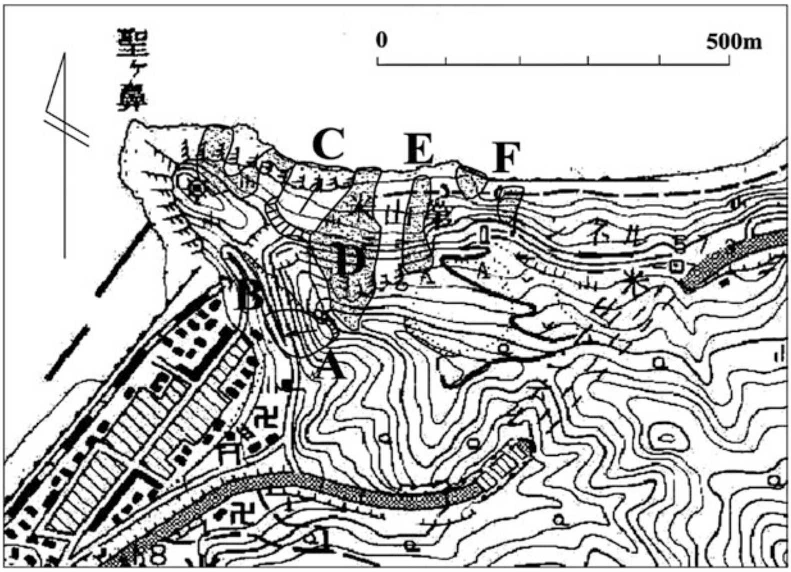

Fig. 14.2 Distribution of landslide units triggered by the earthquake

2 Geology

A late Miocene member of sandstone-rich alternating beds of sandstone and siltstone, part of which was beautifully outcropped along the local road passing through the cape (see Photo 14.2), is conformably overlain by the volcanic rocks, and disconformably underlain by the member of siltstone intercalated with thin beds of sandstone and a thick pumice tuff at its upper horizon (see Fig. 14.3). Both of the upper and the lower members of sedimentary rocks were named Hijirigahana Formation by the Yoneyama Research Group (Yoneyama Research Group, 1973). The disconformity between both members, however, was found during our investigation of this disaster. These strata gently dip (25–30°) toward sea making cataclinal and orthoclinal slopes on north and west side of the cape respectively. This cape is located just on the axis of broad open anticline, of which the axis plunges to north. That is the reason why the aspect of bedding plane in the study area trends EW and dips north in spite of NS trend of the anticlinal axis. Although vertical joints, which were slightly tilted to SW, tend to develop in NW–SE and less other directions, there was no noteworthy tectonic fault except for some bedding-plane slips which were found on a part of new and old sliding surfaces.

3 Landslides Triggered by the Earthquake

Two units of the landslide A and B rotationally moved without clear boundary between them on the western side of the cape, where is rather steep orthoclinal slope. On the other hand, four units of landslides C, D, E, F and small others occurred on northern side, where is gentle and typical cataclinal slope (see Figs. 14.2, 14.3).

3.1 Rotational Slides on the Orthoclinal Slope

On the western side of the cape, the slope looks toward west or southwest, and the strata dip to

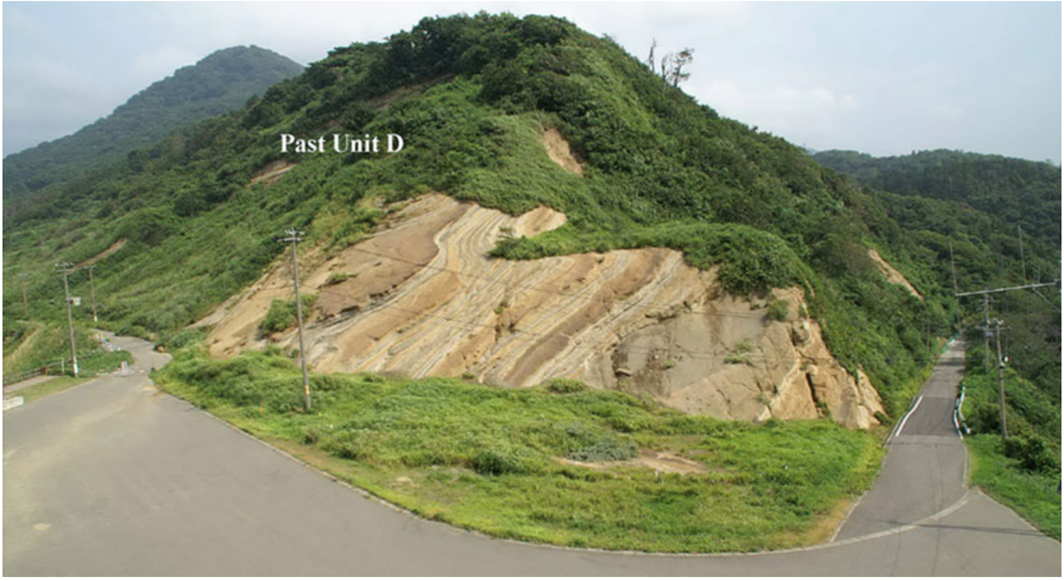

Photo. 14.1 View of the study area before the earthquake (Photograph taken on Aug. 10, 2005 by Atsuo Ueki, Kashiwazaki city education center)

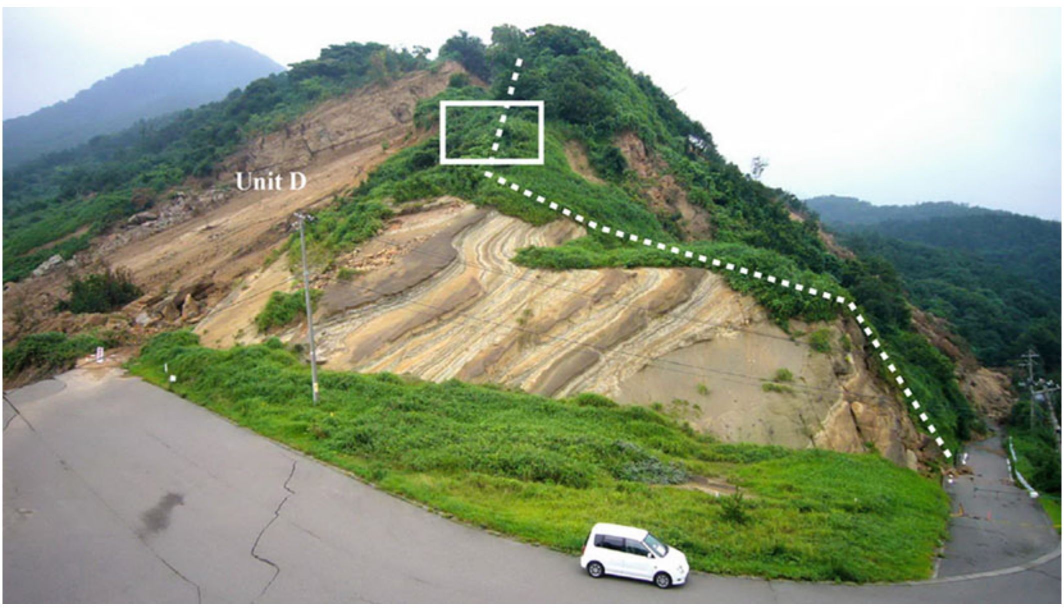

Photo. 14.2 View of the study area after the earthquake (Photograph taken on Aug. 4, 2007. *Dotted line* is trace of the fault observed at the *box*, location of Photo 14.3)

north forming orthoclinal structure. Except for the upper part of the slope, where the rock consists of alternating beds of sandstone and siltstone, basement rock consists of siltstone member intercalated sparsely with thin layers of loosely indurated sandstone and a thick soft pumice tuff at its upper part.

About 5 m high head-scarp was created below the crown of Unit A along the ridge associated with parallel cracks, and the vertical

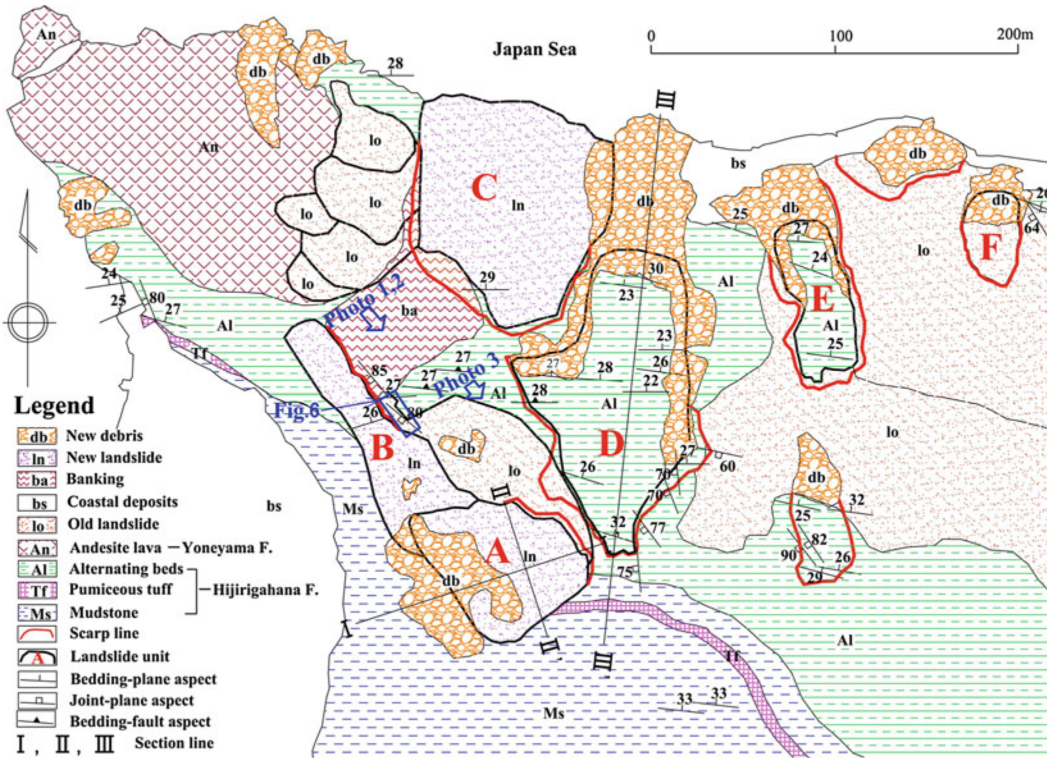

Fig. 14.3 Geological map of the study area

crack which was 0.3–0.7 m high at the head area of Unit B obliquely run across the road. No clear boundary appeared between Unit A and B. Although displacement of Unit B was less than 0.7 m at the head, its width was transversely elongated more than 100 m along the lower part of the slope, and the southern flank was buried beneath the debris of Unit A. The affected area of Unit B was unknown in detail because of the short displacement, and the relationship between the two units was not able to be clarified because of the way of complicated displacement at the boundary. However, the tip of the sliding surface of both units even the toe of the debris of Unit A did not apparently reach to the foot of the slope, and the JR tunnel located just under the landslides had no damage. Although slightly gentler slope than the other part was created at the head of Unit A, the gradient of this orthoclinal slope was more than 40 degrees as a whole. Magnitude of the Unit A was approximately 90 m wide, 120 m long and 10 m thick.

On the outcrop of alternating beds located at the northern end of the ridge which meets with the road, a few consistent vertical joints directed to NW were observed. New open spaces associated with small debris were observed along these joints and bedding-planes, and those sedimentary rocks were evidently loosened by the tremor of earthquake. However, it was clear that some of them had been already loosened by the pre-events because of the evidence of sealing cracks with asphalt on the road and the grass roots invaded into some of those open cracks.

3.2 Translational Slides on the Cataclinal Slope

The most hazardous unit D, which pre-existed before the earthquake, extended mainly to the upper slope, and only thin strata must have been ripped off on the central to lower part of the unit (see Fig. 14.4), because a part of the road, which

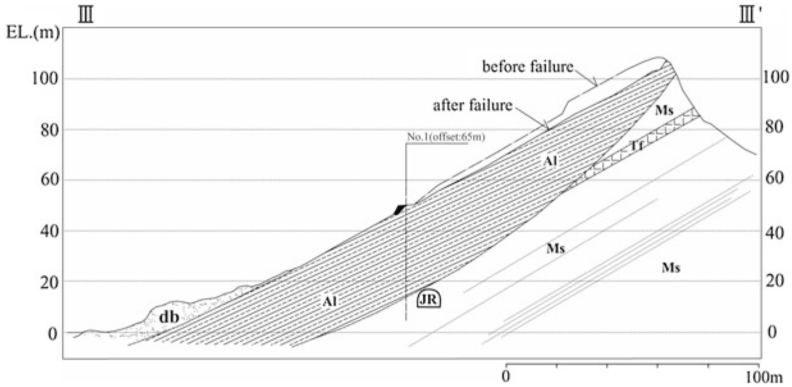

Fig. 14.4 Longitudinal section of Unit D

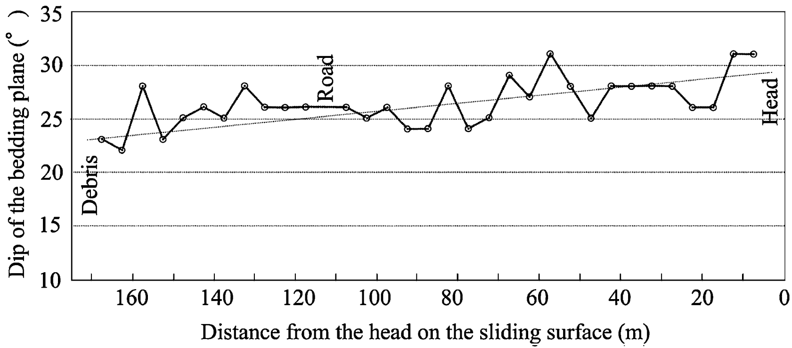

Fig. 14.5 Changing dip of strata along longitudinal section of Unit D

had run across the central part of the unit, remained intact. The maximum width is about 100 m, the length is about 200 m, the head was a little more than 100 m above sea level, and the volume accumulated at the foot of the slope was evidently less than 10,000 m^3. The upper end of the sliding surface reached beyond the ridge along a bedding-plane, hence no head-scarp remained. On the eastern side of the slide, however, "detached scarp" rose sheer more than 10 m, and the sequence of alternating beds of sandstone and siltstone was well-observed there. On the western side of the slide, 5–8 m high side-scarp was created, and a part of it toppled as rock-panels separated by high-angle joints trending NW. Almost entire sliding mass reached to the beach, and the sliding surface was widely exposed.

On the higher portion of the sliding surface, a large number of slicken lines, which was directed approximately to the dip of the strata, were extensively curved on a bed of siltstone. Slicken lines found on the sliding surface at the foot of the western scarp, however, were approximately parallel to the strike of the strata. It means that these slicken lines had evidently occurred as a bedding-plane slip during the past folding : tectonic movement, and functioned as a potential sliding surface. The sliding surface, however, did not occur along only one bedding-plane, but occurred along bedding planes connected in a stepwise manner making a micro-staircase (see Fig. 14.4). This means that the sliding surfaces shifted to the lower sequence of the strata down-slope. The whole sliding surface, therefore, looked a little steeper than the dip of the strata.

Figure 14.5 shows the changing dip of strata at intervals of every 5 m along the center line of Unit D. The attitude of the bedding plane was approximately EW25–30°N, and it became gentler little by little descending from the head to the

Photo. 14.3 Fault appeared on the cut-slope

foot of the slide with undulation. As a result, the configuration of the sliding surface drew a very gentle arc as a whole due to this changing dip and the micro steps.

Unit C was exceptionally rotational making a typical head scarp on the cataclinal slope. The sliding mass had consisted of old debris derived from JR tunnel which run across just under the ravaged area. This unit did not run so long, and stopped on the slope. It is inferred that the sliding surface did not exceed 5 m in depth at most considering on its configuration and dip slope. Unit E occurred adjacently on the eastern side of Unit D was also a translational type, and the sliding surface was exposed in the same manner. Gravelly soil outcropped on its head scarp, however, was evidently old landslide debris; 2–3 m in thickness. Much smaller unit F was located at the east entrance of the old tunnel. Although this unit was also translational, it obliquely cut across the bedding-plane, and the sliding surface of an old landslide unit was observed on the side scarp.

4 Unexpected Structure Found During Excavation Work

A fault tilted with high angle toward SW direction appeared during excavation work for one of the countermeasures at the northern part of the ridge between Unit A and B (see Photo 14.3). Although its precise direction of the separation and the throw was not known, it was evidently a normal dip separation fault. The right side of the fault in the photo was hanging wall; both sides of the wall looked intact. Incidentally, the upper central bushy part in Photo 14.2 was the cut slope in Photo 14.3. On its

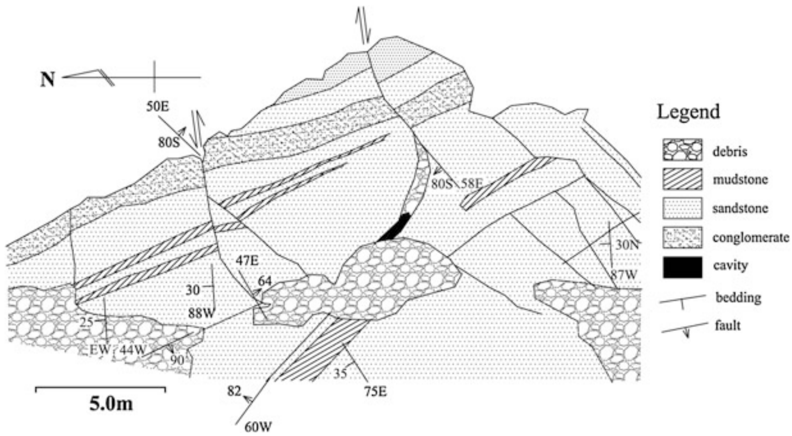

Fig. 14.6 Sketch of outcrop located on the western side slope

extension line on the outcrop in the foreground of Photo 14.2, however, no such a fault was seen. It means that the fault did not extend there. Figure 14.6 shows the sketch of the outcrop observed from west (right hand side), where was right-end portion of this outcrop (see Fig. 14.3). Although this part was loosened a little, and some tiny failures and/or peeling off occurred in places by the tremor, some high-angle faults were observed as shown in Fig. 14.6. We had thought at first, therefore, this outcrop had been a part of the intact rock before the earthquake. However, it was clarified that only a central part of the rock was intact and surrounded by the displaced masses after our detail observation.

Figure 14.7 is the sketch map of the cut-slope observed during the excavation work of the unstable debris, which was made for the stabilization of Unit A. Unfortunately, this sketch had not been schemed before the work, some parts of this map, therefore, were analyzed from the photos taken during the cut-work. We observed, however, all the cores drilled just after the earthquake at this site, and draw this map and geological sections (Fig. 14.8) with reference to those data. Although landslide debris moved by the earthquake had been completely excavated, a high angle fault dipping to west appeared at the head of the cut slope, and thick crush zones along bedding-planes and/or bedding-plane-slip faults also appeared at the middle and lower part of the slope, hence the original scheme had to be changed (Niigata Branch of the JLS 2008). As a result, the excavated volume reached to 70,000 m^3, much larger than the original plan of 20,000 m^3.

5 Mechanism of Landslides

5.1 Landslides on Orthoclinal Slope

It was not discernible during excavation whether the fault shown in Photo 14.3 was tectonic or non-tectonic, because both walls of the fault looked utterly intact. Beautiful alternating beds had widely cropped out around its northern extension line, and sliding surface and/or bedding plane had been widely bared stripping off the mass of Unit D on its southern extension line: no evidence of fault was there on both sides. It is impossible that tectonic fault dies out in such a short distance. On the other hand, throw of the normal fault found behind the head scarp of Unit A was about 10 m tilting with high angle toward west, and it became abruptly gentle and made an arc at the intersection with the bedding-plane-slip fault. In addition, the strata of hanging wall were apparently disintegrated or crushed at random in places, and thick crush zones along bedding-plane-slips were observed (see Fig. 14.8). Therefore, it was clear that this fault was a part of old sliding surface. Although its extension to north was not traceable because of covering of debris or soil, it must be the identical one described above. It reasonably

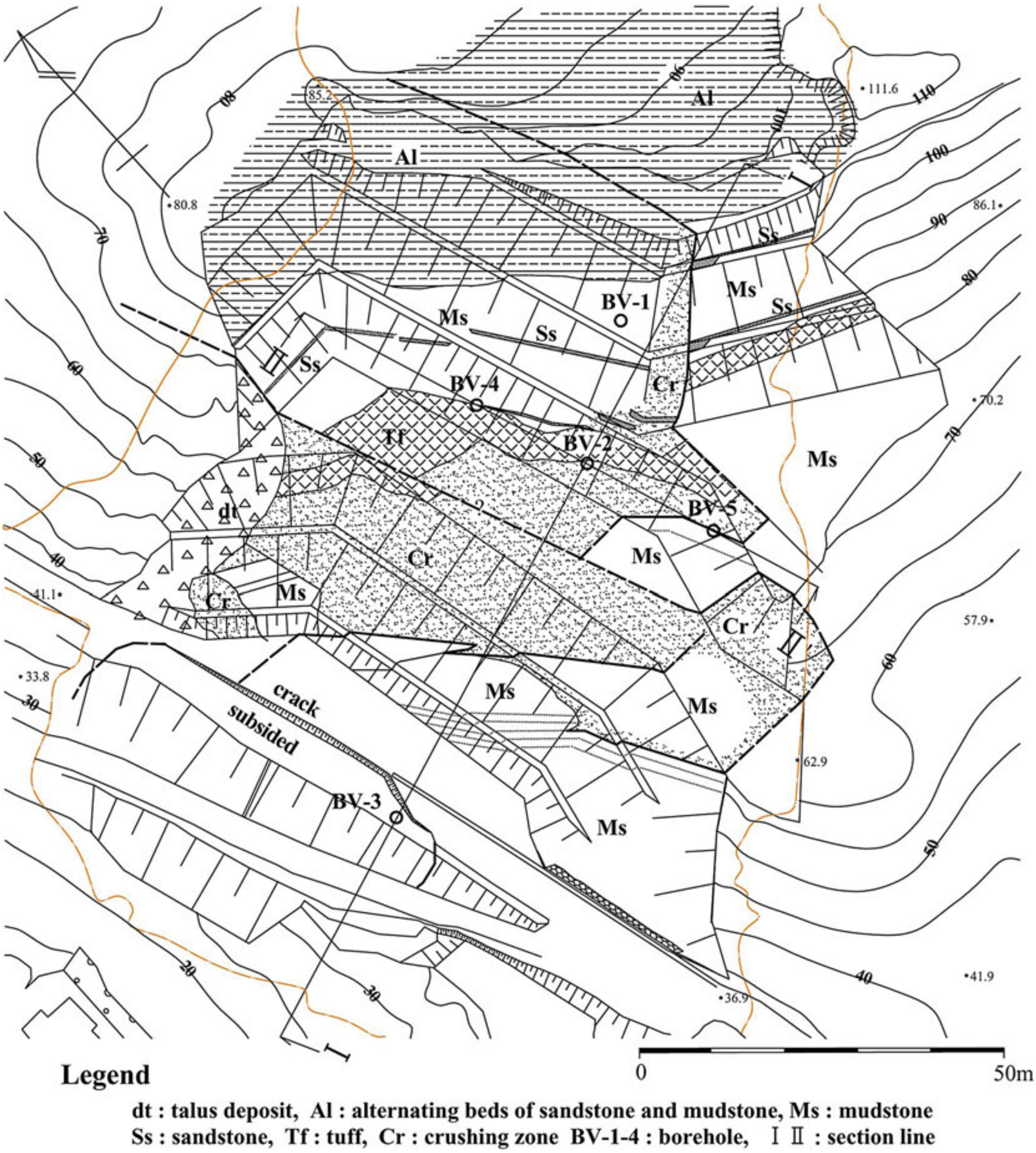

Fig. 14.7 Sketch map of cut-slope during excavation work of Unit A

extends turning to west toward the natural outcrop shown in Fig. 14.6. It means that the whole structure was non-tectonic created by the old gravitational movement except for some bedding-slip faults.

Although the head area of Unit A started to move west, that displacement was deflected from west to north at the lower part. This movement is well-explained with the structure above-mentioned, that is, the head area displaced creating the head scarp along the non-tectonic fault or vertical joints, then the sliding mass was deflected along pre-existed bedding-plane-slip associated with crush zone at the lower slope. Mechanism of Unit B is unknown the detail, because the visible displacement was

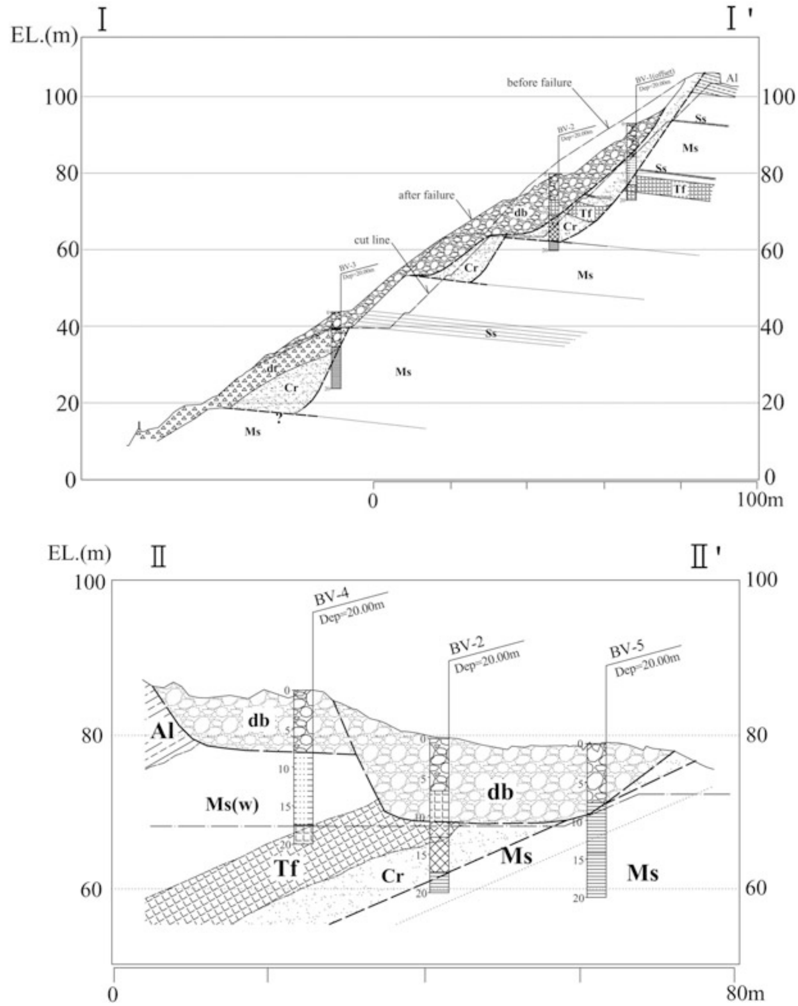

Fig. 14.8 Geological sections of Unit A

limited at the head area and the almost entire area was covered with soil and vegetation. We believe, however, it must be basically same with the mechanism of Unit A, because of the same geological structure.

5.2 Landslides on Cataclinal Slope

As shown in Photos, cataclinal slope consists of beautiful alternating beds of sandstone and siltstone, which are easily sheared off along bedding planes. Moreover, the bedding-plane-slips observed in places also must have fostered the development of gravitational sliding as potential sliding surface. These slips must have occurred with flexural slip on the axial part of anticline, because the slicken lines and the dip of the bedding-plane crossed each other at almost right angles, each of those slips was not so long extended though. The sliding surface of Unit D drew a very gentle arc making micro steps, and this configuration made it a little steeper at its upper part. Therefore, it might have been one of the reasons why the sliding mass was not so disintegrated and reached to the foot of the slope, or might have helped it at least.

Along the ridge located between the cataclinal and orthoclinal slope, vertical joints had developed with NW–SE trend, and the west-side scarp of Unit D was controlled by them. The almost entire slope including Unit C, D, E and F were located in a bigger old landslide area, and it is reasonably inferred that translational slides had been repeated on this slope in the past. In comparison between Photos 14.2, 14.1, we found that extents of Unit D and past Unit D were almost same. Therefore, it is inferred that Unit D must have occurred on the same slope of the past slide extending a little to the head area, and only 2–3 m thick veneer of alternating beds on the upper slope slid down to the beach as a new rockslide including a little old debris, because the volume of the debris was less than 10,000 m^3.

Same type of rapid translational rockslides as Unit D, represented by Yokowatashi landslide (Nagata and Nozaki 2007), were triggered at many places by the 2004 Mid-Niigata Prefecture Earthquake.

6 Conclusions

It looked landslides induced by the 2007 Mid-Niigata off shore earthquake on the cataclinal slope were extensive and more hazardous than those on orthoclinal slope. However, they did not so extend over the limit of the pre-existed slide and those sliding masses were shallow except only the upper part of Unit D. The sliding surface of Unit D made a micro-staircase, and the dip of the strata increases toward the head. This kind of structure might have helped the long travel of the sliding mass.

On the other hand, the mechanism of landslides on the orthoclinal slope was rather complicated and interesting. During the excavation for the countermeasure of those landslides, a vertical fault with some others including bedding faults were found behind the earthquake-induced failure zone. Even after the countermeasure including excavation work, it had been believed that those structures were tectonic or synsedimentary disturbance happened under the sea water. However, the authors clarified that those structures were limited around and/or under the affected area, and they had not reached to the extending nor underlying strata. Therefore, we concluded that those complicated structures must have been created by preceded slope movement, probably induced by the prehistoric earthquake.

Acknowledgments We are grateful to the Niigata Prefectural Office for permitting us to quote their results in advance of publication.

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