Gentle-slope movements induced by the 2003 Tokachi-Oki Earthquake, in the Kyowa area of Tanno Town, Hokkaido, Japan

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Abstract

The 2003 Tokachi-Oki Earthquake caused extensive ground collapses accompanied by slightly lateral displacement, subsidences, and lateral spreads of gentle slopes in the Kyowa area of Tanno Town, situated about 230 km away from the epicenter. The direct inducement of such slope movements was the liquefaction of the volcanic ash that had artificially covered the valley. Especially, at Locality No.1 in the Kyowa area, liquefied volcanic ash of about 10,000 m\(^3\) spouted from the slope to the sides, and a wide farmland collapsed. Such large ground collapses caused by lateral jetting of the liquefied volcanic ash are new phenomena and new landslide disasters induced by the earthquake.

The old landforms of the liquefied and moved area were narrow waste-filled valleys and swamps formerly utilized as paddy, but these were converted into the gently-sloping farmland by the land fill of volcanic ash. Though the field of similar landform transition and ground condition is large in number, it is characteristic that the slope movements caused by the liquefaction of volcanic ash were confined to the fields where the reclaimed planes tilted to the south or south-southwest. In addition to, the dip direction of the reclaimed planes coincided with the direction of the main lateral displacement of the surface in each liquefied area. The dip direction of the reclaimed planes might have brought about the geomorphic effect.

Key words : liquefaction, artificial volcanic ash ground, ground collapses, lateral spreads, lateral sand boils, waste-filled valleys, geomorphic effect

1. Introduction

An earthquake of magnitude 8.0 shook Eastern Hokkaido around 4:50 a.m. on 26 September, 2003. Its epicenter was about 60 km ESE from Cape Erimo, latitude 41.78\(^\circ\) and longitude 144.08\(^\circ\) E. The focal depth was about 42 km. A lot of ground and slope disasters caused by liquefaction and landslide were reported after this 2003 Tokachi-Oki Earthquake (Tajika et al., 2003; Ito et al., 2004; Yagi et al., 2004). In particular, extensive ground collapses, subsidences, and lateral spreads occurred because of the liquefaction of volcanic ash in the Kyowa area of Tanno Town.

We have carried out field investigation, aerial investigation by motor glider, air-photo interpretation, and physical and mechanical tests of soil samples since immediately after the earthquake disaster. Ito et al. (2004) clarified that the liquefied and moved areas in the Kyowa area were waste-filled valley and swamp before, and they had been utilized as the paddy since 1960's, and then, they were the position converted to the field by volcanic ash reclamation of the valley from 1983 age. Yamashita et al. (2004) indicated that the liquefaction strength of the reclaimed volcanic ash is very low.

In the Kyowa area, the fields where the landform and ground conditions are similar to the liquefied and moved areas are distributed in a large number. Because of this, we also carried out the morphometry of waste-filled and reclaimed valleys through time series analysis of air-photographs, in hope of identifying the geoenvironmental differences between the liquefied areas and the non-liquefied ones.

This paper describes the characteristic gentle-slope movements triggered by the liquefaction of volcanic ash, and a singular behavior of the liquefied volcanic ash. Moreover, the characteristic geomorphic environment in the liquefied and moved areas is also dealt with.

2. Investigated area and Earthquake vibration

The Kyowa area of Tanno Town, close to Kitami City, is situated about 230 km from the epicenter and lies to the north of the hypocentral region (Fig.1). The
area forms gently undulating hills and consists of Pleistocene non-welded volcanic ash and pumice, which corresponds to the Kutcharo pumice flow deposits IV (Katsui and Sato, 1963; Okumura, 1991).

According to the Japan Meteorological Agency: JMA (2003) and the Geographical Survey Institute (2003), the Kitami observation point recorded the JMA seismic intensity of 5−, and with a maximum acceleration of 109.4gal (NS component), 123.6gal (EW) and 47.6gal (UD). The horizontal displacement of 6cm to the SSE and the vertical movement of −3cm were also observed after the earthquake. At the Tanno observation point situated about 5km to the northeast of the Kitami observation point, the JMA seismic intensity of 4 was recorded. Landform and ground conditions in the Kyowa area are similar to them in the Kitami observation point installed in volcanic ash hilly area, and it is guessed that earthquake vibration in the Kyowa area was near for it in the Kitami observation point.

3. Gentle-slope movements in the Kyowa area

During the 2003 Tokachi-Oki Earthquake, liquefaction and gentle-slope movement occurred at six places in the Kyowa area, Tanno Town (Fig. 2A). These phenomena were found in the limited area of about 1km to the NE-SW, and 0.5km to the NW-SE. The outline of liquefaction and slope movement is summarized at Table 1. The major slope movements are as follows: extensive ground collapses and slight lateral displacement accompanied by lateral sand boil at Locality No. 1 (Fig. 2B), spoon-like ground subsidences at Locality No. 2 (Fig. 2B), extensive ground collapse accompanied by lateral displacement at Locality No. 3 (Fig. 2B), extensive ground collapses with a small-scale slump at Locality No. 4 (Fig. 2C), a wide lateral spread at Locality No. 5 (Fig. 2C), and small-scale, spoon-like ground subsidences at Locality No. 6 (Fig. 2C). At Localities Nos. 1−5, sand boils in the vertical direction were observed.

One of the characteristic features is that the directions of the lateral ground displacement are biased to the south or south-southwest (Table 1). The disaster took the form of farmland destruction: collapses, subsidences and lateral displacement of ground surfaces, plus cracking.

As evident examples, the slope movements at Local-

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<th>Table 1 Liquefaction and slope movement in the Kyowa area, Tanno Town</th>
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Fig. 2 Location of the liquefied and moved areas

A: Map showing the liquefied and moved areas. B: Oblique aerial photograph of Localities Nos. 1−3, viewed from south. C: Oblique aerial photograph of Localities Nos. 4−6, viewed from west-northwest.
ties Nos. 1, 3 and 5 are described in detail.

3.1 Ground collapse accompanied by lateral displacement and lateral sand boils at Locality No. 1

Farmland which tilted at about 3% gradient to the southwest sank 3.4m deep. 35–62m wide to the NW-SE, 190m long to the NE-SW (Fig. 3A). Moreover, the farmland moved about 1.0–1.5m to the SSW. The scarp 2m high was formed on the margin of the collapsed area, and the open cracks 1.0–1.5m wide were bored along the scarp (Fig. 3B). Black soil 0.3m thick and dry volcanic ash was exposed on the scarp, and the open cracks were filled with the liquefied volcanic ash. The farmland in the southwest margin of the large-scale collapsed area also slightly subsided. Therefore, an area of about 80m wide and 255m long at the maximum fluctuated.

An uplifted area in 0.5–1.5m height was created on the southwestern and southeastern margins of the collapsed area, and compression wrinkles could be detected on the raised surface. Liquefied volcanic ash spouted out of the four exhaust nozzles made in the cracks of the lifted area (Fig. 3A). Many sand boil hills were found in the southwest of the collapsed area. Sand boil mark which made the angle of about 10 degrees was also observed on the wall of an exhaust nozzle. We can observe that the compression mostly occurred on the toe areas of lateral movement. Furthermore, it can be imagined that the volcanic ash spouting was destructive, because the overturned volcanic ash blocks of 1m in maximum thickness were detected inside an exhaust nozzle (Fig. 3C).

The liquefied volcanic ash blasted over the farmland, open ditches and roads for an area of about 100m wide NW-SE, and 100m long NE-SW. Moreover, as the ash flowed into the Ponchashikotsumanai River, the channel was filled for about 900m downstream and 100m upstream (Fig. 3D). The amount of volcanic ash that covered the land reached 6,500m³, and that which filled the channel was about 3,500m³. Therefore, the liquefied volcanic ash spouted out in volume of about 10,000m³ in total.

3.2 Ground collapse accompanied by lateral displacement at Locality No. 3

The farmland adjoining the northeast side of Locality No. 1 sank 1m deep, forming a sink of the size of...
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160m wide to the NW-SE, and 95–125m long to the NE-SW (Fig. 4A). The scarp of 1.0m in maximum height and with open cracks 1.3m wide was formed on the northeast margin of the collapsed area. Black soil 0.3m thick and dry volcanic ash was exposed on the scarp, and the open cracks were filled with the liquefied volcanic ash (Fig. 4B). Many sand boil hills were formed in the southeast of the collapsed area (Fig. 4A). It is imagined that non-liquefied volcanic ash layer 1–2m thick moved about 1.3m to the SSW.

On the northwest margin of the collapsed area, a lateral spread was induced 20m wide to the NE-SW and 5m long to the NW-SE, and the farmland slope along the swamp was pushed about 5m to the northwest.

In the 1994 Hokkaido Toho-Oki Earthquake, liquefaction attacked this area. The scarp of 80m long to the NW-SE and 1.3m in maximum height was created in the farmland. Therefore, it can be said that the restored farmland liquefied again.

3.3 Lateral spread at Locality No. 5

Farmland which tilted at about 3% gradients to the south-southwest moved about 103m wide to the NW-SE, and 20–30m long to the NE-SW (Fig. 5A). A separated scarp 1.8–2.0m high with an open crack of 1.0m, plus the other two scarps 0.5m high each with their 1.0m open cracks were disclosed along the sunken area (Figs. 5B and 5C). Black soil 0.3m thick and dry volcanic ash was exposed on the scarp surfaces. The open cracks were filled with the liquefied volcanic ash, and sand boil hills of 10–15cm in diameter were also observed inside (Fig. 5D). It is estimated that, due to the liquefaction of the volcanic ash layer 1–2m below the surface, the non-liquefied volcanic ash layer 1–2m thick moved about 3m to the south-southwest.

4. Behavior of the liquefied volcanic ash at Locality No. 1

Liquefaction incites vertical sand boils, subsidences, and lateral movements of the non-liquefied layer. At Locality No. 1, in addition to these phenomena, an extensive collapse was caused with the large-scale and singular phenomenon, which was called the lateral sand boils.

4.1 Microtopography

Various microtopographies were created by spouting of the liquefied volcanic ash and ground collapse following it (Fig. 6A). In particular, the uplifted area along the southwestern and southeastern margins of the collapsed area (Fig. 6B), the exhaust nozzles and open cracks on the edge of the uplifted surfaces (symbols a–d in Fig. 6A), many sand boil hills in the southwest of the collapsed area, and convexities and wavy surface in the northeast of the collapsed area (Figs. 6C and 6A) are the characteristic microtopographies in examining the behavior of the liquefied volcanic ash. The microtopographies formed under the compression condition were mainly observed in the southwest of the collapsed area. Therefore, it is considered that as a whole collapsed area, the southwest was the compression field and the northeast was the tension field. However, it is considered that partial upheaval movement in the northeast of the collapsed area was also induced during the sinking of the ground, because the convexities and the open cracks created by the ground uplift were observed.

4.2 Landform conditions

As we will point it out later, the old landform at Locality No. 1 was a narrow waste-filled valley which ex-
Fig. 5 Gentle-slope movements at Locality No. 5

A: Lateral spreads, viewed from northwest sky. B: Ground surface, moved to the side without destroying almost, viewed from west. The head of moving mass has done the slump slip. C: Ground surface, moved to the side without destroying almost, viewed from the east-southeast. Black soil and dry volcanic ash are exposed on the scarps 1–2m high. D: Open cracks, filled with the liquefied volcanic ash. Many sand boil hills are observed inside.

Fig. 6 Microtopography and ground condition at Locality No. 1

A: Various microtopographies, grasped by the field study and the interpretation of the aerial photographs taken after the disaster, and schematic profiles, deduced from the results of the Swedish weight sounding and the photo-instrumentation of the aerial photographs taken in 1971 and 1977. Alphabet symbols, a–d, indicate the exhaust nozzles. B: Uplifted area on the southwestern margin of the collapsed area, viewed from southwest. Arrow is an exhaust nozzle d, shown in Fig. 6A. C: Wavy surface in the collapsed area, viewed from north.
tended from the northeast to the southwest. Therefore, the area was confined within the original volcanic ash slopes on both sides. The northeastern side above the waste-filled valley was enclosed by a dam about 3m high (Fig. 6A), and only the southwest side below was opened fan-shaped. However, it is possible to surmise that the southwest side was also surrounded by well-drained banks of volcanic ash, just like farmland along an open ditch and road embankment. Moreover, it is estimated that the valley floors utilized as paddy fields tilted as a whole at the 1-1.5% gradient to the south-southwest.

4.3 Ground conditions

The volcanic ash exposed on the scarp surfaces was dry, and it is assumed that it marked a clear boundary line between the liquefied volcanic ash layers. Moreover, few materials from the waste-filled valley sediments were included in the volcanic ash which had flowed and been blown over the area. Therefore, it can be deduced that the liquefied volcanic ash layer was from the groundwater level to the waste-filled valley (paddy fields). Investigating the soil condition of the collapsed area through the Swedish weight sounding test (Yamashita et al., 2004), it can be concluded that groundwater level before the liquefaction was about 2.5m deep at the northeast edge of the collapsed area, and it gradually shallowed to the southwest, and then, about 1.5m deep at the opposite side. Consequently, the liquefied layer was from the 2.5m to 7-8m deep at the northeast edge, thinning by degrees to the southwest, where it was 1.5-3.5m deep at the end (Fig. 6A).

The cyclic undrained triaxial test for the undisturbed samples shows that the liquefaction strength of the volcanic ash in landfills is low in comparison with other volcanic ash in Hokkaido and Toyoura sand (Yamashita et al., 2004).

At Locality No.1, it is considered that the landform was like a long and shallow sink or tray extending to the NE-SW, whose bottom faces slightly tilted to the south-southwest, and that liquefied volcanic ash 2-5m thick filled the inside, and dried volcanic ash 1.5-2.5m thick covered the surface like a lid.

On the basis of above-mentioned microtopographies, landform conditions and ground conditions, it is estimated that the whole of the saturated volcanic ash layer 2-5m thick was shaken like the sloshing phenomenon in the oil tanks, and the dry volcanic ash layer which could not stand the swinging was broken through, and then, the liquefied volcanic ash spouted out to the downstream in the old valley. Mukoyama et al. (2004) called such mass movement at Locality No.1 the squeezing fluidization phenomenon. We consider that lateral jetting of the liquefied volcanic ash and ground collapse following it was more destructive than the squeezing phenomenon, because the dry volcanic ash layer 1.5-2.0m thick was broken through, and the ash blocks of 1m in maximum thickness were inverted and turned up. However, as have been pointed out by Mukoyama et al. (2004), the traces of the intense blow such as sand boils which adhered to leaves of crops have not been confirmed. In this region, the rain fell from night of 26 September to early morning of 27 September. On the mid-morning of 27 September in which we undertook the investigation, such traces might have already been flushed by the rainfall in addition to sand boils at the low angle have predominated.

5. Geomorphic environment of the liquefied and moved areas

5.1 Geomorphic transition

All of the areas where liquefaction and slope movement took place are gentle slopes, which are utilized as beet and wheat fields now. However, from the aerial photographs (M588-79, -80) taken in 1947, it is proven that these areas were waste-filled valleys and swamps which formed gently undulating hills (Fig. 7A). In the pictures (HO-65-1X C6-12 and -13) in 1965, waste-filled valleys are exploited to be paddy fields. In the photos (HO-71-2X C6-12 to -14) taken in 1971, in Localities Nos. 1-4, the waste-filled valleys are almost all being changed into the paddy fields, and ponds and dams can also be detected, probably for the irrigation (Fig. 7B). The reclamation seems to have been started with cutting of the hillsides and opening up of the paddy fields in 1983. The region had been converted into gently-sloping farmland by 1986 (Fig. 7C), from the photos (HO-86-2X C6A-25 and -26) taken in 1986. In the pictures (HO-2000-4Y C8-13 and -14) in 2000, Locality No. 1 is shown as a concavo-concave slope inclined 3% to the southwest (Fig. 7D). Localities Nos. 2, 3 and 4 are rectilinear-straight slopes gentler than the one at Locality No. 1. No. 2 slope inclines to the southeast, Nos. 3 and 4 southwest. Localities Nos. 5 and 6 are rectilinear-straight slopes along a stream which flows from the northwest to the southeast.

The areas affected by liquefaction and slope movement are limited to the old waste-filled valleys and old swamps, which hold groundwater well after reclama-
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Fig. 7 Landform transition of the liquefied and moved areas


5.2 Morphometry

Mukoyama et al. (2004) tracked land use transition of this whole region on the basis of the topographic maps at a scale of 1:25,000 the publication year of which differed.

We extracted the positions which changed from waste-filled valley to reclaimed land by time series interpretation of aerial photographs after 1947 (Fig. 8). Moreover, we also carried out the measurement of dip direction (clockwise direction) and dip of reclaimed plane, reclaimed thickness, and dip of surface after rec-
lamination using the digital stereo mapping system for the photogrammetry on the basis of the aerial photographs taken in 1971 and 2000 (Fig. 9).

Most of the reclaimed areas exist in the tributaries of the swamps. Though the differences on dip of reclaimed plane, reclaimed thickness and dip of surface after reclamation are not recognized in the liquefied and non-liquefied areas, dip directions of the reclaimed planes in the liquefied areas are biased. Within six liquefied areas, dip direction of the reclaimed plane is the south-southwest at three localities, the south at two localities and the north-northeast at one locality (Fig. 10). These dip directions agree with the direction of the main lateral displacement of surface in each liquefied area, as shown in Table 1. Within eight locali-
ties in which dip direction of reclaimed plane is the south or south-southwest, five localities are the areas which arisen the slope movement by the liquefaction of land fill volcanic ash.

6. Conclusions
In the Kyowa area, Tanno town, located about 230 km from the epicenter, the large-scale ground collapses, spoon-like subsidences, lateral spreads and slumps were brought about by liquefaction of volcanic ash in the 2003 Tokachi-Oki Earthquake. Especially, at Locality No. 1, when liquefied volcanic ash of about 10,000m³ in volume broke through the non-liquefaction layer and spouted out to the sides, much farmland sank deeply. A similar phenomenon was observed on a much smaller scale in the Hirosato area, Kitami City (Ito et al., 2004). This kind of lateral jetting of liquefied materials causing ground collapses can be defined as a new phenomenon of sand boils, and a new landslide disaster induced by the earthquake.

The old landforms of the liquefied and moved area were narrow waste-filled valleys and swamps formerly utilized as paddy fields, but these were converted into the gently-sloping farmland by the land fill of the volcanic ash from 1980s. Some fields of the similar landform transition exist in the neighborhood, but the liquefied and moved areas lean toward the south or south-southwest, where the reclaimed planes are. In the Kyowa area, Tanno Town which is located in the north of hypozentral region, dip directions of the reclaimed planes might appear as a geomorphic effect.

In order to prevent any future earthquake disaster, it is necessary to investigate the movements of gentle slopes provoked by the 2003 Tokachi-Oki Earthquake. In particular, we need to research the ground conditions in the Kyowa area once more, in the hope of preventing any future damage which could result in fatalities among Hokkaido resident.

Acknowledgements
We wish to express our thanks to Mr. Tsunemitsu Kameda, Mr. Takeyoshi Ishikawa and Mr. Atsuo Hamada for their kind support in the field studies. We are grateful to Shin Eng. Con. Co., Ltd. and Kokusai Kogyo Co., Ltd. for the offers of the air perpendicular photographs. And we are also obliged to Wako Giken Co., Ltd. for the assistance in the photo instrumentation.

We are deeply indebted to Assoc. Prof. Fumiyuki Narushima of Kitami Institute of Technology for the helpful revision of the manuscript. Finally, we thank anonymous referees for critical comments to the manuscript.

References

(REceived April 12, 2005, Accepted June 21, 2005)