THE MECHANISM OF LIQUEFIED LANDSLIDES AND VALLEY OFF TYPE DEBRIS FLOWS

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SUMMARY

When the ground water flows locally in a sandy slope at a relatively high velocity, the void ratio continues to increase there by underground erosion and infiltration and some day it must exceed the critical value for the stress fall phenomenon stated here and also exceed the critical value for liquefaction studied by Castro. The mass above the eroded loose zone will subside some day due to the stress fall phenomenon and the side wall failure at the rise of the ground water level, and the rapid and undrained compression of the loose zone by vertical subsidence causes liquefaction of the loose zone, the mass on the liquefied zone flows rapidly. It is the mechanism of liquefied landslide proposed in this paper.
When a liquefied landslide is narrow and long, it must be what has been known as a valley-off(Taninuke) or a snake-off(Januke) since old times in Japan. In this text the mechanism estimated from our researches since 1968 is stated at first and the field examples of liquefied landslides and valley-off type debris flows are introduced.

Key words Landslide, Debris flow, Liquefaction, Vertical subsidence, Stress fall phenomenon

1. THE MECHANISM OF LIQUEFIED LANDSLIDES AND VALLEY-OFF TYPE DEBRIS FLOWS

The mechanism of liquefied landslide and valley-off type debris flows are characterized by four processes 1)Formation of a loose zone by underground erosion and infiltration 2)Stress fall phenomenon in the loose zone at a rise of the ground water level 3)Vertical subsidence of the mass above the loose zone by the stress fall and the side wall failure 4)Liquefaction of the loose zone by the subsidence and the initiation of flow of the mass.

1-1. Formation of a loose zone

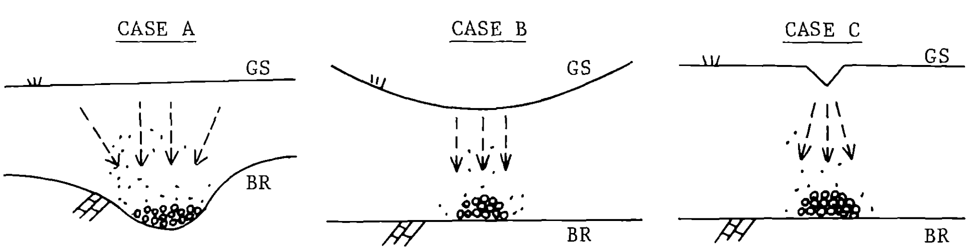
When the ground water flows locally in a slope from some causes, the ground water path is formed by underground erosion. As the path can transport fine particles, it promotes underground weathering and the fall-off of fine particles from the zone above the ground water path by infiltrating water. Accordingly, a loose zone is formed above/surrounding the ground water path. Here, we will describe four basical cases which the ground water flows locally in a slope.

CASE A The shape of bed rock is concave.
This type is often found along faults, crushed zones, geological folds in slopes of high permeability where rainfall infiltrates into the ground without surface run-off and flows in the bed rock. Sometimes it is found where an old landslide buried a valley, too. (Example. The Mizusawa Shinden landslide and the Ichinomiya landslide)

CASE B The ground surface is concave.
Water converges to the bottom of the concavity. The ground water flow and its path comes out on the bed rock under the center of the concavity. (Example. A snake-off in the Anafuki river basin)

CASE C A gully exists on a slope.
It is basically same with Case B. A gully supplys water underground, and the ground water flow and its path comes out on the relatively impermeable layer under the gully. This is found in new slopes which are very weak against erosion such as volcanic slopes. (Example. A valley-off in the Sakurajima volcanic island)

CASE D Others.
Where the slope inclination changes from the gentle to the steep, the ground water may converge and flow locally. The ground water can converge along a slightly weak zone or nearly by chance, too. (Example. The Hidakamura valley-off)



: Ground water path : Loose zone --> Infiltration of water
BR Bed rock GS Ground surface

Fig.1 Formation of a loose zone

1-2. Stress fall phenomenon

It is well known that subsidence/settlement takes place when saturating a loose sand layer. It has been used for long and known as the hydraulic fill method to compact a loose sand.
Subsidence by saturation must be the result of the decrease of stress inside the sand layer. And the decrease of stress by saturation is explained as the result of the decrease of effective stress due to the disappearance of capillary suction.
If stable side walls prevents a loose sand from subsidence, the decrease of stress is not followed by subsidence and it remains after saturation. To examine the change of stress, we measured stress in a model sand layer

sandwiched by stable side walls(steel and glass). Used sand is the Toyoura standard sand(taken from the Toyoura seashore, the grain size is 0.1 - 0.3 mm, the specific gravity of solid particles is 2.67). The used apparatus can control the ground water level in a model sand layer(200 cm in length, 90 cm in depth, 27 cm in width) formed in it by changing the water pressure inside nine independent water tanks(seven on the bottom and two on the ends) surrounding the sand layer. Slope inclination of model sand layers was 30 degrees and the ground water level was lifted from 0 to 80 cm (10 cm below the ground surface) step by step, each step was 20 cm. The variation of stress in the sand layer was measured by twelve pressure gauges. Fig.2 shows some examples of 11 experiments, 118 stress measurements. All pressure gauges in Fig.2 face vertical direction and locate at 15 cm in level except Exp.2(5 cm in level). The void ratio and the dry density are listed in Table 1.

Table 1 Void ratio (e) and dry density (γ_d g/cm^3)

	Exp2	Exp3	Exp4	Exp9	Exp10
e	0.89	0.89	0.93	0.92	1.02
γ_d	1.41	1.41	1.38	1.39	1.32

When the ground water surface rised to 20 cm in level, a rapid stress fall took place in loose sand layers in eight experiments including Exp.4, 9, 10. In this step the upper relatively dry layer was supported by the side walls of apparatus. When the ground water surface came to 40 cm, an additional wetted zone of 20 cm in thickness settled down or deformed downward, and it caused a considerable stress increase. However, the upper relatively dry layer was still supported. And an exact subsidence(more than 0.1 mm) was firstly found on the surface, when the water level was lifted to 80 cm in level(10 cm below the ground surface) as shown in Table 2. On the contrary, such a stress fall and subsidence did not take place in sand layers of medium density in three experiments including Exp.2, 3 in Fig.2.

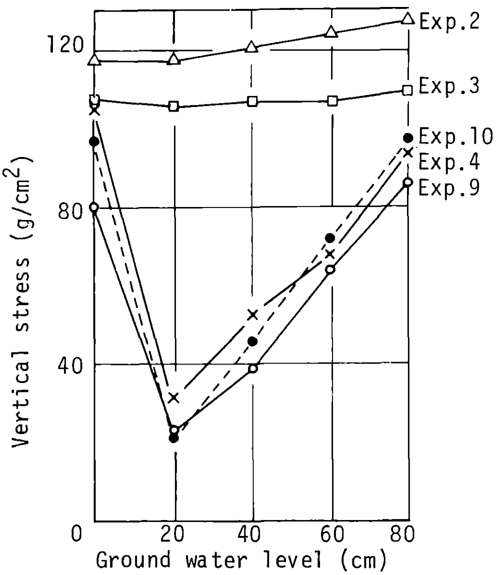


Fig.2 Variation of vertical stress with the ground water level

Table 2 Vertical movement of the surface of sand layer (unit 0.1 mm, + : upheaval, - subsidence)

Water level	20 cm	40 cm	60 cm	80 cm
Exp.2	0	0	0	+0.2
Exp.3	0	0	0	+0.3
Exp.4	0	+0.2	+0.2	-2.1
Exp.9	0	+0.1	-0.2	-21.4
Exp.10	0	+0.1	-0.3	-24.7

We measured stress at a series of model experiments of landslides in use of the same sand and a different shape of apparatus(the size of sand layer is 150 cm in length, 20/40/80/160 cm in width, 30/50 cm in depth, 30° in inclination). According to stress measurement in thoes two series of experiments, the critical void ratio for the stress fall phenomenon is 0.85 - 0.89, stress fall took place in every experiments(7 times) more than 0.89, and did not take place in every experiments(18 times) less than 0.85. And in 6 of 9 experiments of 0.85 - 0.89 stress fall was not found and it was observed in the rest three.

1-3. Vertical subsidence

When the ground water level rised to the level which the side wall friction can not support the relatively dry layer above the ground water surface or the stress fall is so great as the side wall friction can not support it, vertical subsidence takes place. Table 2 shows the vertical movement of the surface of sand layer in the experiments of Fig.2. Vertical subsidence is found in Exp.4, 9, 10 and not found in Exp.2, 3.
A similar subsidence was measured in a field, too. A vertical subsidence of 1 - 2 m over an area of 1.0 km in length and 10 m in width took place in the Matsunoyama tertiary landslide area of Niigata Prefecture in 1962. The subsidence could be explained neither by consolidation of clay due to the decrease of the ground water level, nor by extension crack due to landslide movement. Then, M. Tsumoto(1966) measured the ground water level and the vertical movement in the subsided zone to examine the mechanism in 1965 when the subsidence had still continued a little. And he obtained the result of Fig.3. In this figure subsidence is found at the rise of the ground water level This result means that the phenomenon similar to Table 2 really takes place in fields, too.

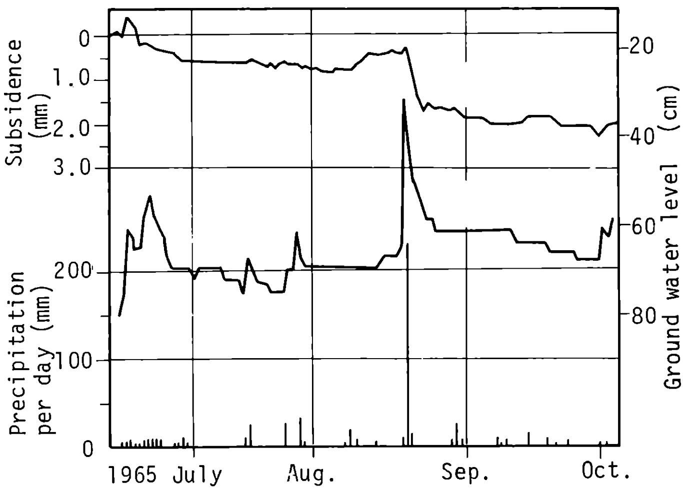


Fig.3 Subsidence in the Matsunoyama area (after Tsumoto et al. 1966)

Whether vertical subsidence takes place or not depends on the value of Young's modulus before/after saturation, the value of modulus of shear deformation, the level of ground water, the width of loose zone and others. The stability analysis for the vertical subsidence was proposed and the characteristics of the vertical subsidence were presented by K. SASSA et al. (1980-2).

1-4. Liquefaction

As the final step of liquefied landslides, we would show schematically how vertical subsidence initiates a rapid flow of mass in Fig.4.
Fig.4 is illustrated in a simplified form. The structure of eroded loose zone is depicted from the observation of a heavily eroded zone of Fig.14 and the microscopic photo of a very loose sand(Hanzawa, 1980). Here, we supplement Fig.4.

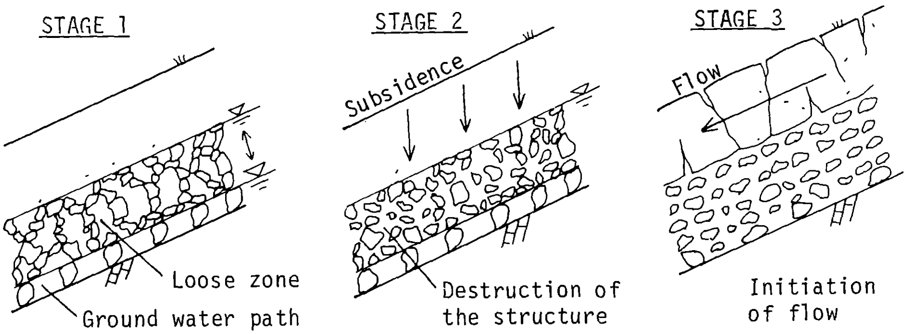


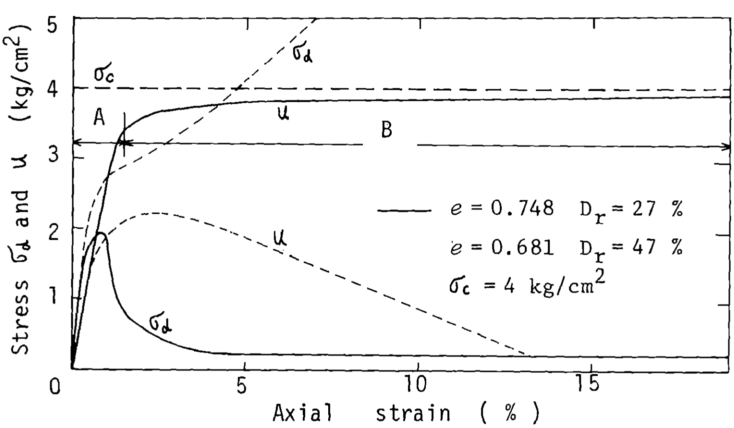
Fig.4 Illustration of the liquefaction caused by subsidence

STAGE 1 Underground erosion and infiltration takes off excess particles other than thoes supporting the upper layer and it results in a very loose structure. The zone under the high water level may be well eroded by repeated change of the ground water level.

STAGE 2 Subsidence destructs the structure supporting the upper layer, accordingly the structure can not support the upper layer any more. Then, the upper layer sits on water.

STAGE 3 The upper layer flows rapidly on the water cussion and it is much disturbed and mixed during flow.

To examine STAGE 2, 3 from soil mechanical aspects, the research by C. Castro is valuable. He performed undrained compression tests of a loose sand by adding weight step by step. Fig.5 is the result of it, where e : void ratio, D_r : relative density, σ_c confinig pressure, σ_d deviator stress($\sigma_1 - \sigma_3$, applied weight per unit area), u pore pressure.
When weight was added step by step and it reached 1.9 kg/cm2 in stress, the loose sand abruptly started flowing and strain reached 25 %(the limit of the apparatus) in 0.18 seconds after the peak stress, while pore pressure approached the confining pressure. This result can be regarded to corresponds to what the increase of load due to subsidence(similar to undrained



A Destruction of structure B Flow sitting almost on water

Fig.5 Results of undrained compression test
(Reproduced from C. Castro, 1969)

compression due to its rapidness) destructs the structure of a loose sand(A in Fig.5) and the support of confining pressure is replaced by water from the sand structure(B in Fig.5). This can give a soil mechanical background to the illustration of Fig.4

On the contrary with the loose sand, a medium sand was not liquefied and the stress increased monotonically until the stop of test. He performed tests of various conditions of void ratio and confining pressure, and obtained a border line(having a certain zone for an intermediate state) separating the state causing liquefaction(Fig.6). This figure indicates that the void ratio to cause liquefaction like Fig.5 varies with the magnitude of confining pressure.

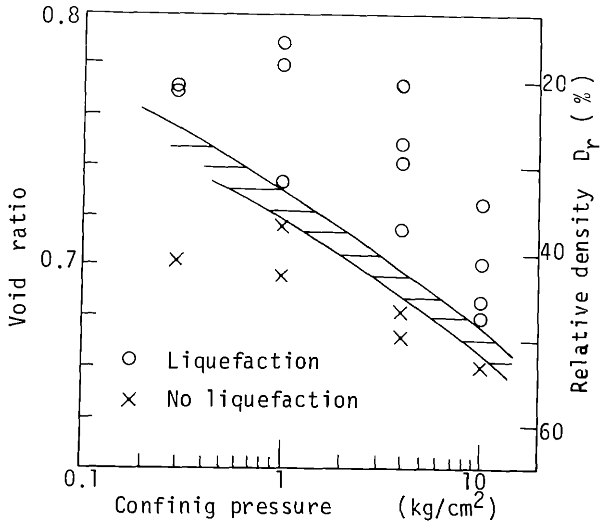


Fig.6 The range of void ratio and confining pressure to cause liquefaction (Reproduced from C. Castro, 1969)

2. EXAMPLES OF LIQUEFIED LANDSLIDES AND VALLEY-OFF TYPE DEBRIS FLOWS

2-1. Examples of liquefied landslides

A) The Ichinomiya landslide

In September 1976 a big landslide took place in a sandy slope(weathered granitic rock) in Ichinomiya-cho, Hyogo Prefecture. The slided mass was about 1×10^6 m^3, it destroyed 40 houses and 17 public buildings including a school, a kindergarten, a post office, a police office and others. This landslide was witnessed by many people, and a movie film of 8 mm and a series of colour photos of the moving landslide were taken. Fig.7 is an air photo of the landslide. Fig.8 is the topographical map of it after the landslide. Fig.9 is the section of its central line before and after the landslide. From the photos, the film and the field investigations, we estimated the process and the mechanism of this landslide as follows.

There was an underground valley in this slope as illustrated in Fig.1 (A). The underground valley is visualized by the topographical map after the landslide(Fig.8), and its direction is shown by Mark ① in Fig.7, 8. When we investigated the landslide one month later, the water which had flowed along the underground valley was found to flow like a stream still. The underground erosion and the increase of void ratio had proceeded in/above this underground valley, and the void ratio exceeded the value which stress fall took place by saturation and liquefaction took place by subsidence(near undrained compression). Due to the lift of the ground water level at the typhoon of 1976, the side wall failure and the resulting vertical

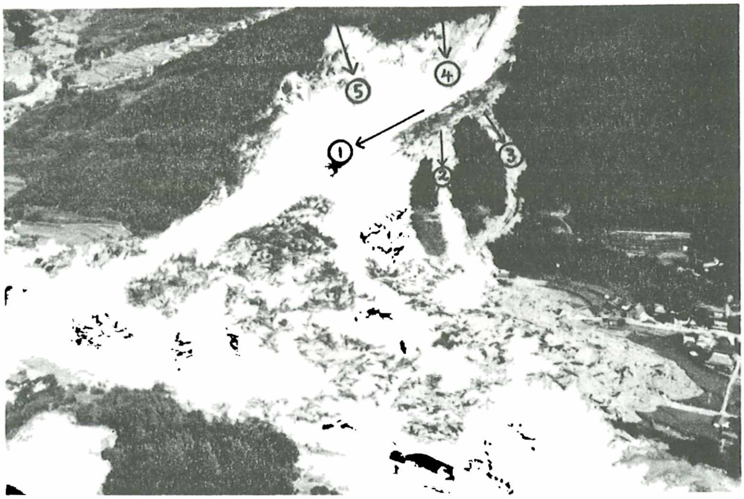


Fig.7 The Ichinomiya landslide (by Hyogo Prececture)

subsidence occurred, and the subsidence liquefied the loose and saturated zone in/above the underground valley like Fig.4, 5. The liquefied zone was compressed by the upper layer, then the liquefied sand was squeezed through cracks(like STAGE 3, Fig.4) which was taken by photos and a film(Mark ②, ③ are the traces of the flows by these squeezed liquefied sand). Therefore, the subsided mass flowed down on the liquefied sand along the gentle bed(8 - 13 degrees, quite stable for usual landslides in granitic slopes) of the underground valley and deposited in 2 - 8 degrees. Mark ④, ⑤ in Fig.7, 8 are sub-landslides which moved by the disappearance of toe support due to the liquefaction in the underground valley Mark ①.

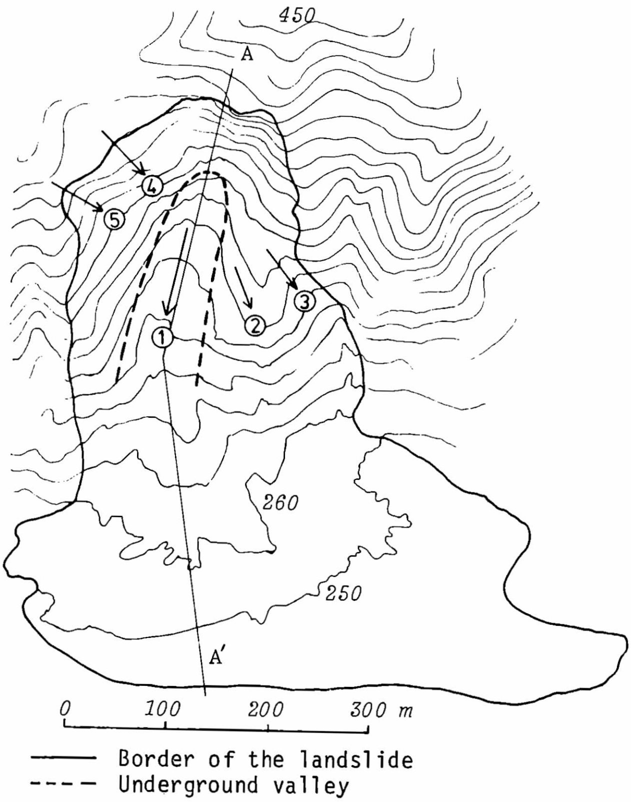


Fig.8 The topographical map after the Ichinomiya landslide

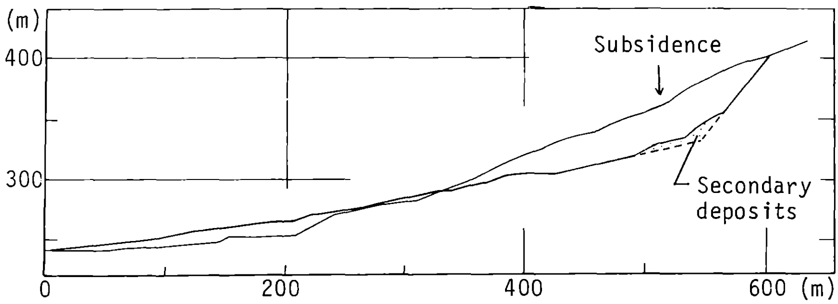


Fig.9 The section of A-A' line before/after the landslide

B) The Mizusawa Shinden landslide

In April 1964 a great landslide of 840,000 m^3 in volume took place in a sandy slope(tertiary sedimentary rock) in the Mizusawa Shinden area of Niigata Prefecture, and the liquefied mass of landslide flowed down at a speed of 2.5 - 15 m/sec. and destroyed 10 houses and buried 8 persons to death. Plan and a section of the Mizusawa Shinden landslide are shown in Fig. 10, 11. In prior to stating our interpretation of this landslide, we introduce two reports on it. According to the Sabo Section, Niigata Prefecture(1969), this landslide was initiated by a heavy subsidence, and the subsided mass flowed out from the both sides of the bed rock noticed in Fig.10, 11. According to Tsuda et al (1970), at the initial stage of the landslide(subsidence) sand was squeezed out through cracks and it deposited at the area ⓐ (100 m^2 in area, 7 cm in depth) and it was very similar to the phenomenon of flowing sand(liquefaction in soil mechanics) at the Niigata earthquake(1964). These both reports suggest this landslide broke out by the mechanism of liquefied landslide proposed here. Here, we depict the process of this landslide by our expression.

The ground water had flowed along the zone sandwiched by two faults in Fig.10(the zone of Sand & Gravel in Fig.11, which corredponds to CASE A of Fig.1) for long. Due to the underground erosion and infiltration the void ratio in this zone continued to increase and some day before the landslide it exceeded the value which stress fall took place by saturation and liquefacton took place by subsidence. Since the side wall friction was very effective as in Fig.10, 11, subsid-

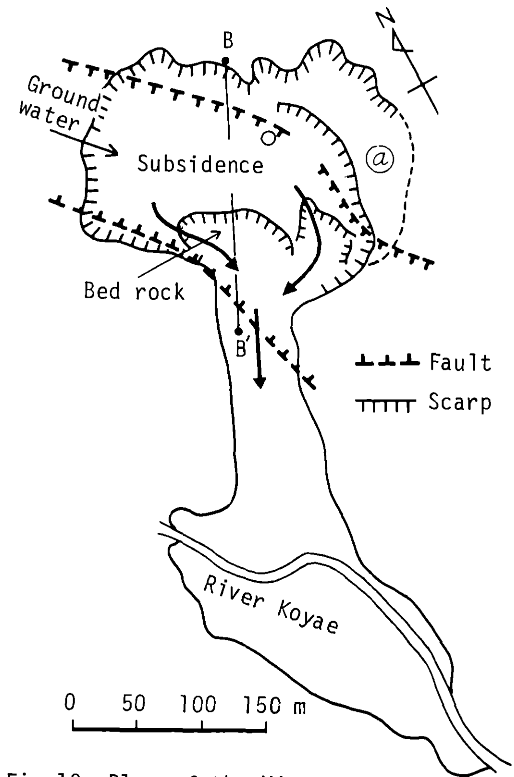


Fig.10 Plan of the Mizusawa Shinden landslide(after Sabo Section)

ence had not taken place easily. Therefore, the void ratio probably became very big. Accordingly, when the ground water level rised at the snow melting season of 1964, the magnitude of stress fall was great and subsidence was so great that people could eyewitness and recognize it. This heavy subsidence caused the squeezing of liquefied sand to Mark ⓐ and a very rapid flow(2.5 - 15 m/sec.) of the mass.

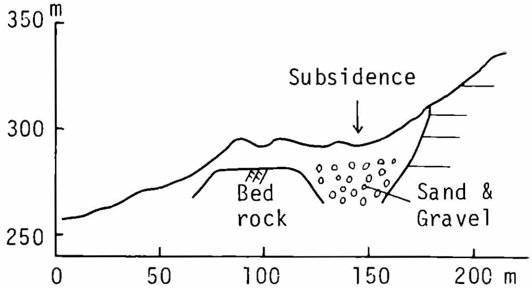


Fig.11 Section along B - B' line in Fig.10 (after Sabo Section)

2-2. Examples of valley-off type debris flows

If a narrow and long liquefied landslide takes place along a ground water path, the trace must be as if a valley or a snake got out of the slope. It must be what has been called as a valley-off(Taninuke) or a snake-off(Januke) since old times in Japan.

A) The Hidakamura valley-off

At the typhoon in 1975 a valley was formed by single landslide in a slope(weathered serpentine, 25° in inclination) of the Nishiyama golf club in Kochi Prefecture. That is one of typical valley-off. Fig.12 is a photo facing to the golf club from the valley-off, and Fig.13 is its section. The section is very deep in comparison with the width which is apparently different from usual landslides. When we investigated this valley-off, we found a gravel and sand zone(Fig.14) where fine particles were completely eroded out at the lower part of the scarp and the ground water flowed out at a velocity of some tens cm/sec. from the zone. In this case, there is no structural underground valley like the Ichinomiya and the Mizusawa. The subsidence and the liquefaction took place in a weathered and comparatively homogeneous slope. The ground surface had been only slightly concave, but there had been no gully. Therefore, this may be classified in CASE D mentioned in 1-1. From the existence of a heavily eroded zone we can estimate that the ground water continued to increase the void ratio along its water path. Stress fall and subsidence took place along the ground water path. The loose eroded

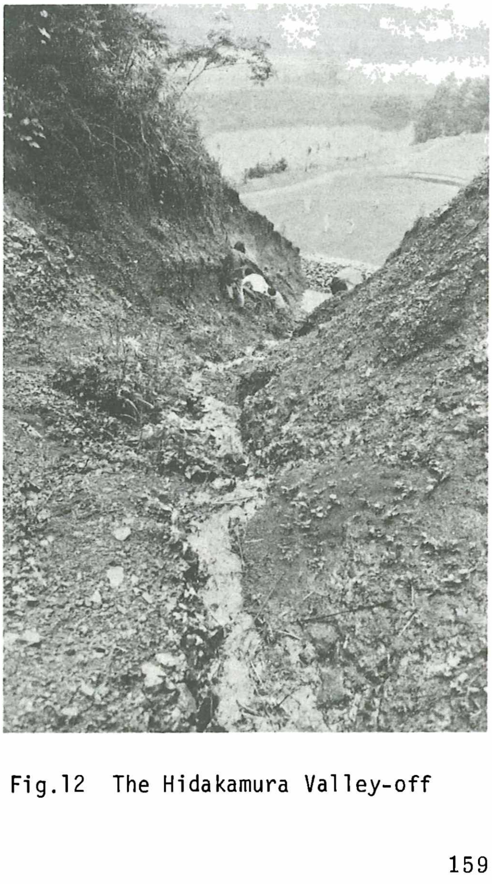


Fig.12 The Hidakamura Valley-off

zone along the path was liquefied by the subsidence, then the whole mass along the ground water path flowed out of the slope
This mechanism enables to explain the unusually narrow and deep and curved landslide.

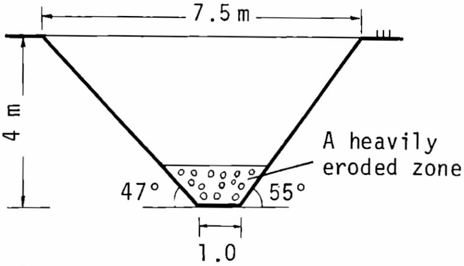


Fig.13 The section of the Hidaka-mura valley-off

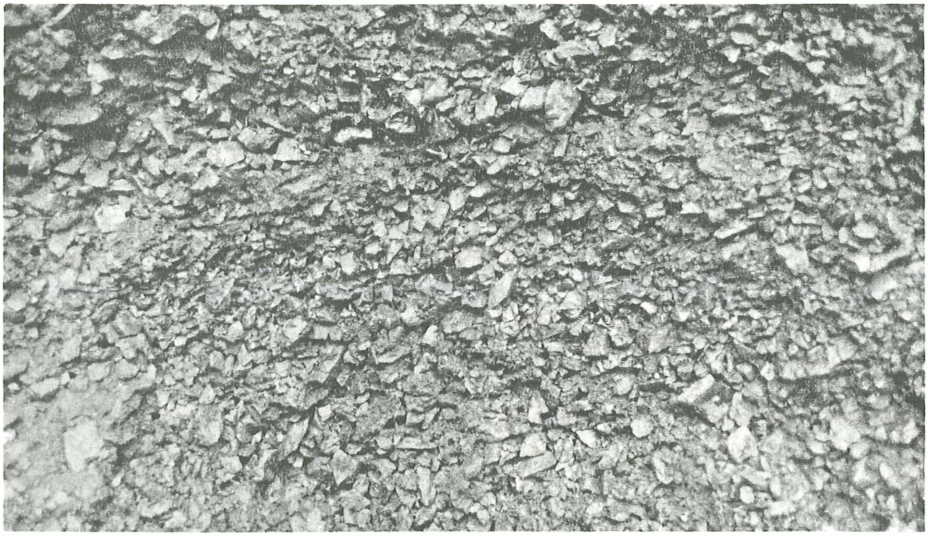


Fig.14 A heavily eroded zone in the Hidakamura valley-off (Grain size 0.5 - 3.0 cm)

B) Other valley-offs and snake-offs

We observed another valley-off in a slope(pumice and volcanic ash) of the Sakurajima island. That was CASE C in 1-1. There was a small gully of 30 x 30 cm in the section. The volcanic deposit slope is made of alternation of pumice and ash. Water flows on the layer of ash whose permeability is low. In that slope water flowed on the ground surface covered by ash along the gully and on the ash layer 2.5 m below the surface. Probably, the gully promoted water supply to the ground water path. And underground erosion proceeded along the ground water path. Finally, a small vally-off of about 60 m in length, 2.5 x 2.5 m in the section took place in 1979.

When a valley-off is very long and winding, it is called as a snake-off. We found a snake-off of 300 m in length, 10 - 20 m in width, 4 - 5 m in depth in a crystalline schist slope, by our field investigation of the Anafuki river basin after the typhoon of 1976. It was the combination of CASE A and CASE B, namely the ground surface and probably the bed rock was concave.

A similar case was reported by Tsukamoto(1976) in the Japanese Conference on Forestry. A snake-off broke out in a slope of weathered sand stone. The magnitude of it is 420 m in length, 7.7 x 7.8 m in the section. And people had noticed the sound of flowing water from the underground(the under ground water path) at typhoon seasons. To hear the sound of the ground water flow is not very rare. We, ourselves, have heard such testimonys from inhabitants in some landslides. We have some experiences to hear the sound of the flowing ground water through boring pipes in some landslides.

CONCLUSION

1) Liquefied landslides and valley-off type debris flows could be reasonably explained by the mechanism of liquefaction due to vertical subsidence.
2) Stability for subsidence is quite different from Stability for usual sliding. So, liquefied landslides can take place either in a very gentle slope, or in a curved form like a snake.
3) Liquefied landslides are not always equal to landslides triggered by vertical subsidence, because liquefied landslides can be caused by other undrained loadings such as earthquakes.
4) Castro who also researched liquefied landslides of no earthquake origin did not present an idea how undrained loading occurs in fields.

Zusammenfassung

Wenn Grundwasser örtlich in einem sandigen Hang mit relativ hoher Geschwindigkeit fließt, nimmt dort die Porenzahl und Infiltration ununterbrochen zu, und eines Tages muß der kritische Wert die hier dargestellte Spannungsabfall-Erscheinung und auch jener für die "Verflüssigung" nach Castro überschritten werden. Das Material über der erodierten lockeren Zone wird eines Tages bei gestiegenen Grundwasserspiegel wegen des Festigkeits-Zusammenbruches und des Seitenwandbruches einsinken und die schnelle und unentwässerte Pressung der lockeren Zone durch vertikales Absinken verursacht die "Verflüssigung" der lockeren Zone, so daß die Masse auf der verflüssigten Zone rasch fließt. Es ist dies der Mechanismus der "Fließ-Rutschung", welcher hier in diesem Bericht vorgeschlagen wird.

Wenn eine Fließ-Rutschung schmal und lang ist, dann ist es das was Japan bereits seit langem als "Tal-Ab" (valley-off, Taninuke) oder "Schlangen-Weg" (snake-off, Januke) bekannt ist. In diesem Bericht werden der auf Grund unserer Forschungen seit 1968 eingeschätzte Mechanismus zuerst dargestellt und (dann) die Feld-Beispiele von Fließ-Rutschungen und Tal-Ab-Muren bekannt gemacht.

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