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THE MECHANISM TO INITIATE DEBRIS FLOWS AS UNDRAINED SHEAR OF LOOSE SEDIMENTS

Der Porenwasserdruck in Lockersedimenten als Auslösemechanismus von Muren

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SUMMARY

Debris flow is an interdisciplinary problem between fluid mechanics and landslide mechanics. It was initially studied by Bagnold and others in the field of fluid mechanics, however, the researches were naturally for the flowing mechanism of debris flows. The initiation of debris flows must be near in the field of landslide mechanics. The author having done researches of landslides has proposed the mechanism to initiate debris flows on the basis of field observation and indoor study as follows.

Debris flows are classified in two types, 1) Debris flows initiated in a torrent bed 2) Debris flows initiated in a slope.

1) Torrent bed type debris flows
A loose state of deposit on a torrent bed is formed in places where soil falls or slope failures supply materials, and also where the ground water flows through the torrent deposit and increases its void ratio gradually by underground erosion.
When such a loose deposit is rapidly loaded at the saturated state by falling masses from slopes above the torrent bed, the structure of loose deposit is destroyed and the overburden pressure is supported by water, accordingly, the mass sitting on water starts to flow like a hovercraft (in another expression the loose deposit loses its shear strength by loss of effective confining pressure and starts to flow.)

2) Slope type debris flow
When the ground water flows locally in a sandy slope at a relatively high speed, the void ratio increases there by infiltration and underground erosion and a loose zone is formed. The mass above the eroded loose zone will subside someday at rise of the ground water level, subsidence causes rapid loading and things after it are same with the torrent bed type debris flow. The mass starts to flow from the slope.

Both types of debris flows are the same in the sense they are caused by rapid loading (undrained shear) of loose sediments. This paper reports it in detail.

Zusammenfassung:

Die Muren stellen einen interdisziplinären Bereich zwischen Flüssigkeitsmechanik und Rutschungsmechanik dar.
Die meisten Forscher vertraten die Ansicht, daß in Muren Vorgänge der Flüssigkeitsmechanik stattfinden. Die Auslösung von Muren liegt jedoch näher bei einem Rutschungsmechanismus. Der Autor hat Rutschungen untersucht und kam zu dem Ergebnis, daß die Auslösungsmechanik von Muren auf Grund von Feldbeobachtungen und Laboruntersuchungen folgendermaßen aussieht.

Es wurden zwei Typen von Muren festgestellt:

1. Muren die in einem Wildbachbett entstehen
2. Muren die sich von einem Hang lösen.

1. Muren des Wildbachbett-Types
Der lockere Zustand von Ablagerungen im Wildbachbett wird an Stellen wo Bodenkriechen und Hanggleitungen Material herbeischaffen verursacht. Ebenso wächst der Porenwasserdruck in Abhängigkeit zur Unterbodenerosion an, wenn das Grundwasser die Ablagerungen im Wildbachbett durchfließt.

Wenn eine solche lockere Ablagerung rasch bis zum Sättigungspunkt durch seitlich einfallende Rutschungsmassen belastet wird, wird die Struktur des Lockersedimentes zerstört und der überschüssige Druck wird durch das Wasser verstärkt, folglich beginnt die auf dem Wasser aufsitzende Masse wie ein Luftkissenboot zu schwimmen (in anderer Weise ausgedrückt, das Lockersediment verliert seine Scherfestigkeiten durch den Verlust von effektiver Kohäsion und beginnt zu fließen).

2. Muren des Hang-Types
Wenn Grundwasser örtlich in einem sandigen Hang mit relativ hoher Geschwindigkeit fließt, wird der Porenwasserdruck durch Infiltration und Unterbodenerosion erhöht und es bildet sich ein Gleithorizont.

Die Masse über dem erodierten Gleithorizont wird eines Tages absacken bei gleichzeitigem Anstieg des Grundwasserspiegels, wobei die Absackung die rasche Belastung bewirkt und die Vorgänge gleich werden wie bei der Mure des Wildbachbett-Types. Die Masse beginnt vom Hang zu fließen.

Beide Typen der Muren sind in diesem Sinne gleich, daß sie durch rasche Belastung von Lockersedimenten verursacht werden (Porenwasserdruck).

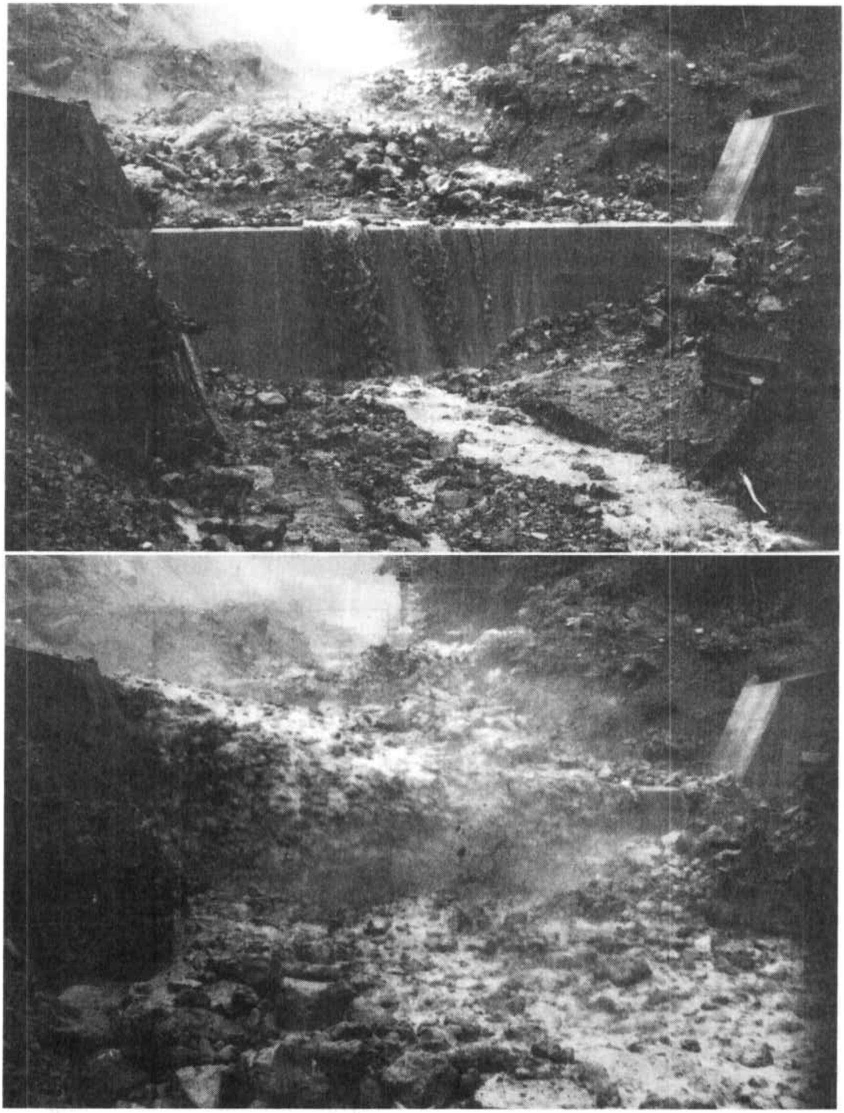


Fig.1 Photos just before/after the arrival of debris flow (taken by the Applied Geomorphology Section, Disaster Prevention Research Institute, Kyoto University and the Ministry of Construction in Japan

1. The mechanism of liquefaction

Debris flow is a mixed flow of sediment and water. It may be regarded as a limit of water flow including sediment, but also it can be regarded as a liquefied state of sediment deposit.

In general, torrents which debris flows take place are not rich in water. It is often observed that water flow is very limited before initiation of debris flows(Fig.1), and debris flows take place not only in torrents, but also in slopes. Taking those facts into consideration, it should be more general to estimate the initiation of debris flow as liquefaction of a saturated sediment layer, than to estimate it as a result of gradual inclusion of sediment into water flow. Fig.1 is photos some seconds before/after the arrival of debris flow in a volcanic torrent in Japanese alps. It shows a dramatic change of water discharge.

As a phenomenon of liquefaction of sand, quick sand is known since old times, that is, when animals or human beings step into a saturated loose sand deposit, sand is liquefied and they are swallowed by sand. Quick sand is soil mechanically interpreted as undrained shear of loose sand.

Fig.2 is results of constant volume direct shear test of 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 2.66, the diameter of sample is 100 mm). In drained shear tests, a dense sample proceeded from A → B → C and failured at C, a loose sample failured at B similarly. While, in undrained shear tests, a dense sample proceeded from A upwards along the failure envelope of dense sand, conversely a loose sample failured at a low peak stress and arrived at D on the failure envelope of loose sand. Though this sand recovered its shear resistance after the point D, along its failure envelop, some tests by

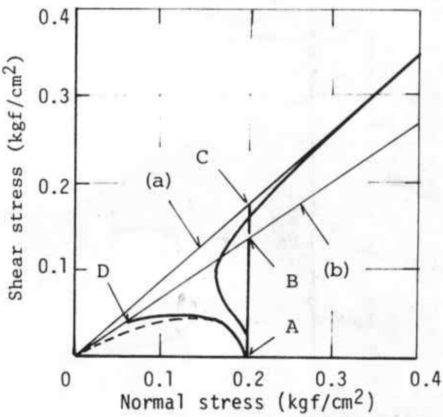


Fig.2 Stress path of sands in drained and undrained shear tests

(a) : Failure envelope of dense sand (Void ratio $e_o = 0.64$)

(b) : Failure envelope of loose sand (Void ratio $e_o = 0.85$)

Bishop(1971, river sand. triaxial test) did not recover, and the tests by Castro(1969) where stress was loaded by dead weight and flow took place after peak, proceeded like the dotted line of Fig.2(though stress level is different) and arrived at about 5 % stress of the peak. Therefore, when a loose sand is sheared under the undrained state, it may fail at a low stress and exert a less resistance after peak.

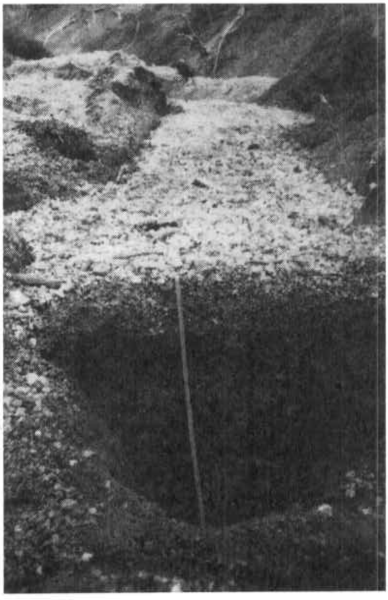
Fig.1 suggests debris flows are caused by the liquefaction of saturated sediments more than the inclusion of sediments into water, Fig.2 suggests that flow(liquefaction) is the easiest to take place by undrained shear of loose sediments among possible four cases of shears.

2. The mechanism to initiate the torrent bed type debris flows

Debris flows in granite areas and crystalline schist areas occur at unusual heavy rains, but those in some volcanic areas take place almost annually since abundant loose sediments deposit there. Mt.Usu erupted in 1977 and debris flows killed 5 persons and caused damages to many facilities which were estimated as about 15 billion yen(1 billion Austria Schilling) in 1978. Thereafter, many debris flows take place annually in torrents of Mt.Usu.

We investigated the upstream of the Kousu torrent in Mt.Usu during 2-12 August 1981 when a series of heavy rains attacked there, and small debris flows were caused in the investigating torrent three times. Some hours before the initiation of the second debris flow, we investigated the torrent bed. The ground water flowed at 10 cm below the surface of torrent bed. We walked on the bed and felt soft reaction, then stepped heavily. One or two heavy step caused liquefaction or semi-liquefaction of the sediment, an area of 1 m in diameter behaved like a water cushion, then ground water came out with the proceeding of consolidation.

Fig.3(above) is the photo of it which is similar to the state of Fig.1 though materials are a little different. The photo(below) is a section of the point(the deposit depth was about 1 m, it was trenched between the second and the third debris flow). Experimentally I stepped on the saturated same deposit reducing its depth to 10 cm, in the case water drained quickly and gravels & stones were polished by water, liquefaction or the state of Fig.3(above) was not reproduced.
Those simple experiments and observations put forward that stepping on this sediment of 1 m depth is enough rapid to cause undrained shear, therefore, some rapid loading corresponding to stepping can liquefy the sediment deposit. While about 10 cm deposit of the sediment is not enough deep, so stepping



drained water smoothly in the sediment and pore pressure did not build up. Then, a condition to cause undrained shear is for the depth of sediment as well as loading speed and permeability.

Fig.4 is a sketch of the top of the torrent. There are a narrow chute and a talus and a scarp above the sediment of Fig.3. Fig.5 is a photo of the slope above the scarp and the portable direct shear test designed and produced in 1980 by K. Sassa (Refer to Sassa & Kaibori 1982 and Kaibori & Sassa 1984), Fig.6 is results of shear tests of samples from the slope (Sample 1, dry density 1.18 g/cm^3) and the talus (Sample 2, dry density 1.12 g/cm^3). The talus is very loose and critically deposits, which is proved from the facts that the gradient of talus deposit is about 30°, and its internal friction angle is 28°. So, when a ground water table will be formed in the talus,

Fig.3 Liquefied sediments by stepping at some hours before the initiation of debris flow (above) and its section (below)

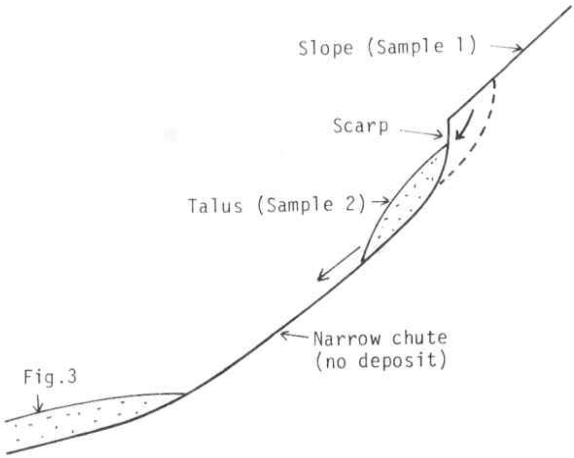


Fig.4 Sketch of the head of the Kousu torrent

Fig.5 Photo of the point of Sample 1 and the new direct shear test (designed by Sassa) beside it

necessarily it will start to slide and ride on the sediment of Fig.3 enough rapidly in comparison with stepping by foot, then the sediment will be liquefied and start to flow as a debris flow. When the talus moves, it takes off the toe support of scarp, necessarily it results in a failure of the scarp as a dotted line suggests, which is backed by the shear strength parameters of Fig.6($\varphi' = 33°$, $C' = 30$ gf/cm^2) and the average gradient(40-45°) and the depth(about 1.5 m) of the dotted line of Fig.4. Therefore, another talus is formed again. During

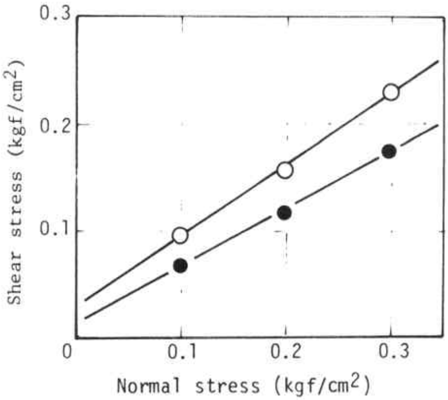


Fig.6 Results of shear tests of samples

○ (Sample 1) : Slope above the top scarp
$\varphi' = 33°$, $C' = 30$ gf/cm^2
● (Sample 2) : Talus below the top scarp
$\varphi' = 28°$, $C' = 14$ gf/cm^2

our investigation, debris flows took three times and the talus was reformed three times.

In this torrent, failures of the side slopes were observed, too. They could trigger debris flows, too. Besides this observation of the Kousu torrent, observations of debris flow areas in other districts(weathered granite, weathered andesite, weathered crystalline schist and also volcanic deposit) have suggested the three cases depicted in Fig.7 as causes of rapid loading on torrent beds. Some locally unstable deposits such as those in an outlet of small branch stream or below a step of torrent bed, can slide slowly in drained condition like Case C of Fig.7, its sliding mass is possible to ride on the loose deposit enough rapidly to cause liquefaction.

Here, let us state the mechanism of torrent bed type debris flows in use of Fig.8.
In places where there are a lot of sediment supply by soil falls or surface failures(the talus of Fig.4 is an example), a loose sediment is formed. In torrent deposits where the ground water flows through them rather rapidly(including the case of Fig.3), the void ratio of the deposits increases by transportation of fine particles(underground erosion), then a loose sediment is formed.
The loose layer of Fig.8 is such loose sediments, depicted from the observation of loose sediments and the microscopic photo

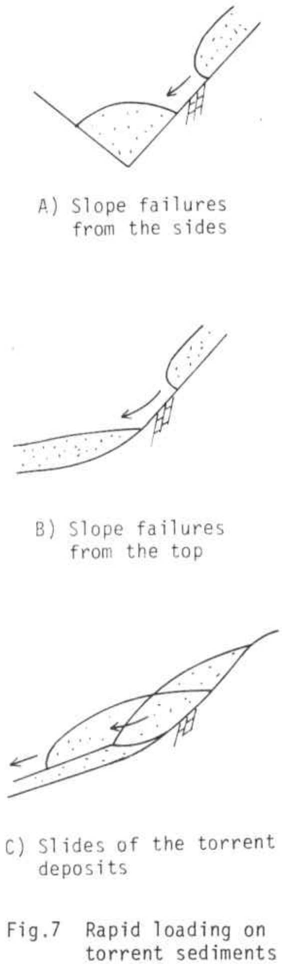


Fig.7 Rapid loading on torrent sediments

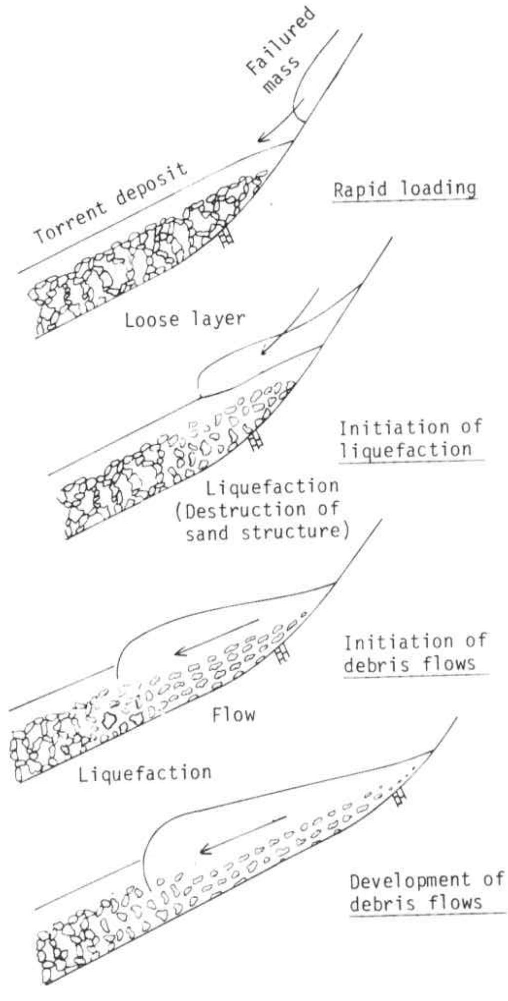


Fig.8 Initiation of debris flows in torrents

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of a very loose sand(Hanzawa, 1980).

When a failured mass rides on the loose sandy layer, the structure is destroyed and the mass sits on water(which means that water supports its overburden pressure, namely a high pore pressure is built), then shear strength much decreases and the torrent deposit starts to flow. The advance of debris flow causes a rapid loading and liqufaction on its top and the debris flow develops.
Though there may be other cases, probably this mechanism is the most popular case of initiation of the torrent bed type debris flows in Japan.

3. The mechanism to initiate the slope type debris flow

Debris flows sometimes take place on slopes where there is no torrent.
Fig.9 is a slope type debris flow which we call as "Valley-off" in Japan. A long liquefied landslide occurred in an usual slope of weathered serpentine at a heavy rain in 1975, the trace is as if a valley went off. Fig.10 is another slope type debris flow which took place in a concave slope of a weathered crystalline schist at a heavy rain in 1976. The trace is as if a big snake went out of the slope. These slope type debris flows are not interpreted by the mechanism of Fig.8

The author has proposed the mechanism of liquefied landslides as undrained shear of a loose zone by subsidence, from the investigations of the Ichinomiya liquefied landslide and the Mizusawa Shinden liquefied landslide and some indoor experiments (Sassa et al. 1981-1). The liquefied landslides and slope type debris flows must be the same in its mechanism, the difference is only in its shape, namely debris flows are long.

The mechanism is shown in Fig.11 & 12. When the ground water flows locally in a slope from some causes(A: Concave shape of the bed rock, B: Concave shape of the ground surface, C: The existence of gully, D: Others), a 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 it by infiltrating water. Accordingly a loose zone is formed in a slope. When the void ratio of loose zone exceeds a certain critical value, it is going to subside at submergence. It is well known that subsidence/settlement takes place by saturating a loose sand, it is used to compact a loose sand as the hydraulic method.
The phenomenon that the lift of the ground water level causes subsidence was observed in model experiments and in a field(Sassa


Fig.9

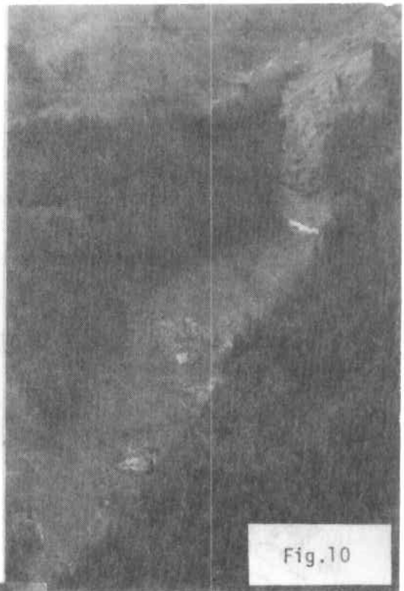
Fig.10


Fig.10

Fig.9 Slope type debris flow (Valley-off) in Kochi Prefecture, Japan, 1975

Fig.10 Slope type debris flow (Snake-off) in Tokushima Prefecture, Japan, 1976

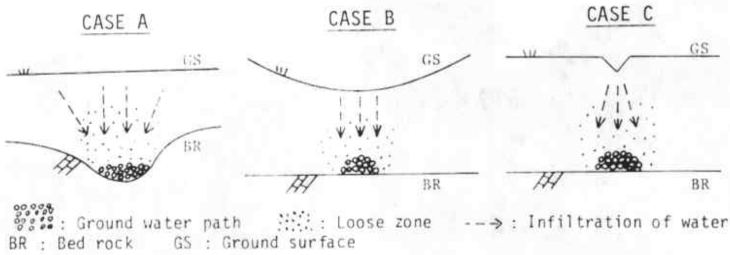

Fig.11 Formation of a loose zone in a slope

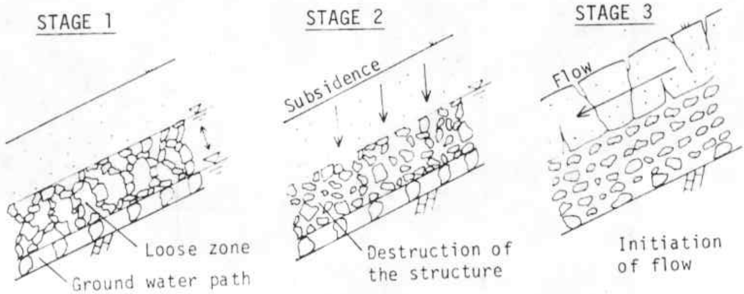

Fig.12 Illustration of liquefaction caused by subsidence

et al. 1981-1). Since both side layers of the loose zone give supports, the loose zone does not subside easily. However, it will subside someday at a lift of the ground water level by further increase of its void ratio. The subsidence destroys the structure of the loose zone, and the layer above the loose zone sits on water cushion like a hovercraft. The mass starts to flow. It is the same with Fig.8.

Fig.9 is similar to Case A of Fig.11. Fig.10 is similar to Case B of Fig.11. Some of the traces of slope type debris flows remain as torrents, but some of the traces such as Fig.10, Case B of Fig.11 are apt to be buried by supplied sediments from the slopes beside it like Fig.13. When the depth of such a deposit exceeds a certain value and it satisfies a condition for undrained shear by subsidence, it will be susceptible to liquefaction again. The Mizusawa Shinden liquefied landslide is this repeated type, which was estimated to have slided in 1370 ± 40 years before it from Carbon dating of a buried wood(Sassa 1977).

Finally we examine condition of the critical void ratio for liquefaction. Since liquefaction is related to volume change during shear, the critical void ratio must be a function of confining pressure. Fig.14 shows a range of void ratio and confining pressure susceptible to liquefaction in undrained triaxial tests loaded by increasing dead weight(Castro 1969). Though the value of Fig.14 itself is not general, its relation is likely to be qualitatively general for other materials. The confining pressure in Fig.14 corresponds to the depth of sediments. So, the case of Fig.13 is like a arrow A of Fig.14. The depth of deposit gradually increases with a little decrease of void ratio, and it enters into a state susceptible to liquefaction. Thereafter, if some rapid(undrained) loading take place, it will be liquefied. The cases of Fig.11 are like an arrow B. The void ratio gradually increases with a little decrease of confining pressure(loss of weight) and it enters into a state susceptible to liquefaction, then undrained shear causes liquefaction.

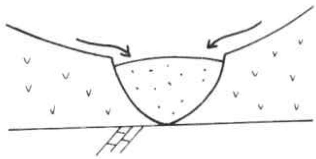

Fig.13 Re-deposit of sediments into the debris flow trace

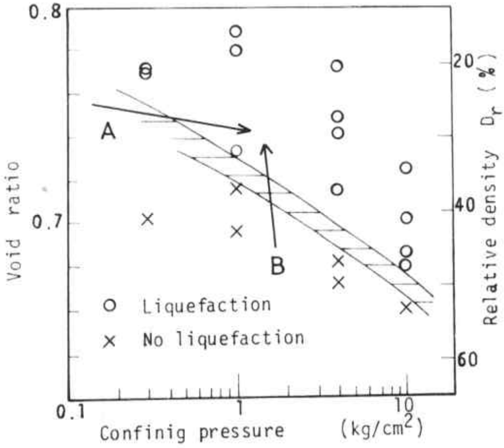

Fig.14 Range of void ratio and confining pressure susceptible to liquefaction (Reproduced from C. Castro 1969)

As the causes of undrained shear, some cases other than subsidence are possible to exist. A possible case is a rapid build up of pore pressure when a ground water path is blockaded by its failure. I observed a rapid lift of the ground water level by blockade of a ground water path(Sassa et al. 1980-3, 1981-2). However, I have not known exact examples of debris flows initiated by failure of a ground water path(which was not caused by subsidence). Another possibility is the case which an initial slide causes a rapid stress change in a slope behind it. Casagrande(1976) proposed that even toe erosion as well as an initial slide causes liquefaction. However, I have not encountered those cases in Japan. Acçording to my field investigation of disasters, the most popular and exact case of rapid loading in a slope is subsidence. And probably the next is a rapid build up of pore pressure by failure of a ground water path, though I have encountered no exact case until now.

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