The mechanism of debris flow

Le méchanisme d'écoulement de débris

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SYNOPSIS A new big and high speed ring shear apparatus was designed to study debris flows. The velocity control constant volume tests produced liquefaction of loose grains. The velocity control constant normal stress tests gave the same internal friction angle independent of flow velocity, which gave no support to the existence of "flow structure" of grains proposed by Casagrande, 1976. Rotation of saturated debris in a ring channel increased the specific gravity of pore liquid due to floatation of particles. Those experiments and field observations put forward a hypothesis that debris flow is initiated by rapid loading of the loose torrent deposits due to the failed mass from slopes, then "flow" of the deposit causes a high specific gravity of pore liquid, and resulting in a low shear resistance during flow.

INTRODUCTION

The common type of debris flows is initiated in torrents, then the torrent deposit must be sheared in prior to its movement. Torrent deposits are sandy. "Shear" of sands is classified in four cases shown in Fig. 1. (a), (b) are failure envelopes of dense and loose states of sands, respectively. The stress paths of A, B are those of drained shear of loose and dense states, the stress paths of C, D are those of undrained shear of loose and dense ones, too. The undrained shear of loose sands should be most probable for the initiation of debris flow because only its case shows a low shear resistance after failure necessary for "flow".

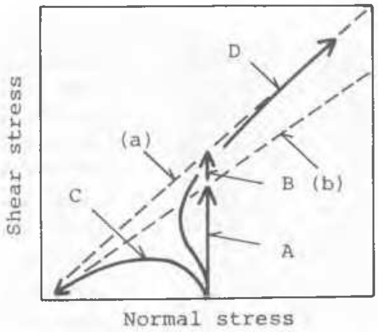


Fig. 1 Typical Stress Paths of Sands

LIQUEFACTION OF LOOSE SANDS

The undrained shear of loose sands was studied by Castro, 1969 and Casagrande, 1976 in use of the so-called load control triaxial test in which the axial load was increased by putting a weight on the load hanger. The most typical example of liquefaction by Castro is shown in Fig. 2. A sudden failure took place at a strain less than 1 %, a rapid flow and a very low resistance was observed, where load (stress) on sample was not controlled after failure probably because of the acceleration of weight. Sassa & Kaibori did the similar undrained triaxial tests, where the axial load was supplied by a series of air regulator – air tank – air cylinder to avoid the acceleration effect of weight, samples of 10 × 25 cm in size three times larger than Castro's one were used to obtain a longer flow distance and to be able to test coarse torrent deposits. A

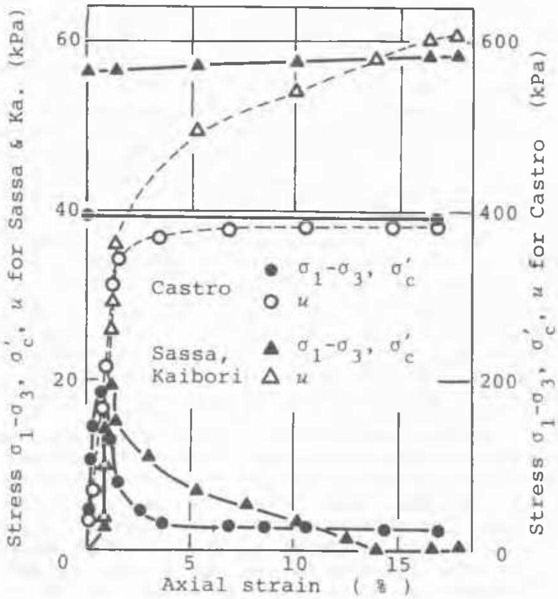


Fig. 2 Liquefaction of Sands by Triaxial Test
Castro e=0.75, D_r=27 %
Sassa & Kaibori e=0.98, D_r=0.3 %
(Void ratio e is after consolidation)

multi-pen recorder was set to take digital values of each 1.5 millisecond before/after the failure in use of trigger as well as continual analog record. Pore air was replaced by CO_2 gas for full saturation, and the lubricated ends were not used.
Fig. 2 shows one of the most typical liquefaction (Its relative density is calculated from the JSSMFE, 1979) of 25 tests in use of the Toyoura standard sand (D_{10}=0.15 mm, D_{60}=0.18 mm). Observation of Video tape at 1/30 sec. stop motion visualized that loading could not follow the samples deformation enough, especially in the greater strain. The value of pore pressure 2 kPa over the cell pressure expresses the increased specific gravity of pore liquid due to floatation of particles, which is examined in Fig. 8. In this type of tests, the stress-strain relation strongly depends on loading method, and flow distance is too small for study of a steady flow.

A NEW HIGH SPEED RING SHEAR APPARATUS

Casagrande (1976) proposed "flow structure" expressing the state which each grain rotates so as to offer a minimum frictional resistance during flow. To study the shear characteristics of grain flow, namely "flow structure", a rapid strain control test or a real stress control test having enough flow distance is desired. Sassa designed a new high speed ring shear apparatus for this purpose.
Fig. 3 illustrates its structure. In this figure the sample's size is 30 - 48 cm inside and outside diameter, 9 cm in height. The lower ring and the hatched table is rotated by a motor and gear in the speed of 0.3 mm/min. - 90.76 cm/sec. in the center of ring. While the upper ring and the dotted plate is stopped its rotation and kept still by the load cell for shear stress measurement.
Normal stress is supplied by a compressed air, and the loaded normal stress on shear plane is measured by the load cell to avoid a possible loss of stress transmission to the ring wall. The loading plate is locked for constant volume tests at three vertical rods to keep it horizontal. The edges of two rings are vertically tapered at 1:6, those are much easier to keep a minimal slit without contact of two edges and leaking of samples than the horizontal straight edges. When it is necessary, silicon rubber is sticked on the inside edge of the upper ring so as to slide on the inside edge of the lower ring with a negligible contact stress. A spring balance is used to take off a little clearence in the rotary joint and the gear of gap adjuster. Fig. 4 is a photo of the front view, where the transparent acryl for water bath is removed.

Fig. 5 is the test results of glass beads of 1 mm (Silicon rubber was used). Since the influence of suction will be negligible, tests were done in the air dry for dense and medium states, tests for the loose state were done in a damp state (1 - 3 % in water content). The results of constant volume tests are shown as three lines, their stress paths are similar to C, D of Fig. 1 and their intermediate one. The loose one was sheared by about 1 m/sec. which is the order of debris flow velocity monitored in Japan (Okuda et al, 1977), it once reached the origin and it went into a steady flow with a very low shear resistance of 0.8 kPa.
However, the undrained condition is not maintained during flow because pore water can move to the phreatic surface freely. Then, shear during a steady flow must be the drained condition, accordingly the constant normal state. To study the shear characteristics of a steady flow, the constant normal stress tests were done in various shear speeds at the medium void ratio. The results of Fig. 5 showed that all stood in the same failure envelope (the friction angle is 19°. Usual triaxial tests gave the same value, too) independent of shear speed. Therefore, it

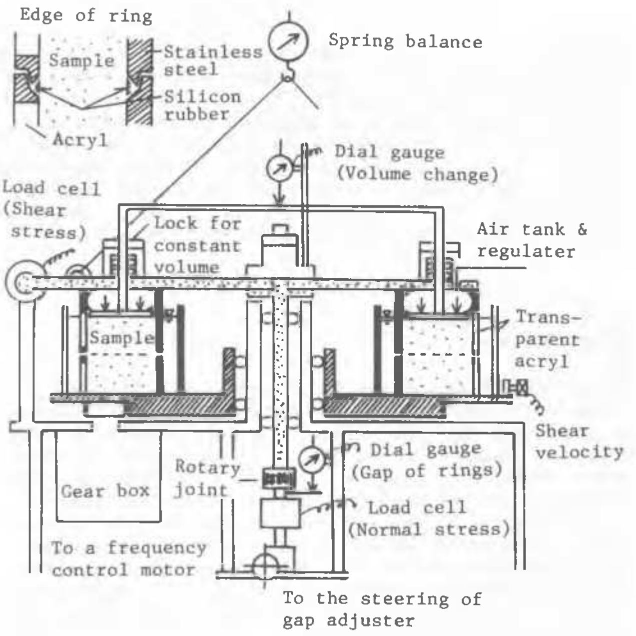
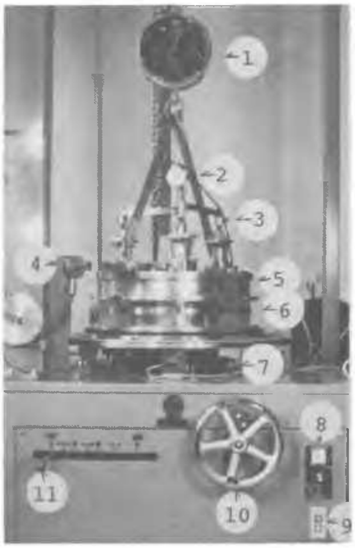


Fig. 3 Schematic Diagram of the New High Speed Ring Shear Apparatus



1) Spring balance
2) Dial gauge for volume change
3) Arm connecting the loading plate
4) Load cell for shear stress
5) Loading unit
6) Sample box
7) Gear for rotation
8) Electrical speed controller
9) Power switch
10) Steering of the gap adjuster of two rings
11) Change lever of gears

Fig. 4 Front View of the New Apparatus

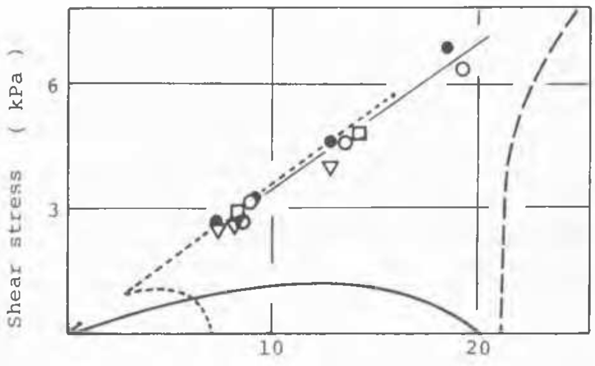


Fig. 5 Results of the New Ring Shear Apparatus

will be of no doubt that the reason why debris flow continues its movement until several degrees can not be explained by the special structure of grains "flow structure".

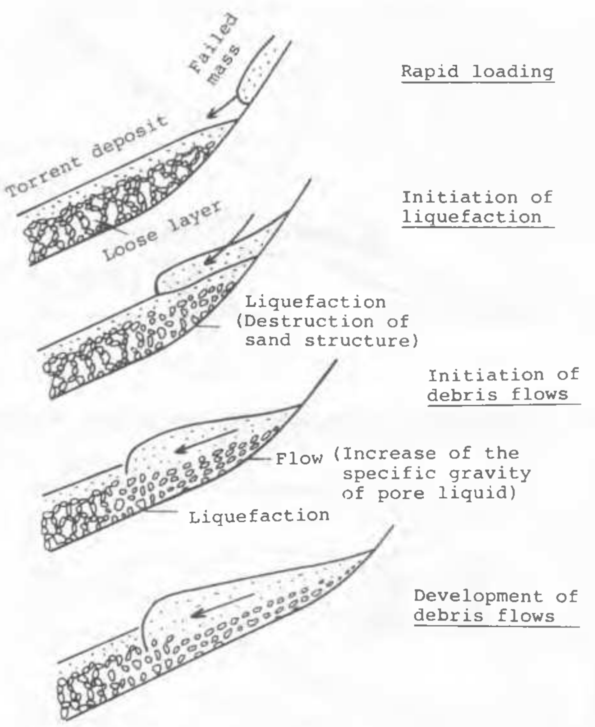


Fig. 6 Illustration of the Mechanism of Debris Flows

THE MECHANISM OF DEBRIS FLOWS

Fig. 6 is the mechanism of debris flows illustrated from both of field observations of over one hundred debris flows during 1975 - 1983 in Japan and laboratory liquefaction tests. Torrent deposits which have a loose and unstable structure can disjoint its structure by rapid loading due to the failed mass, accordingly the failed mass and the upper layer sits on water (1st & 2nd figure), the torrent deposit starts to flow causing liquefaction at its front and increasing its volume (3rd & 4th figure). Hutchinson & Bhandari (1971) proposed a similar mechanism for mudslides in England, and Tabata & Ichinose (1973) suggested that debris flows could be triggered by the energy of failed mass.

To give more exact supports to the hypothesis of Fig. 6, a small volcano (640 m in height) often causing debris flows was selected for a detailed study. The Usu volcano erupted in 1977, thereafter, small - medium debris flows were caused repeatedly. During a series of very heavy rains in 1981, field observation, survey, direct shear test in the field were done for 11 days. Three small debris flows took place in the investigating torrent at that period.

In the top of torrent, a talus deposited so critical that its partial submergence has to slide it, and it must have given a rapid loading on the torrent deposit according to the direct shear tests and survey. Furthermore, the torrent deposit behaved like a water cussion when the author gave a rapid loading by stamping at the saturated state in some hours before a debris flow (Sassa, 1984). Fig. 7 is the results of the so-called load control triaxial test of the torrent deposit (Grains greater than 12 mm were eliminated. Then, D_{10}=0.13, D_{50}=2.7, D_{90}=8.0 mm, G=2.46). 26 tests were done in the same procedure with Fig. 2, except the degree of saturation was changed.

T-1 is the result of typical liquefaction of full saturation, the void ratio is 0.74, which is in the range of the torrent deposit in field, 0.61 - 0.77. T-3 and T-4 are the tests to study the behavior of less saturated sample. T-3 showed the torrent deposit can be liquefied even if it were not fully saturated by unnatural high back pressure and use of CO_2 gas, (though the critical void ratio for liquefaction seems to change from 0.7 at the full saturation to about 0.8 at 85 % saturation).

Fig. 8 is the results of very simple experiment to look for the reason why a low shear resistance is maintained even during a steady flow. The Toyoura sand and water is poured into a small ring channel and rotated by a bar while pore pressure is measured at the bottom through a filter. During a steady flow, an excess pore pressure to cause "flow" to the phreatic surface does not exist, but the recorded pore pressure is proportional to the velocity of the bar. This is interpreted by the idea of sedimentation method for the grain size distribution. The greater the flowing velocity of sands, the greater percent of particles floats in water, then the specific gravity of pore liquid increases. It will be the reason why pore pressure exceeded the cell pressure during flow in Fig. 2.

The same tests of the Usu sample used in Fig. 7 could not be done in a wider range because of its big grain size for this channel. However, the specific gravity increased up to 1.25 at 70 cm/sec.. Usual speed of debris flows is 1 - 10 m/sec. by monitoring in Japan, therefore, the value probably will reach 1.4 or more at the

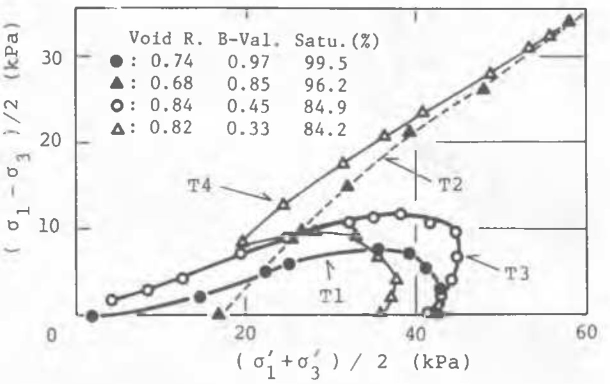


Fig. 7 Results of Undrained Triaxial Tests of the Usu Torrent Deposit

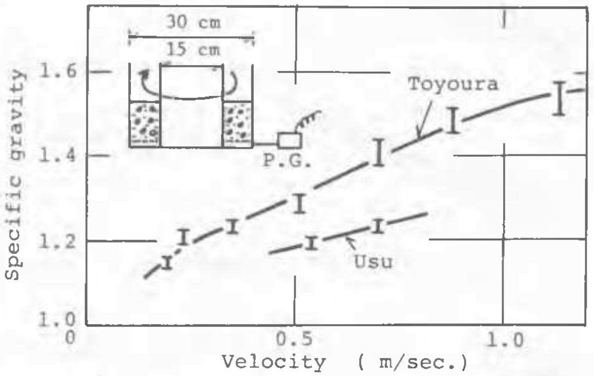


Fig. 8 Specific Gravity of Pore Liquid during Flow
(Saturated unit weight: 17.2 - 18.6 kN/m^3 for the Toyoura, 16.9 - 17.9 kN/m^3 for the Usu)

usual velocity range. At that time we will calculate the critical angle of stoppage (θ) by

$$\tan\theta = (\gamma_b / \gamma_t) \times \tan\phi$$

The total unit weight (γ_t) of the less disturbed samples of torrent deposit including volcanic porous stones at the naturally submerged state was 16.1 kN/m^3-18.0 kN/m^3. The measured internal friction angle of the torrent deposit was 32°, the bouyant unit weight (γ_b) is $\gamma_t - 1.4 \times 9.8$ in kN/m^3. It gives 5.2 - 8.5° as the critical angle of stoppage which agrees with the real deposit angle of debris flows in Japan and also the Usu, 4 - 10°.

CONCLUSION

1. The so-called load control undrained triaxial tests can produce liquefaction, but its stress-strain relation depends on the loading method, and it is not enough to create a steady state of flow.
2. A new big and high speed ring shear apparatus was designed, and the tests of glass beads of 1 mm showed that the loose grains are liquefied, when they are sheared in the constant volume state.
3. The constant normal stress tests showed that the internal friction angle of grains is independent of the shearing speed in 0 - about 1 m/sec.. Therefore, the special "flow structure" of grains to offer a minimum resistance proposed by Casagrande was not found there.
4. A simple experiment to rotate sands and water put forwards that pore water becomes a dense pore liquid having a higher specific gravity by floatation of fine particles during flow.
5. Field observations and laboratory tests of 1) - 4) gave supports to the hypothesis stated in 6) and 7) as the mechanism of debris flows.
6. A loose torrent deposit is rapidly loaded by the failed mass from the top or the sides of torrent. The loose structure of deposit is destroyed and the failed mass and the upper layer sit on water (liquefaction), then the mass starts to flow. During a steady flow any excess pore pressure to cause "water flow" to the phreatic surface can not be maintained, because water can move freely.
7. Rapid flow of debris causes floatation of their particles in water, and it results in the increase of the specific gravity of pore liquid. It will be the reason of a low shear resistance and the low deposition angle of debris flows, 4° - 10°.

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