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SOIL PROPERTIES AND FLUIDITY OF LONG-TRAVELING LANDSLIDES

N. USUKI[(*)] & T. MIZUYAMA[(**)]

[(*)]Asia Air Survey Co., Ltd. - Japan
[(**)]Graduate School of Agriculture, Kyoto University, Japan

ABSTRACT

Better knowledge of the movement mode of fluidized landslide masses, which cause severe damage over wide areas, is very important for preventing sediment-related disasters. We analyzed a population of long-traveling landslides in Japan in terms of their travel coefficient and the conditions of the landslide mass, defining the ratio of travel distance ($L2$) to the original length of a landslide mass ($L1$) as the travel coefficient ($Tr = L2/L1$). After classifying long-traveling landslides by movement mode into fully fluidized and partly fluidized landslides, we found that the travel coefficient of fully fluidized landslides is roughly $Tr \geq 0.5$. The grain size distributions of landslide masses suggest that the proportion of clay and silt is one factor behind a large travel coefficient. To evaluate the effect of grain size distribution on landslide travel coefficient and movement mode, we conducted soil mechanics tests on experimental soil specimens. These tests showed that soils having an intermediate grain size distribution, containing roughly equal proportions of gravel and sand, clay, and silt, have the smallest shear stress in the depth range of 10 - 15 m below the ground surface.

Key words: *long-traveling landslide, movement characteristic, soil properties of landslides*

INTRODUCTION

Some landslide masses travel long distances in a fluidized state without developing into a debris flow. The July 1985 Jizuki-yama landslide in Nagano Prefecture, for example, caused severe damage because it traveled over a long distance. Sassa *et alii* (2000) studied the travel speed of these kinds of highly fluidized long-traveling landslides, but did not focus on their travel distance. Other studies have included estimates of the travel distance of landslide masses (Moriwaki, 1987), case analyses of the travel distance of landslides (Kusumoto *et alii*, 2003), and an examination of the topographical conditions of large-displacement landslides (Morishita *et alii*, 2003), but did not evaluate the movement mode of these landslides. Our study therefore focused on the movement mode of long-traveling landslides in Japan by examining their features, soil properties, and distribution characteristics in relation to travel distance.

ACTUAL STATE OF LONG-TRAVELING LANDSLIDES

LANDSLIDE DATA FOR STUDY

We collected data on landslides caused by rainfall and snowmelt, and whose masses moved continuously after sliding began. Of the 376 major landslide disasters in Japan from 1947 to 2000, we selected landslides that have a complete dataset including a plan chart; data on site geology, landslide scale, soil volume, and travel distance; and photos showing the conditions of landslide masses. We excluded 1) landslides caused by earthquakes and artificial causes, 2) landslides that blocked a mountain stream first and then

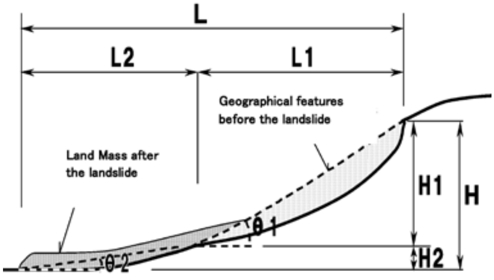

Fig. 1 - Measurements related to the travel distance of a landslide mass

of landslide masses (Fig. 3). The travel coefficient is distributed between 1 and 3.4. We defined landslides with a travel coefficient of $Tr \geq 0.5$, which is equal to those with a cumulative relative frequency of 20% or more, as long-traveling landslides. The average travel distance of these long-traveling landslides is about 350 m, and their maximum travel distance is about 2000 m. Of these landslides, 22 have a travel coefficient of 1.0 or greater (which means the travel distance is longer than the original length of the landslide mass).

underwent secondary movement, as identified from interviews and field surveys, and 3) landslides that formed a landslide dam that subsequently burst. We measured the travel distance and related dimensions of the remaining 109 landslides as shown in Fig. 1.

DEFINITION OF A LONG-TRAVELING LANDSLIDE

Figure 2 shows the distribution of the travel distances (*L2*) of our set of landslides. The travel distance of landslides varies widely, ranging from a slight movement at the landslide tip to as long as 2300 m. We defined the ratio of travel distance (*L2*) to the original length of a landslide mass (*L1*) as the travel coefficient ($Tr = L2/L1$) and used it to evaluate the movement scale

DEFINITION OF A LONG-TRAVELING LANDSLIDE

Figure 4 shows the distribution of long-traveling landslides in Japan. Their distribution corresponds roughly to areas of Neogene formations and metamorphic rocks, which are known to be landslide-prone areas. The 109 landslide locations selected for our study have a similar distribution. According to the landslide classification by Koide (1955), these are areas where the so-called Tertiary formation landslide and fracture zone landslide tend to occur. Long-traveling landslides have occurred mainly in the Hokuriku and Shikoku regions but occur in other areas as well, in particular in areas of Neogene rocks and along the geological tectonic lines.

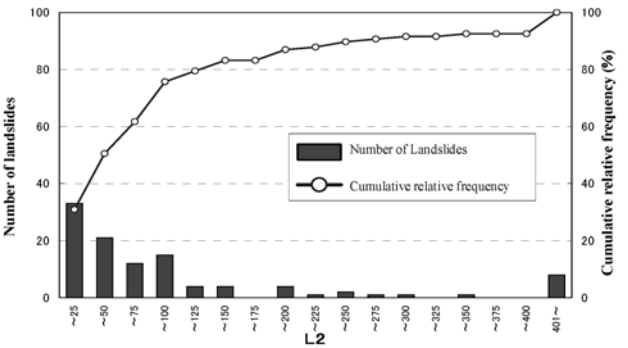

Fig. 2 - Histogram of the travel distance (L2) of landslides

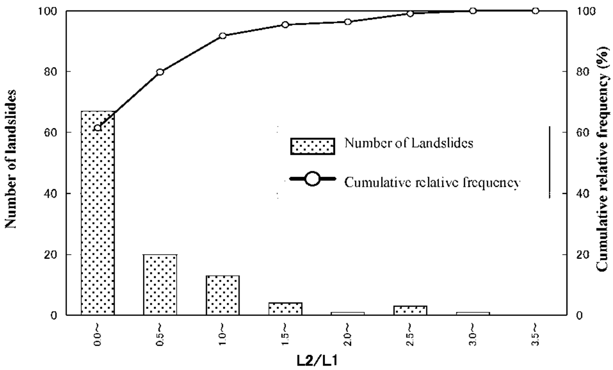

Fig. 3 - Histogram of the travel coefficient (Tr) of landslides

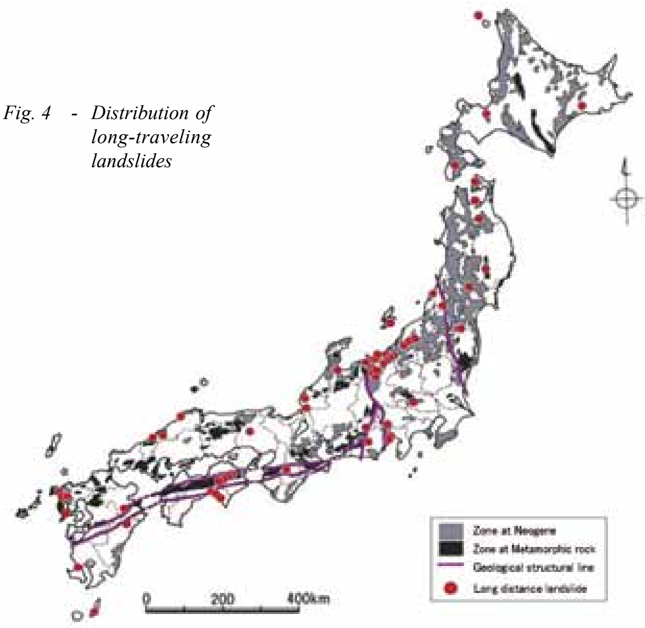

Fig. 4 - Distribution of long-traveling landslides

CHARACTERISTICS OF LONG-TRAVELING LANDSLIDES

CLASSIFICATION OF MOVEMENT MODES OF LANDSLIDE MASSES

Landslides are often classified by sliding area, movement mode, moving speed, and various landslide scales. The movement modes of landslides are topple, fall, spread, flow, slide, and creep. Longtraveling landslides are mainly of the flow mode. We classified the landslide masses in our study in one of the following three classes (see Fig. 5):

1. The landslide mass and its surfaces are hardly disturbed, and it slides as an intact mass.
2. The surfaces of the landslide mass are slightly disturbed. Most trees in the landslide site, if they exist, have not fallen.
3. The landslide mass does not retain its original shape, and its surfaces are severely disturbed. Most trees in the landslide site, if they exist, have fallen.

Fig. 5 - Classification of landslide masses by movement mode

In the first case, sediment moves along the slide plane as a mass that retains its original shape with little or no fracturing of the internal structure. In the second case, the landslide mass is deformed but flows without fully fracturing the internal structure (partly fluidized). In the third case, the internal structure is completely fractured after sliding begins and the flow is fully fluidized.

EQUIVALENT FRICTION COEFFICIENT AND MOVEMENT MODE

The relationship between the equivalent friction coefficient (*H/L*; see Fig. 1) and the soil volume of landslides is summarized in Fig. 6, also showing the three movement modes of landslide masses just described. The equivalent friction coefficient is in the range of μ = 0.1-0.9. As the soil volume increases, the equivalent friction coefficient decreases, though this tendency is not very conspicuous.

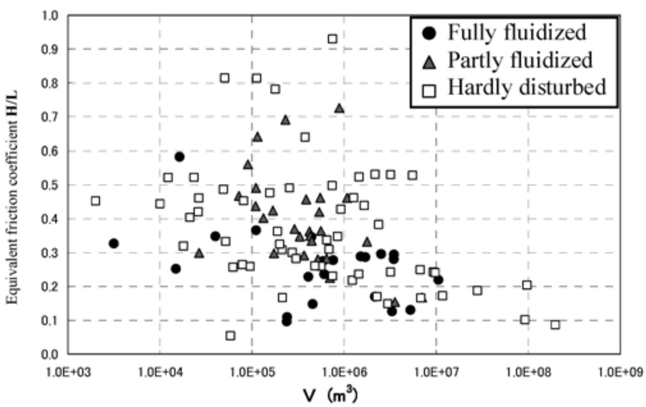

Fig. 6 - Relationship between equivalent friction coefficient and soil volume of landslides

SOIL VOLUME AND MOVEMENT MODE

The relationship between the soil volume and travel distance (*L2*) of landslides is summarized in Fig. 7, including the three movement modes described above. The well-known tendency of travel distance of landslides (in particular, that of debris slides) to become longer as the soil volume increases is seen in Fig. 7. But it is also apparent that the plots of fully fluidized, partly fluidized, and hardly disturbed landslides are widely distributed, implying that factors other than soil volume should also be considered regarding the fluidity of landslide masses. We examined slope gradient as a factor, but found no clear relationship between slope gradient and movement mode.

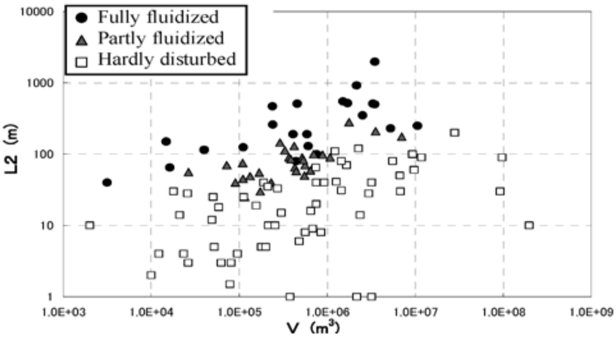

Fig. 7 - Relationship between soil volume and travel distance of landslides

TRAVEL COEFFICIENT AND MOVEMENT MODE

The travel coefficients of our landslides are summarized in Fig. 8, along with their classification in our threefold scheme. The travel coefficient of fully fluidized, partly fluidized, and hardly disturbed cases is roughly $Tr \geq 0.5$, $0.3 \leq Tr < 0.9$, and $Tr \leq 0.3$, respectively. This means that long-traveling landslides can be classified to some extent based on the travel coefficient and movement mode.

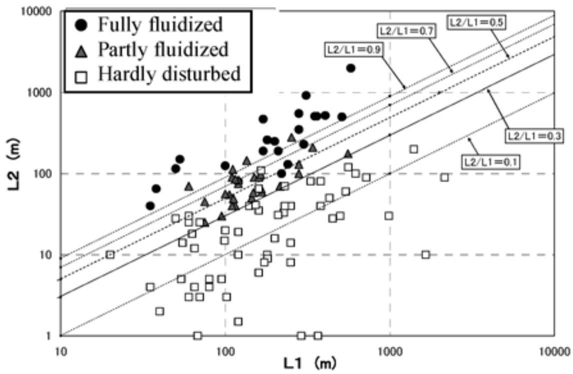

Fig. 8 - Relationship between travel distance and original horizontal distance of landslides

SOIL PROPERTIES OF LONG-TRAVELING LANDSLIDES

DATA FOR STUDY

Although large amounts of data are available on soils at the slip surface, the amount of test data from landslide masses is very limited. However, Niigata Prefecture, which is one of the most landslide-prone prefectures in Japan, has accumulated a significant body of soil test results from the 1478 major landslides that occurred in the prefecture during 1982-2004. We selected those from 15 landslides whose travel distance was measureable, whose soil test results were available, and which were not triggered by earthquakes or artificial causes. Their travel distances were 50-600 m and their travel coefficients were Tr = 0.2-6.0. Of those landslides, 13 had a travel coefficient of $Tr \geq 0.5$, which means they were fully fluidized. Therefore, we decided to focus not on the separability between fully fluidized and partly fluidized landslides, but on the scale of their travel coefficients. The distribution of those landslides and their travel coefficients are shown in Fig. 9.

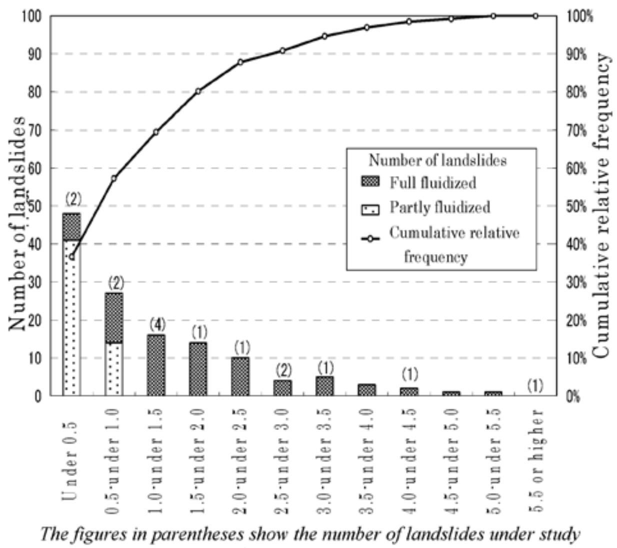

Fig. 9 - Histogram of travel coefficients

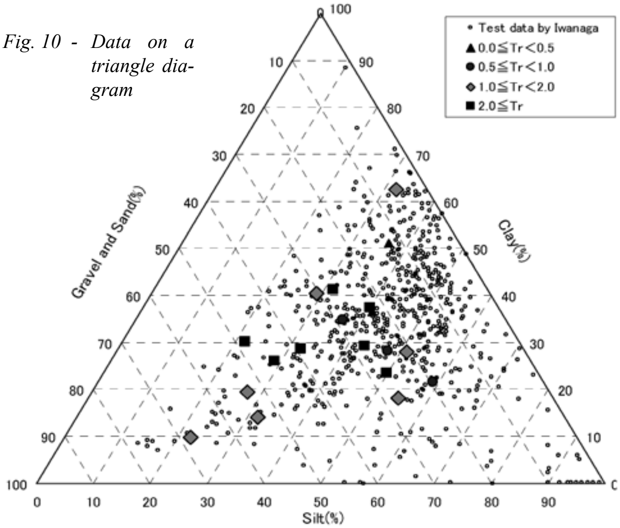

Fig. 10 - Data on a triangle diagram

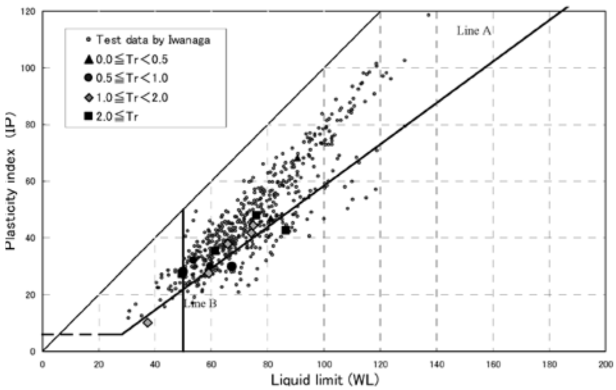

Fig. 11 - Figure of plasticity

TRAVEL COEFFICIENT AND SOIL PROPERTIES OF LANDSLIDE MASSES

Iwanaga (1983) summarized soil test data for about 130 landslides in Niigata Prefecture in a data base used as a standard source for the general physical characteristics of landslide soils. To evaluate the soil properties of landslides with large travel coefficients, we obtained and analyzed data on the grain size and liquid and plastic limits of the 15 Niigata landslides of our study and compared these with the data on landslide masses from Iwanaga's collection.

GRAIN SIZE DISTRIBUTION: We produced a ternary grain size distribution figure from our landslide data in accordance with the Japanese Unified Soil Classification System and compared it with the grain size distribution of Iwanaga (Fig. 10). Iwanaga's data are mainly distributed in areas of the diagram representing large proportions of clay and silt. In contrast, landslides with a large travel coefficient are distributed in the center area representing more than 20% of gravel and sand, silt, and clay. It is also apparent that as the percentage of gravel and sand exceeds 20%, the travel coefficient becomes larger, but as the gravel and sand percentage exceeds 50%, the travel coefficient becomes smaller again.

PLASTICITY: Using a similar soil classification system, we analyzed plasticity for our landslide data and compared it with the plasticity analysis of Iwanaga (1983) (Fig. 11). Line A is a boundary separating large and small volumetric changes and permeabilities. Line B is a boundary separating large and small compressibilities. Landslides with a large travel coefficient are distributed on or near Line A and Line B.

SOIL PROPERTIES OF LANDSLIDES WITH A LARGE TRAVEL COEFFICIENT: In Figure 10, the data of Iwanaga (1983) are mostly for sediments containing a large percentage of clay and silt, which are typical soils of landslide-prone areas. In our data, landslides with a large travel coefficient tend to contain a relatively large percentage of gravel and sand. According to Iwanaga (1983), the Uonuma formation group in Niigata Prefecture has the former type of grain size distribution and tends to trigger collapse-type landslides. The travel distance of collapse-type landslides is unknown, but their travel speed is probably faster and the travel coefficient is probably larger than those of ordinary landslides in view of their failure mode.

However, sediments from landslides with a large travel coefficient, $Tr \geq 2.0$, are distributed in the center area that represents 20% or more of gravel and sand, silt, and clay. From this, it may be said that the travel coefficient becomes larger when the landslide mass contains not only a large percentage of gravel and sand but also a certain percentage of clay and silt.

MECHANICAL TESTS OF SOILS WITH VARYING GRAIN SIZE DISTRIBUTIONS

TEST METHOD

Various factors affect the travel coefficient by controlling the movement mode of landslide masses. They include soil volume, slope gradient, water content, and catchment area. The soil test results from Niigata Prefecture suggest that soil properties, particularly mechanical properties that vary with grain size distribution, have an effect on landslide movements. To evaluate these effects of grain size distribution, we tested four types of specimens with varied grain size distributions: physical tests (grain size analysis, water content), consistency tests (liquid limit, plastic limit, liquidity index), uniaxial compression tests, and triaxial compression tests (unconsolidated undrained conditions). Similar specimens were also immersed in water for 48 hours to evaluate any decrease in strength due to water immersion.

PREPARATION OF SPECIMENS

We performed grain size analysis using a sieve based on the Japanese Industrial Standard (J1S-A-1204) and the Japanese Geotechnical Society Standard (JGS0131), and produced four types of specimens: coarse-grained soil, intermediate soil, fine-grained soil 1, and fine-grained soil 2. A core material used for dams was used as the base material of the specimens. Undisturbed materials were used for the specimens of fine-grained soil 1 and fine-grained soil 2. Coarse-grained soil and intermediate soil for specimens were compacted at 0.5 Ec, which is half of the standard energy, in the compaction test to approximate natural conditions.

TEST RESULTS

The test results and consistency characteristics of each specimen are shown in Table 1.

GRAIN SIZE DISTRIBUTION AND PLASTICITY: Comparisons of the grain size distributions and plasticity analysis for our experimental samples with the data of IWANAGA (1983) are shown in Figs. 12 and 13, respectively. In Fig. 12, the intermediate soil plots in the area of sediments from landslides having a large travel coefficient, $Tr \geq 1.0$. The fine-grained soil 1 and fine-grained soil 2 specimens plot in the area of ordinary landslides. The coarsegrained soil specimen plots in the area where landslide occurrence is unlikely. But, in Fig. 13, all of these soils plot roughly in the same area of the plasticity diagram where ordinary landslides occur.

RESULTS OF UNIAXIAL COMPRESSION TESTS: The uniaxial compression test results show that the strength of our experimental samples is in the order: fine-grained soil 2 > finegrained soil 1 > intermediate soil > coarse-grained soil. Also, an intermediate soil had the smallest modulus of deformation (E_{50}), a modulus indicating vulnerability to deformation. In the test after 48- hour water immersion, all the specimens tested (the fine-grained soil 2 specimen absorbed so little water that we did not conduct this test on it) lost their strength, particularly the specimens of coarse and intermediate soil. These results suggest that intermediate soil will lose its strength significantly during the snowmelt season and after a long period of rain.

RESULTS OF TRIAXIAL COMPRESSION TESTS: Figure 14 shows the results of triaxial compression tests (Mohr's circle). At compressions equivalent to a depth of 5-10 m from the ground surface, intermediate soil had the smallest shear stress. But when the equivalent depth was 15 m or more, fine-grained soil 2 had the smallest shear stress. From this, we infer that landslide masses having a grain size distribution close to intermediate soil are apt to fracture easily if they are deformed under sliding loads. Fracture-prone landslide masses, such as those composed of intermediate soil, will be quickly fractured if a sliding movement occurs. If a flow layer is formed on the slide plane, the fractured mass will be incorporated into that flow layer.

Name of sample		Coarse-grained soil	Intermediate soil	Fine-grained soil 1	Fine-grained soil 2
Soil grain density ρ_s %		2.754	2.748	2.697	2.582
Natural water content w %		14.1	23.7	47.9	97.4
Grain size	Gravel and sand %	88	57	22	8
	Silt %	7	19	40	38
	Clay %	5	24	38	54
Consistency	Liquid limit w_L %	46.8	56.7	61.1	109.5
	Plastic limit w_P %	21.2	21.5	25.6	39.1
	Plasticity index I_P	25.6	35.2	35.5	70.4
	Consistency index I_C	1.277	0.938	0.372	0.171
	Flow index I_f	8.87	9.58	6.39	8.37
	Toughness index I_t	2.89	3.67	5.56	8.41
Uniaxial	qu kN/m^2	46.50 (11.60)	59.55 (30.80)	95.80 (87.70)	87.65 –
	E_{50} MN/m^2	7.21 (1.18)	2.17 (1.22)	8.09 (4.38)	3.70 –
Triaxial	C kN/m^2	15.2 (5.9)	23.9 (15.1)	40.8 (38.4)	40.1 –
	ϕ °	36.0 (22.8)	14.2 (12.1)	13.9 (12.3)	8.6 –

Figures in parentheses show test results after 48-hr water immersion

Tab. 1 - Results of physical tests and consistency characteristics

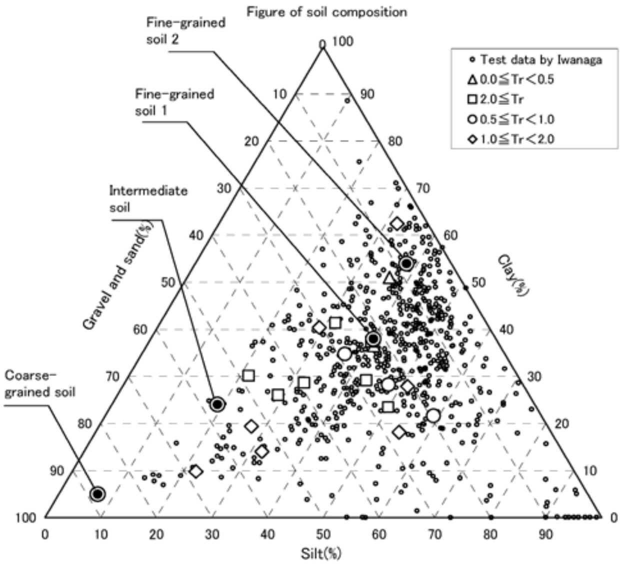

Fig. 12 - Data on a triangle diagram

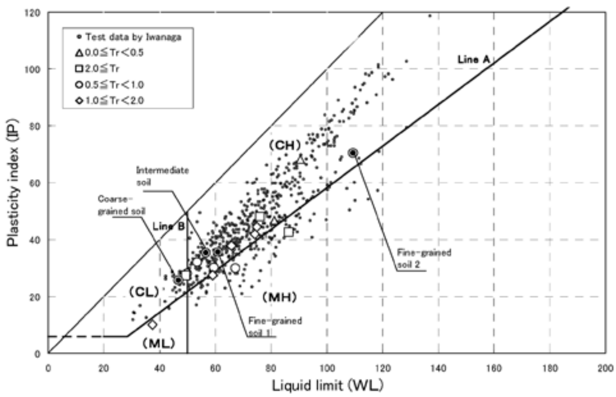

Fig. 13 - Figure of plasticity

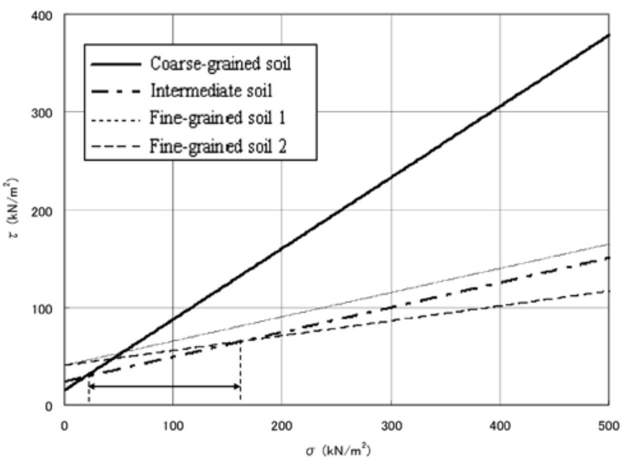

Fig. 14 - Results of the triaxial compression test

FLOW MODE OF LONG-TRAVELING LANDSLIDES

We examined the movement mode of long-traveling landslides based on the results of our soil mechanics tests. We infer that longtraveling landslides occur by the following mechanism if landslide masses are fully water saturated.

1. A landslide starts to slide on the slide plane.
2. Fracturing of the landslide mass begins due to sliding loads and deformation.
3. A flow layer forms below the sliding landslide mass.
4. The fractured landslide mass is incorporated into the flow layer and the layer continues to grow.
5. If sufficient water is supplied (including the water in the landslide mass), the flow layer grows until it affects the entire mass.
6. Due to the fracturing of the landslide mass and its incorporation in the flow layer, the landslide mass becomes severely disturbed, losing its original shape.

If a landslide mass is fully saturated and there are no large topographic changes (such as slope gradient), soil properties close to those of an intermediate soil have an effect on fracturing of the landslide mass (item 2 above), and on development of a flow layer (item 4 above), and become one of the factors that determine the travel coefficient.

Landslides with a large travel coefficient do not retain their original shape; their masses are severely disturbed and enter a fully fluidized sliding mode. This is probably because a landslide mass is fractured as sliding advances and the fractured mass is incorporated into the flow layer.

If grain size distribution of a landslide mass is close to that of an intermediate soil, the mass is prone to fracturing and incorporation into the flow layer. Landslides composed of intermediate soil and those with a large travel coefficient have low liquid limits and low plasticity indexes and tend to be distributed around Line A of the plasticity analysis (see Fig. 11). If the water content is increased, these landslides tend to liquefy and undergo a large volume change. During the snowmelt season or after long periods of rain, the landslide mass will probably be saturated to a state close to the liquid limit. Entering a liquid state means there is a change in volume and the enlargement of voids. If a sliding action is triggered in that state, the void ratio will further increase due to the disturbance of the landslide mass. Then, those voids will be filled with gravel and sand in addition to liquefied clay and silt. The developed flow layer will enter a mode like that of a debris flow, producing a large travel coefficient.

On the other hand, if a landslide mass contains a high percentage of clay and silt (such as fine-grained soil 1 and finegrained soil 2), it will not be easily fractured even when sliding begins. Consequently, the landslide mass will not be incorporated into the flow layer and the layer will not grow. Because of its content of clay and silt, the flow layer will show a behavior close to that of a Bingham fluid, which is very viscous. If the flow layer remains thin, or thinner than the flow layer of the plug that has a smaller shear force than the yield strength, the landslide mass will stop sliding and enter the partly fluidized movement mode with little disturbance.

FUTURE PERSPECTIVES

There have been few studies on the movement mode of longtraveling landslides, including their occurrence, flow, and deposition. Also, their soils have not been extensively sampled. It would be helpful to conduct field surveys, collect samples, perform soil mechanics tests, and accumulate data on this kind of sediment movement. It would also improve understanding of the range of long-traveling landslides to investigate the formation and development mechanism of a flow layer that grows in a fractureprone intermediate soil.

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