BRITTLE FAILURE OF A VOLCANIC ASH SOIL "SHIRASU"

FAILLE FRAGILE DU SOL DE CENDRE VOLCANIC "SHIRASU"

ХРУПКОЕ РАЗРУШЕНИЕ ВУЛКАНИЧЕСКОГО ПЕПЛА "ШИРАЗУ"

T. YAMANOUCHI, Professor, Kyushu University, Fukuoka
H. MURATA, Lecturer, Kagoshima Technical College, Kagoshima-Ken, Japan

SYNOPSIS. The so-called "Shirasu" which is widely distributed in southern Kyushu of Japan is known as a typical structurally-unstable-soil of volcanic product, and lately it has been the cause of frequent damage involving slope failures and other accidents, resulting from heavy rains and earthquakes. This paper deals with the brittle failure of undisturbed Shirasu with an eye on the fact that it has more or less tensile strength. The authors carried out uniaxial and triaxial strength tests as well as the Brazilian splitting test on various kinds of undisturbed Shirasu specimens, and investigated such failure criterion as is suitable for undisturbed Shirasu. They made clear that the modified Griffith criterion by McClintock and Walsh and Coulomb-Navier criterion are applicable to it, showing the relations between such criteria and physical properties. Based on those laboratory studies on undisturbed specimens of Shirasu, some examples of failure in cut-off slopes are explained.

INTRODUCTION

Shirasu, which is a soil originated from volcanic eruptions in Pleistocene geological age and widely distributed in southern Kyushu of Japan over the area of about 4,700 sq km, is known as a typical structurally-unstable-soil. Since Shirasu-distributed area happens to be frequented by heavy rains, such as recorded in 1949 and 1969, and earthquakes, such as Ebino earthquakes of 1968, it has suffered devastating damage from time to time. And the damage from Shirasu has led to drive 1,500,000 residents in that area to disaster, even constituting a social problem.

The damage from Shirasu is quite diversified, and its general phases from the viewpoint of soil mechanics have been already reported in a previous paper (Yamanouchi, 1972). This paper treats of undisturbed Shirasu with its brittle failure paying attention to the fact that undisturbed Shirasu has more or less tensile strength. The authors believe that brittle failure of Shirasu is an important factor for the stability of Shirasu, especially for its cut-off slopes.

Greater part of Shirasu is composed of particles in the state of crushed glass with much pumice included in it. As conceivable causes for the strength of undisturbed Shirasu we can enumerate the cementation or welding, interlocking and electrostatic bonding between particles, but the mechanism of them is not made clear yet. Besides, Yamanouchi and Haruyama (1969) have investigated undisturbed Shirasu concerning the interlocking effect among those factors. The phase of origin and damage of Shirasu are very akin to that of "yellow brown pumice soil" of New Zealand, while the secondary deposit of Shirasu is apparently most resembled to the soil. The primary deposit of Shirasu discussed mostly in the present paper is, however, generally known as isotropic and homogeneous in its appearance. As far as the phase of damage is concerned, damage of Shirasu is resembled to that of loess soils.

LABORATORY STUDIES

Since Shirasu is rather diversified in its properties according to the place, the undisturbed samples used for the experiment were collected widely, as shown in Fig. 1. All of those samples are undisturbed ones which can be made granular in water with fingers.

Index Properties and Uniaxial Strength

The index properties of the samples given in Fig. 1 and their uniaxial compressive and tensile strengths are, as shown in Table 1, in the order of their numbers. In the uniaxial strength test, there appeared invariably a conspicuous peak between strain and stress, whereas in the compressive test there occurred cracks in the vertical direction, causing brittle failure. The authors have confirmed through the Brazilian splitting test that its tensile strength is equivalent to strength according to the direct uniaxial tensile strength test, provided that the ratio of the diameter of sample to its length is 0.5, as the one used in the present experiment.

Characteristics of Uniaxial Compressive and Tensile Strengths

As understood from Fig. 2 which shows the relation between uniaxial compressive or tensile strength and dry density γ_d of sample, σ_t makes a rapid increase when it rises higher than 1.35 g/cu cm and so does

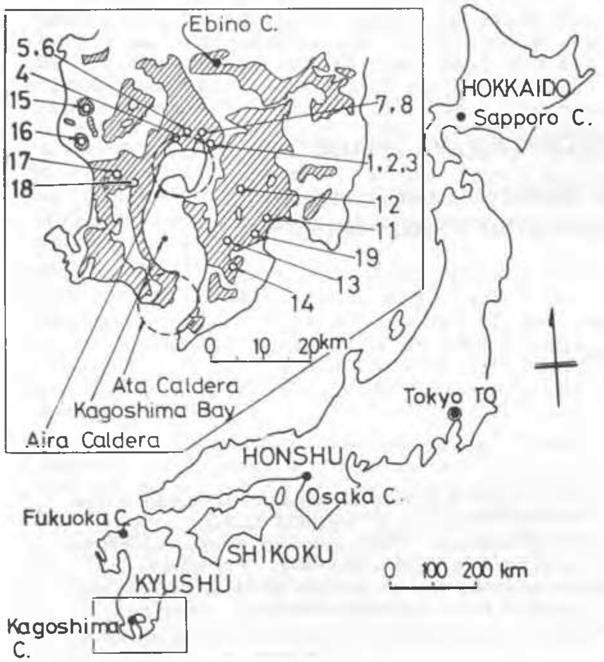

FIG. 1. DISTRIBUTION OF SHIRASU AND SITES OF SAMPLING

uniaxial compressive strength S_c at above 1.25 g/cu cm. As the increase rate of σ_t surpasses the one of S_c. the value of S_c/σ_t has a tendency to decrease with the increase of γ_d, though the tendency shows considerable scattering.

S_c/σ_t value stays between 4 to 10 with average rock, it reaches as high as 30 at the most in the case of Shirasu; The problem of how to seek the factors of classification and identification of undisturbed Shirasu, in connection with the design of cut-off slope of Shirasu, is to be solved in the future, but more attention will have to be paid to tensile strength, therefore brittle failure, instead of restricting many researches to dry density or compressive strength as we have done before.

From the result of investigations made on the relation between moisture content ratio w and S_c or σ_t by using a loose sample No.1, it has been made known that there is an optimum moisture content ratio for strength, as shown in Fig. 3. With a dense sample No. 8, however, there is found no optimum moisture content ratio just as it lacks in an ordinary rock. Since Shirasu has high moisture retention capacity, it seldom gets dry at the field below the moisture content ratio of about 5%. On the other hand, since the saturation moisture content ratio is about 30%, the strength within that moisture content ratio should be taken up for discussing the stability of undisturbed Shirasu.

Triaxial Compressive Strength Test

In the relation between strain and deviator stress according to the triaxial compressive strength test, the larger lateral confining pressure σ_3 is, the more conspicuous the peak appears. The authors have, however, detected that the repeated loading number up to brittle failure under repeated loads suffers little confining pressure, as shown in Fig. 4.

According to Terzaghi (1960), the principal stresses of a rock according to the triaxial compression test are measured by the relation $\sigma_1 = S_c + (N_\phi - 1)\sigma_3$, $N_\phi = tg^2(45^\circ + \phi/2)$, where ϕ is angle of internal friction. Undisturbed Shirasu follows this relation, as shown in Fig. 5. From the figure we can see that undisturbed Shirasu has the properties of a rock.

FAILURE CRITERION FOR UNDISTURBED SHIRASU

Since Shirasu has a small value of S_c/σ_t, if the moisture content ratio is higher than the natural moisture content ratio, its failure is not expressed sufficiently according to the Mohr-Coulomb criterion of shear failure. The authors took three kinds of criteria, such as Griffith, modified Griffith proposed

Table 1. Index Properties and Uniaxial Strength of Undisturbed Shirasu Samples

Sample Number	Natural Moisture Content Ratio w(%)	Specific Gravity of Particle G_s	Void Ratio e	Dry Density $\gamma_d(g/cm^3)$	Uniaxial Compressive Strength $S_c(kg/cm^2)$	Tensile Strength σ_t (kg/cm^2)	S_c/σ_t Value
1	18.5-20.2	2.546	0.850	1.376	3.41	0.16	21.3
2	21.4	2.584	0.758	1.470	6.75	0.85	7.9
3	22.0	2.580	0.843	1.400	2.05	0.070	29.3
4	24.1	2.446	0.839	1.330	4.94	1.00	4.9
5	29.0	2.457	1.207	1.113	0.33	0.04	7.5
6	33.6	2.459	0.970	1.248	0.76	0.063	12.1
7	19.4	2.522	0.693	1.490	8.64	1.90	4.5
8	19.0	2.522	0.702	1.482	7.71	1.75	4.4
11	7.7	2.386	1.077	1.149	0.90	0.044	20.2
12	30.0	2.545	1.471	1.030	0.76	0.026	29.4
13	13.8-16.3	2.456	1.285	1.075	0.72	0.035	20.7
14	24.6	2.089	1.100	0.995	1.22	0.048	25.4
15	24.1	2.473	1.252	1.098	0.91	0.045	20.3
16	19.1	2.418	0.910	1.266	0.92	0.043	21.0
17	21.0	2.461	1.300	1.071	0.50	0.037	13.7
18	22.0	2.454	1.283	1.075	0.63	0.044	14.4
19	22.4	2.421	1.187	1.107	1.15	0.058	20.0

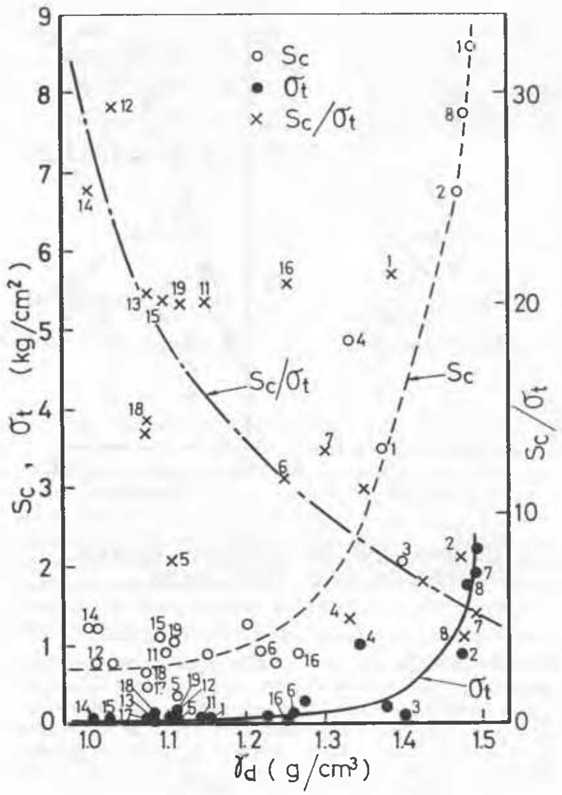

FIG. 2. RELATION BETWEEN DRY DENSITY AND UNIAXIAL COMPRESSIVE OR TENSILE STRENGTH

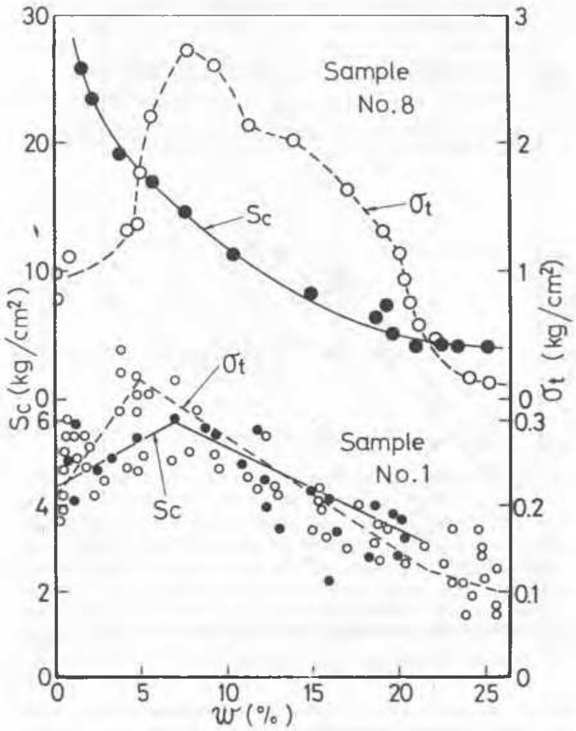

FIG. 3. RELATION BETWEEN MOISTURE CONTENT RATIO AND UNIAXIAL COMPRESSIVE OR TENSILE STRENGTH

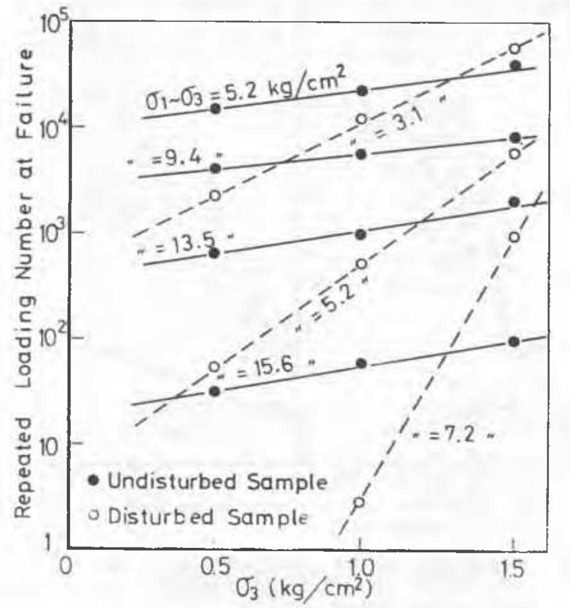

FIG. 4. RELATION BETWEEN CONFINING PRESSURE AND LOADING NUMBER AT FAILURE UNDER REPEATED LOADS

by McClintock and Walsh and Coulomb-Navier, to find out which of them is most adaptable to undisturbed Shirasu, as stated below.

Griffith and Modified Griffith Criteria of Failure

As it is known well, Griffith assumes in his criterion of tensile failure that tensile failure is started by the largest tensile stress generated at the edge of the largest crack, which turns to the most dangerous direction among the cracks and which are brought forth by principal stresses σ_1 and σ_3. Under such a stress condition of $\sigma_1 + 3\sigma_3 > 0$ as triaxial compressive test, failure is assumed to begin under the following condition.

$$(\sigma_1 - \sigma_3) + 8\,\sigma_t\,(\sigma_1 + \sigma_3) = 0$$

The authors investigated the adaptability of the above given criterion using the relation of σ_1/σ_t versus σ_3/σ_t, as shown in Fig. 6, and found it absolutely inappropriate.

Now let us turn to the following criterion which was modified by McClintock and Walsh (1962), with S_t as uniaxial tensile strength.

$$\mu_f\,(\sigma_1 + \sigma_3 - 2\sigma_o) + (\sigma_1 - \sigma_3)(1 + \mu_f^2)^{1/2} = -4S_t\,(1 - \sigma_o/\sigma_t)^{1/2}$$

where, μ_f: coefficient of friction on the surface of crack, σ_o: stress which is necessary for letting crack close and which corresponds to $A\,\sigma_o$ with A as contact area. As a result, this criterion is found

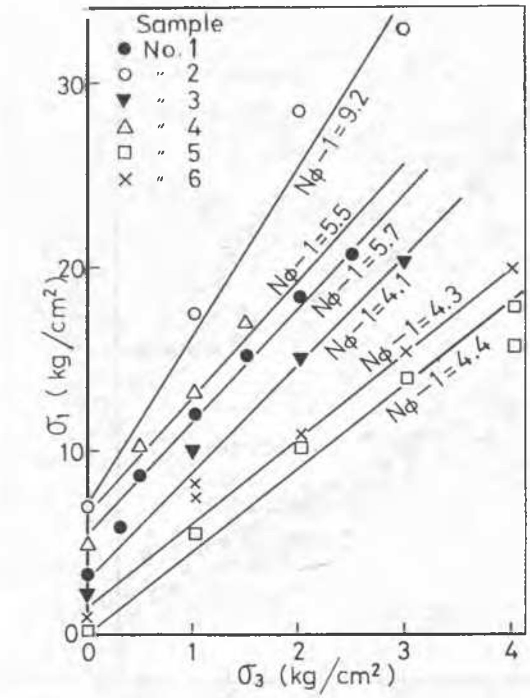

FIG. 5. RELATION BETWEEN PRINCIPAL STRESSES IN TRIAXIAL COMPRESSIVE TEST

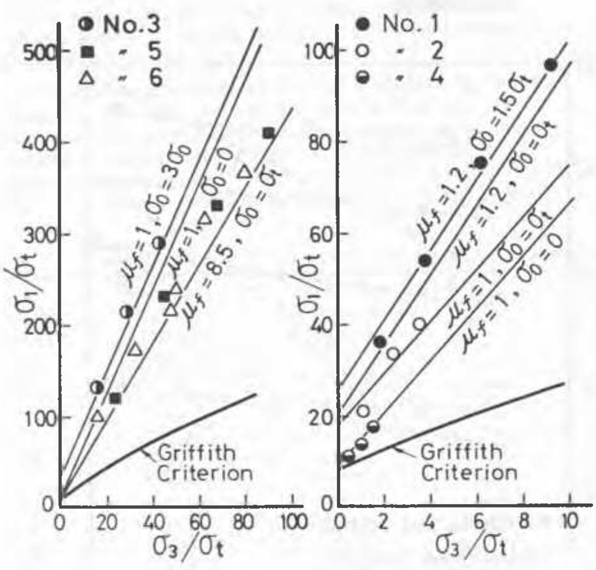

FIG. 6. COMPARISON OF ADAPTABILITY OF CRITERIA OF GRIFFITH AND MODIFIED GRIFFITH

to conform with the modified Griffith criterion by selecting the values of μ_f and σ_o, as shown in Fig. 6.

Coulomb-Navier Criterion of Failure

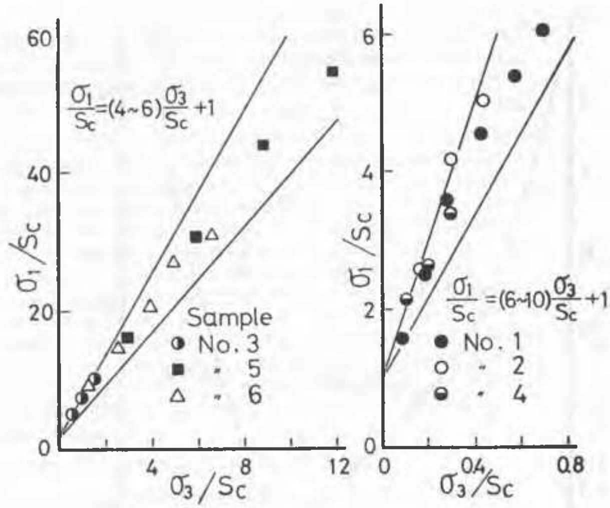

FIG. 7. COMPARISON OF COULOMB-NAVIER CRITERION AND TEST DATA

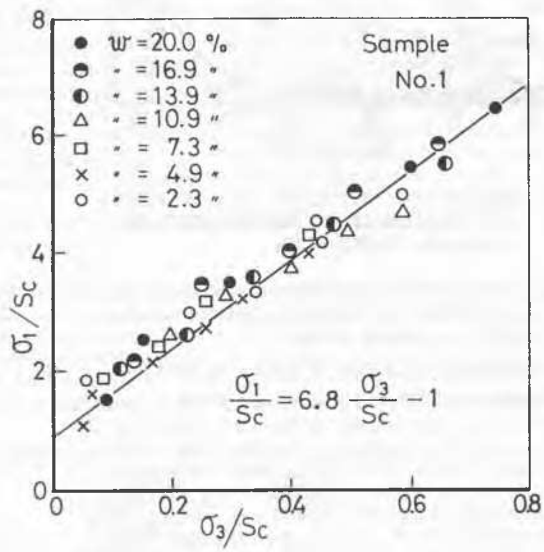

FIG. 8. EFFECT OF MOISTURE CONTENT RATIO ON THE COULOMB-NAVIER CRITERION

This criterion is based on an assumption, as generally known, that, if

$$\tau = S_s + \mu\sigma$$

is made to hold with S_s as shear strength and μ as coefficient of internal friction between shear stress τ and normal stress σ, there will occur shear sliding failure along that surface. Under the stress condition of triaxial compression we get $\sigma_1 = 0$, $\sigma_3 = -\sigma_t$ in the case of tensile failure and $\sigma_1 = S_c$, $\sigma_3 = 0$ in the case of compressive failure. Hence

$$S_c/\sigma_t = [-\mu + (\mu^2+1)^{1/2}]/[\mu + (\mu^2+1)^{1/2}]$$

and $\sigma_1/S_c = (\sigma_3/S_c)(S_c/\sigma_t) + 1$

Non-Elastic Shirasu

No.	S_c (kg/cm²)	σ_t (kg/cm²)	S_c/σ_t	γ_d (g/cm³)
4	4.94	1.00	4.9	1.330
7	8.64	1.90	4.5	1.490
8	7.71	1.75	4.4	1.482

Semi-Elastic Shirasu

No.	S_c (kg/cm²)	σ_t (kg/cm²)	S_c/σ_t	γ_d (g/cm³)
2	6.75	0.85	7.9	1.470
5	0.33	0.044	7.5	1.110

Quasi-Elastic Shirasu

No.	S_c (kg/cm²)	σ_t (kg/cm²)	S_c/σ_t	γ_d (g/cm³)
6	0.76	0.063	12.1	1.248
17	0.50	0.037	13.7	1.071

Plastic Shirasu

No.	S_c (kg/cm²)	σ_t (kg/cm²)	S_c/σ_t	γ_d (g/cm³)
1	3.41	0.16	21.3	1.376
3	2.05	0.07	29.3	1.400
11~16				

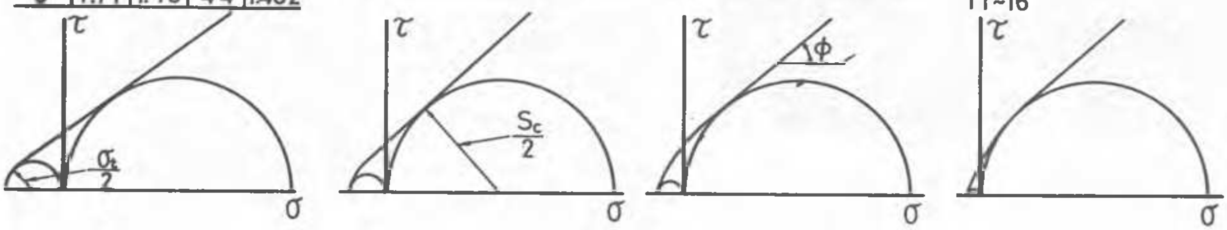

FIG. 9. CLASSIFICATION OF UNDISTURBED SHIRASU AFTER FARMER'S METHOD

Through a comparison made on undisturbed Shirasu, in the relation of σ_1/S_c versus σ_3/S_c, with this criterion, it was found to conform with S_c/σ_t as parameter and according to the kind of Shirasu, as shown in Fig. 7. When the sample No. 1 among those samples was checked on the similar relation, it was found to be independent of the change of moisture content ratio, as shown in Fig. 8.

Furthermore, when elastic and non-elastic classification of the materials were carried out on undisturbed Shirasu after Farmer's method (1968) and using the value of μ, it was disclosed that they almost belong to one of those four kinds, as shown in Fig. 9. This method therefore makes it possible to enable classification and identification of undisturbed Shirasu by its brittle properties.

EXAMPLES OF BRITTLE FAILURE IN CUT-OFF SLOPE

Some examples of brittle failure that occur on the cut-off slopes of Shirasu which are common in Shirasu-distributed area are introduced here with considerations on their causes.

There occurred brittle failure in various places at the time of 1968 Ebino earthquakes (Yamanouchi, et al., 1970) and one of them was such failure as accompanying cracks near slope toe, as shown in Fig. 10 and other was followed by random occurrence of long cracks which appeared on the cut-off surface of the slope. The actual state of things with these failures are that brittle failure of undisturbed Shirasu is apparently subject only to deviator stress under the same repeated loading number, as stated before, independently of the effect from confining stress.

Next consideration is directed to the cause of brittle failure in the slope by the effect of rainfall, that is, the increase in the moisture content in Shirasu. The failure of cut-off slope takes place more often at the slope than any other place, which is considered to be resulted from the repeated loading of perpendicular effective stress upon the base of slope for a few years after natural slope has been cut off in a steep gradient, as shown in Fig. 11, and consequently, there is caused horizontal tensile stress acting upon the part

FIG. 10. AN EXAMPLE OF BRITTLE FAILURE IN CUT-OFF SLOPE

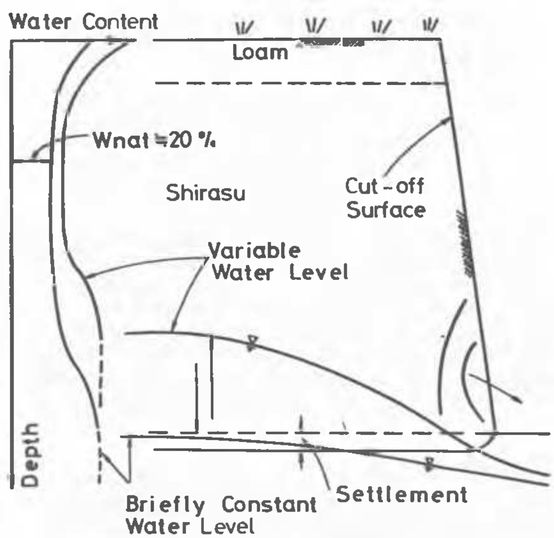

FIG. 11. AN EXPLANATORY SKETCH OF BRITTLE FAILURE AT THE TOE OF CUT-OFF SLOPE

FIG. 12. AN EXAMPLE OF BRITTLE FAILURE AT THE TOE OF CUT-OFF SLOPE

around the slope toe. Since the moisture content at this time is high, tensile strength is reduced, making it easy for cracking, as exemplified in Fig. 12. The failure is considered to be resulted by the effect of the onion structure, which is supposed to be formed in Shirasu deposit according to the authors' view. It is often the case with failure of cut-off slopes which actually occur after rain, that is seldom found in the condition other than that of erosion failure ultimately, even when brittle failure has taken place. When the slope toe has been scored by running water, splash water or artificially, there appears typical brittle failure on the part above it.

CONCLUSIONS

After uniaxial compressive and tensile strength tests as well as triaxial compressive test were carried out on undisturbed Shirasu samples from the places of wide area, the authors obtained the following results.

1) It has been made clear that undisturbed Shirasu is a material to be treated from the viewpoint of brittle failure instead of treating it only from the view of shear sliding failure, as done formerly, and that the criterion of the failure of it conforms with both the criteria of modified Griffith by McClintock and Walsh and Coulomb-Navier.

2) It has been made known that there is a close relation between undisturbed Shirasu and brittle failure within the range of the moisture content to be considered, that is, in the range of 5 to 30%. Standing on that viewpoint, we can explain the failures which actually take place on the cut-off steep slopes.

3) Hitherto there was no sufficient methods of classification and identification of undisturbed Shirasu in connection with the stability of cut-off steep slopes of Shirasu, but we have a prospect to be able to establish a method to perform it from the viewpoint of brittle failure. Especially, the envelop in τ versus σ under Coulomb-Navier criterion which depends upon Farmer's method will answer the purpose for the moment.

REFERENCES

FARMER,I.W. (1968), "Engineering properties of rocks", E. & F.N. Spon Ltd., London, Chapter 5.

MCCLINTOCK, F.A. and WALSH,J.B. (1962), "Friction on Griffith cracks in rock under pressure", Proceedings of the Fourth Congress on Applied Mechanics", Berkeley, Vol. II, pp.1015-1021.

TERZAGHI,K. (1960), "Stress condition for the failure of saturated concrete and rock", Proceedings of the ASTM, Vol. I, pp. 771-801.

YAMANOUCHI,T. and HARUYAMA,M. (1969), "Shear characteristics of such granular soil as Shirasu", Memoirs of Faculty of Engr., Kyushu University, Vol. 29, No. 1, pp. 53-64.

YAMANOUCHI,T., TANEDA,S. and KIMURA,T. (1970), "Damage features in Ebino earthquakes from the viewpoint of soil engineering", Soils and Foundations, Vol. 10, No. 2, pp. 129-144.

YAMANOUCHI,T. (1972), "Damage features of "Shirasu" and their causes and countermeasure", Preprint, The Third Southeast Asia Conference on Soil Engr., Hong Kong.