조립토와 건설재료(steel)사이의 동마찰계수
Dynamic Interface Friction Behavior Between Soils and Construction Material(Steel)

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개요: 지진등에 의해 유발된 동 하중에 의한 지반-구조물 계의 응답은 지반-구조물사이의 경계에서의 마찰특성과 미끄러짐에 의해 크게 영향을 받게 된다. 본 논문에서는 진동대(Shaking table)를 이용하여 조립토와 건설재료(steel)의 경계에서 지반으로부터 지중구조물에 전달되는 전단응력의 전달정도를 파악하기 위한 실험을 실시하였다. 본 실험에서 설정한 미끌어짐속도 범위내에서는 미끄러짐속도 변화에 따른 조립토와 건설재료(steel)사이의 동마찰계수의 변화가 작다는 사실이 관찰되었다. 그리고 조립토의 평균유효입경의 변화가 동마찰계수에 미치는 영향도 함께 조사되었다. 또한 이 동마찰계수를 같은 조립토에 대한 평면변형률시험을 통해 얻어진 최대내부마찰각으로부터 구한 마찰계수와 비교하여 정량화하였다.

주요어 : 지진, 동마찰계수, 미끄러짐속도, 진동대

1. INTRODUCTION

Intense earthquakes in recent years have left many sliding traces on underground structures, including water conduits, tunnels, and other facilities, which are usually made of steel and concrete. Discussion of the sliding and separation on the soil-structure interface is very important in understanding shear stress transfer from the soil to the structure.

Many numerical approaches to model sliding between soils and construction materials have used Mohr-Coulomb hypothesis to explain the sliding phenomena. The necessary parameters in determining the failure envelope are cohesion, friction angle, and normal stress. For the friction angle of the hypothesis, many approaches have used not the interface friction angles between the soils and construction material but the internal friction angles of the soils. In order to understand the properties of interface frictions between the soils and construction material, the surface roughness of the construction material and the size and the shape of soil particles etc. must be taken into account. Also, it is necessary to investigate whether or not the interface friction angles can be assumed as constant values, irrespective of the different levels of interface sliding velocities.

There have been numerous attempts to obtain static friction coefficients between soils and construction material. Potyondy (1961) proposed expressing skin friction between various soils and construction material in a form similar to the Coulomb failure envelope for soils. Yoshimi and Kishida (1981) showed that the frictional resistance between soils and metal surfaces is primarily governed by the roughness of the steel surface, irrespective of the density of the sand. Rabbat and Russell (1985) conducted an experiment to determine the static friction coefficients between a rolled steel plate and cast-in place concrete or grout. They recommended that the coefficient of static friction for concrete cast on a steel plate and grout cast below the steel plate should be taken as 0.65 for a wet interface and 0.57 for a dry one. The interface strengths can be obtained using one of a number of tests, including the direct shear test, the simple shear test, and the torsion or ring shear test. Kishida and Uesugi (1987) summarized the advantages and disadvantages of each method. O'Rourke (1990) developed a general model for sand-polymer interface frictional resistance, in which the ratio of the interface angle of friction and the direct shear angle of soil was related to the Shore D hardness. Frost and Han (1999) performed an experimental study to quantify the interface behavior between fiber-reinforced polymer composites and granular materials.

In addition, efforts to understand the dynamic interface friction properties of geomembranes and geotextiles were given by Yegian and Lahlaf. (1992). They observed that there is a limited shear stress to transmit from one geosynthetic to another. Marone (1998) reviewed rate- and state-dependent friction laws to apply them to seismic faulting.

However, few attempts have been made to investigate dynamic interface friction behaviors between soils and construction material (steel). The purpose of this paper is to look over experimentally dynamic interface friction behaviors between soils and construction material (steel).

2. SELECTION OF VARIABLES

To obtain experimentally the dynamic interface friction behavior between dry soils and construction material (steel), 21 cases of dynamic direct shear tests were performed between soils and steel plates. The parameters for these tests are as follows:

1) Three different levels of maximum sliding velocities (2,15,154mm/sec)
2) Three soils having different mean grain sizes: Toyoura sand, Ticino sand, and Hime gravel
3) Three different levels of normal stress (13.5,45,75kPa)

Considering that Newmarks calculation (1965) overestimates the permanent displacement, the above ranges of the maximum sliding amplitude and velocity for this experiment are evaluated not to be so exorbitant. Normal stresses of 13.5, 45, and 75kPa were applied over the range of soil overburden pressures from the surface to a depth of 5m.

3. TESTING EQUIPMENT

The steel plates were put on an H-beam that was fixed on to the shaking table. **Fig. 1** shows a front view of the testing set-up. Two load cells, which are fixed on the aluminum plate attached to a box-type frame anchor, having the same capacity of 25kgf measured shear reactions at the left and right wings of the ring. Two hinges in front of the load cell could minimize the rotational moment caused by movement of the ring.

Two accelerometers were placed on the H-beam to measure the horizontal and vertical accelerations of the plates. Mechanical and laser displacement sensors, with a minimum resolution of 0.01mm, were used to measure shaking table movement and the volume change of the soil specimen during shear.

The devised direct shear box was ring-shaped, 40mm high, 10mm thick, and had an inner diameter of 90mm. A disk cap 20mm high was used to cover the soil specimen. **Fig. 2** shows the cap and the ring.

4. PROPERTIES OF THE SOILS AND CONSTRUCTION MATERIAL

4.1 Soils

Three kinds of soils were used in the test, and the properties of the soils are shown in **Table 1**. Toyoura sand (D50: 0.2mm), which is frequently used in Japan as a standard sand, is rich in quartz. To check the influence of different grain sizes on the dynamic interface friction, Ticino sand (D50: 0.5mm) and Hime gravel (D50: 2mm) were also chosen for the test. **Figs. 3(a)** and **(b)** show the microscopic images and grain size distribution curves of the soils. Dense specimens, which have a relative density of 95%, were made to obtain the maximum interface friction coefficient that can transfer the maximum interface shear stress from the soil to the structures.

4.2 Construction Material(Steel)

The steel plates (21 pieces), as shown in **Fig. 4**, were cut from a sheet of general rolled construction steel (SS40) for construction purposes into a rectangular shape. Its specified size is 300mm length, 140mm width, and 10mm thickness.

The surface profile was measured by means of a laser displacement sensor with $1\mu m$ spot diameter. The surface roughness along the traverse length with respect to the shearing direction of the steel plates was measured at 8 locations. **Fig.5** is typical examples of the surface roughness profile of the steel plates.

The surface roughness was described in terms of maximum height $R_{max,gage\ length}$, defined as the relative height between the highest peak and the lowest trough along the surface profile over a specified gage length. **Table 2** shows the ranges of the surface roughness of the steel plates. Maximum heights $R_{max,gage\ length}$ are measured with respect to two gage lengths, *2.5mm* and *12mm*. The surface roughness of the steel plates ranged from 20 to 40 μm for $R_{max,2.5}$ and from 30 to 50 μm for $R_{max,12}$. The gage length of 12mm was determined as six times of D50 of Hime gravel (=2mm). For reference, the usual ranges in $R_{max,2.5}$ are 10 to 20 μm for steel, according to Esashi et al.(1996)

5. TEST METHODS AND PROCEDURES

5.1 Test Method

The method taken in the course of this test was, in principle, similar to direct shear testing except that a shaking table was used as an actuator to apply shear forces to the interface between soils and construction material. **Fig. 6** shows a schematic diagram of the dynamic direct shear test using a shaking table.

The motion of the shaking table activated relative sliding displacement between the soils and the construction materials, while the ring containing the soil specimen was stationary. This method could minimize inertial forces occurring from the movement of the ring. Also, the interface area didnt change with increase in sliding displacement.

As input motions of the shaking table, sinusoidal waves with amplitude of 10mm were used. The maximum sliding velocities were 2, 15, and 154mm/sec, respectively, as shown in **Fig. 7**.

5.2 Test Procedures

The following preparations were made before each test:

1) The steel plate to be tested was put on the H-beam.
2) Four sheets of thin plastic paper 0.1mm thick were placed on the plate as spacers to keep necessary clearance between the ring and the plates.

3) A ring was put on the sheets and linked to the load cell using long steel rods.
4) Soils were air pluviated from a height of 5cm and leveled out.
5) The soil specimen was covered up with a cap.
6) Continuous and steady taps with a wooden hammer were given to the soil specimen through the cap until it was compacted to the desired relative density of 95%.
7) Guide rails, which are attached to the side of two wings of the ring, were adjusted to move the ring smoothly and steadily without allowing any rotational movement, as shown in **Fig.1**
8) An aluminum rod hanging dead weights was put on the cap of the soil specimen.
9) A displacement sensor was put slightly over the aluminum rod to measure the volume change in the soil specimen during a shear.
10) The surface of the plates was thoroughly cleaned with acetone.
11) The spacers previously inserted between the ring and the plate were pulled out prior to the tests.

6. SHEAR STRESS-SLIDING DISPLACEMENT RELATIONSHIP FOR INTERFACES

The shear stress ratio (SSR) is defined as the ratio of the measured shear stress (τ) to the applied normal stress (σ). The interface friction angle (δ) can be obtained from the SSR, $\tan^{-1}(\tau/\sigma)$, in dry soils. The curves between the SSR and sliding displacement for Toyoura sand, Ticino sand and Hime gravel with the steel plates are shown in **Figs. 8(a), (b)**, and **(c)**, respectively. The obtained hysteresis curves showed post-peak plastic behavior. Even if the peak post-peak strain softening behavior was shown in the high normal stresses (75kPa), because the difference between the peak and residual shear stress ratios was small, only peak shear stress ratio (**PSSR**) was defined as the average value from the bending point to 3mm of sliding displacement. The reason that 3mm was chosen is that the PSSR was most frequently measured at 1-3mm of sliding displacement, which is less than 2-5% of the shear box dimensions in the direct shear test (O'Rourke et al., 1990). **Table 3** summarizes the test results of the PSSR between soils and the steel plates. In **Table 3**, **S** represents the steel plates. **L1**, **L2**, and **L3** indicate the cases of normal load 13.5kPa, 45kPa, and 75kPa, respectively. **V1**, **V2**, and **V3** express the cases of maximum sliding velocity 2, 15, and 154mm/sec, respectively.

The PSSR of Toyoura sand, Ticino sand, and Hime gravel were in the ranges of 0.3~0.5, 0.2-0.3, and 0.2-0.25, respectively. **Fig.9** shows that the average values of the PSSR of Toyoura sand, Ticino sand, and Hime gravel were 0.39 (δ_{peak}=21.3 degrees), 0.25 (δ_{peak}=14.0 degrees), and 0.22 (δ_{peak}=12.4 degrees), respectively. These interface friction angles were about 1/3~1/4 of the peak internal friction angle of the same soils by plane strain compression shown in **Table 4** (Yoshida, 1994).

The effect of dilatancy on the obtained shear stress was also investigated by the measured vertical displacement of the cap of soil specimens. The ratio of the horizontal displacement of the shaking table to the change in height of the soil specimens was less than 3%. This is negligible even if it has an effect of decreasing normal stress.

7. INFLUENCE OF MEAN GRAIN SIZE OF GRANULAR MATERIALS

Fig. 10 shows how the mean diameters of soil particles affect the PSSR between soils and the steel plates. The figure includes all data having different velocities and normal loads excluding the case of **SL3V2**. The figure showed the smaller the soil particles, the bigger the PSSR. Roundness and circularity can affect this result because angular particles are more interlocked and thus more resistant to shear than are rounded particles. However, this finding is consistent with the conclusion of Rowe (1961) that large particles have lower friction angles than small particles with the same mineralogy when a mass of the particles slide on identical rough surfaces. The regression curve and corresponding equation showing the relationship between the PSSR and mean grain size (D50) are obtained.

8. INFLUENCE OF NORMAL STRESS

Fig. 11 shows the PSSR decreases with the increase of normal stress. This means that the relationship between shear stress and normal stress is not linear and the interface friction coefficient decreases with the depth. The small soil particle (Toyoura sand) has a tendency of relatively big decrease of the PSSR with the increase of normal stress.

9. CONCLUSIONS

Dynamic interface friction behavior between soils and construction material was investigated. The following conclusions are drawn from this study:

(1)Dynamic direct shear tests were performed using a newly designed ring-type shear box and a shaking table. In the tests between soils and steel plates, the variation of the PSSR (peak shear stress ratio) for the soils depending on the maximum sliding velocities was small in the velocity range employed in this study.

(2)The PSSR for Toyoura sand, Ticino sand, and Hime gravel with the steel plates were in the ranges of 0.3-0.5, 0.2-0.3, and 0.2-0.25, respectively. The interface friction angles between soils and the steel plates were about 1/3-1/4 of the peak internal friction angle of the same soils by the plane strain compression test.

(3)The smaller the soil particles, the bigger the PSSR. To decrease the transfer of interface shear stress from the soils to the structures, it is desirable that soils having a large mean particle size be used for filling up the excavated area surrounding the structures.

(4)The PSSR decreased with the increase of normal stress. The relationship between shear stress and normal stress was not linear and the interface friction coefficient decreased with the depth. The small soil particle (Toyoura sand) had a tendency of relatively big decrease of the PSSR with the increase of normal stress.

REFERENCES

1. Esashi, Y., Kataoka, T., and Yasuda, M. (1966), Uplift Resistance of Piles: Part 1, Cohesionless Soil, in Report 66037, Central Research Institute of Electric Power Industry, Tokyo, pp.1-60 (in Japanese).

2. Frost, J.D., and Han, J.(1999), Behavior of Interfaces between Fiber-Reinforced Polymers and Sands, Journal of Geotechnical and Geoenvironmental Engineering, Vol.125, No. 8, pp.633-640.

3. Kishida, H., and Uesugi, M. (1987), Tests of the Interface Between Sand and Steel in the Simple Shear Apparatus, *Geotechnique* 37, No. 1, pp. 45-52.

4. Kobayashi, M., Ando, H., Iwasaki, K., and Tatsuoka, F. (1998), Evaluation of Velocity

Effects on axial restraint force acting on Polyethylene coated steel pipes by direct shear tests, *Proceedings of the 33rd Geotechnical Engineering Symposium*, pp.2021-2022 (in Japanese).

5. Marone, C. (1998), Laboratory-derived Friction Laws and Their Application to Seismic Faulting, Annu.Rev., Earth Planet. Sci., pp.643-696.

6. Newmark, N.M. (1965), Effects of Earthquakes on Dams and Embankments, Fifth Rankine Lecture, pp.139-159.

7. O'Rourke, T.D., Druschel S.J., and Netravali A.N. (1990), Shear Strength Characteristics of Sand-Polymer Interfaces, Journal of Geotechnical Engineering, Vol.116, No. 3, pp.451-469.

8. Potyondy, J. G. (1961), Skin Friction Between Various Soils and Construction Materials, *Geotechnique*, Vol.11, No. 4, pp.339-353.

9. Rabbat, B.G., and Russell, H.G. (1985), Friction Coefficient of Steel on Concrete or Grout, Journal of structural engineering, Vol.111, No.3, pp.505-515.

10. Rowe, P.W. (1961), The Stress-dilatancy Relation for Static Equilibrium of an Assembly of Particles in Contact, *Proc., Royal Soc. Of London*, A(269), pp.500-527.

11. Tatsuoka, F., Sakamoto, M., Kawamura, T., and Fukushima, S. (1986), Strength and Deformation Characteristics of Sand in Plane Strain Compression at extremely Low Pressures, Soils and Foundations, Vol.26, No.1, pp.65-84.

12. Yegian, M.K., and Lahlaf, A.M.(1992), Dynamic Interface Shear Strength Properties of Geomembranes and Geotextiles, Journal of Geotechnical Engineering, Vol.118, No.5, pp.760-779.

13. Yoshida, T.(1994), Strain Localization and Shear Banding during Failure of Sands, A dissertation submitted for the degree of doctor of engineering at the graduate school of civil engineering, University of Tokyo (in Japanese).

14. Yoshimi, Y., and Kishida, T. (1981), A Ring Torsion Apparatus for Evaluating Friction Between Soil and Metal Surfaces, Geotechnical Testing Journal, GTJODJ, Vol. 4, No. 4, pp.145-152.

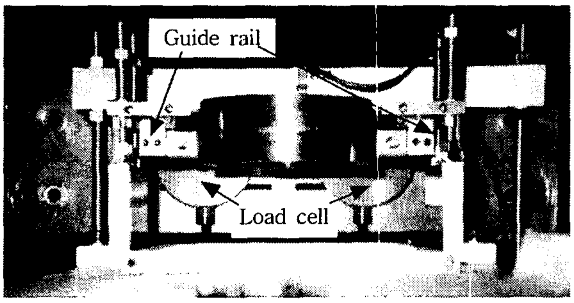

Fig.1 Front view of the testing set-up

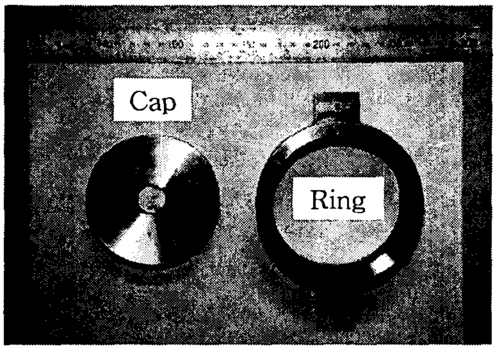

Fig.2 The cap and the ring of the shear box

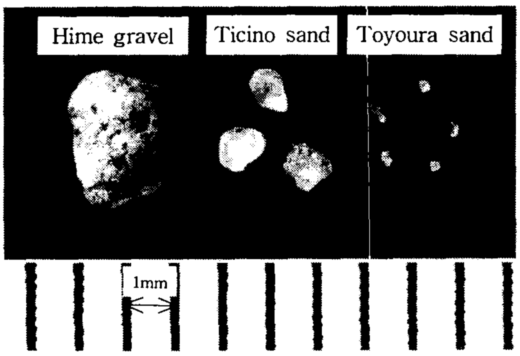

Fig.3(a) Microscopic images of the soils

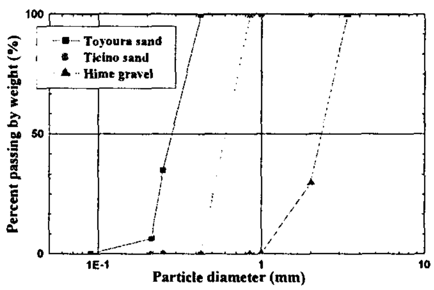

Fig.3(b) Grain size distribution curves of the soils

Fig.4 Steel plate

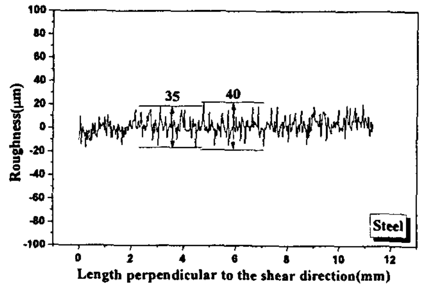

Fig.5 Roughness of steel plate

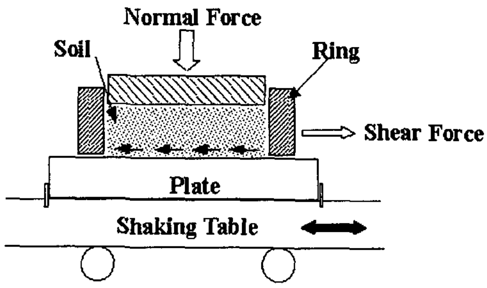

Fig.6 Schematic diagram of the dynamic direct shear test using a shaking table

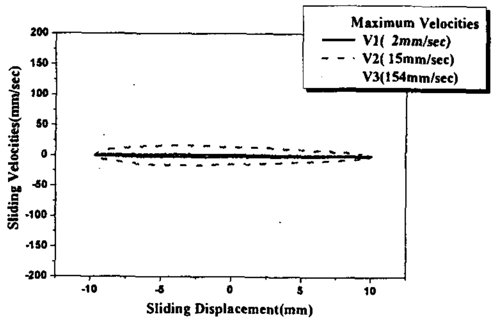

Fig.7 Velocities of input motions

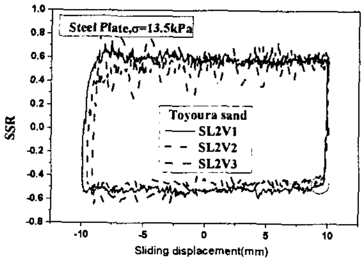

Fig.8(a) SSR versus sliding displacement (Toyoura sand)

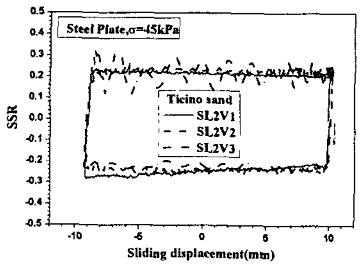

Fig.8(b) SSR versus sliding displacement (Ticino sand)

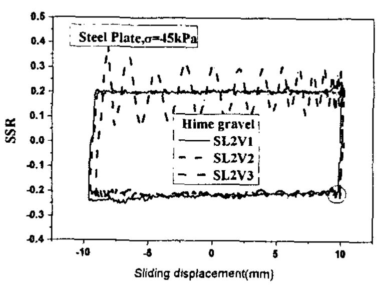

Fig.8(c) SSR versus sliding displacement (Hime gravel)

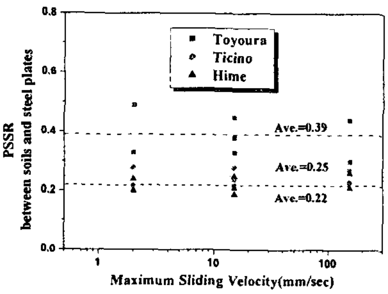

Fig.9 PSSR between soils and steel plates

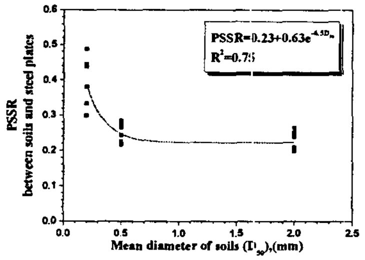

Fig.10 Variation of PSSR with D50 between soils and steel plates

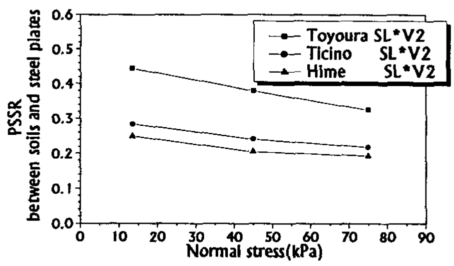

Fig.11 Variation of PSSR with normal stress

Table 1 Properties of soils

Parameter	Soils		
	Toyoura sand	Ticino sand	Hime gravel
D10 (mm)	0.137	0.372	1.50
D50 (mm)	0.206	0.527	2.01
D60 (mm)	0.216	0.564	2.09
Uc	1.58	1.52	1.40
Gs	2.636	2.680	2.650
e_{max}	0.973	0.960	0.633
e_{min}	0.612	0.590	0.514

Uc = uniformity coefficient,
Gs = specific gravity,
e_{max} = void ratio of soil in loosest condition,
e_{min} = void ratio of soil in densest condition

Table 2 Surface roughness of the steel plate

Plate	$R_{max,2.5}$(μm)	$R_{max,12}$(μm)
Steel	20-40	30-50

Table 3 PSSR for steel plates(refer to Fig. 7 for notations V1 through V3)

Specimen	Types of Plates	Sand types / Normal Stresses (kPa)	Toyoura sand	Ticino sand	Hime gravel
			PSSR	PSSR	PSSR
SL1V1	Steel	13.5	0.49	0.28	0.24
SL1V2	Steel	13.5	0.45	0.28	0.25
SL1V3	Steel	13.5	0.44	0.27	0.26
SL2V1	Steel	45	0.33	0.22	0.20
SL2V2	Steel	45	0.38	0.24	0.21
SL2V3	Steel	45	0.30	0.23	0.21
SL3V2	Steel	75	0.33	0.22	0.19

(Note: L1:13.5kPa, L2:45kPa, L3:75kPa, V1:2mm/sec, V2:15mm/sec, and V3:154mm/sec)

Table 4 Peak and residual internal friction angles from the plane strain compression test

Soils	ϕ_{peak}	ϕ_{res}
Toyoura sand	45 ° - 46 °	33 ° - 40 °
Ticino sand	46 ° - 48 °	34 ° - 35 °
Hime gravel	48 ° - 50 °	36 ° - 40 °

(Note: All tests were conducted at relative density of 70%-90% under σ_3 = 80-400 kPa with direction perpendicular to the bedding plane)