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Dynamic Friction Behavior of Interfaces Between Granular Materials and Steel

조립토와 건설재료(steel)사이의 동마찰계수

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요 지

지진 등에 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)와의 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 조사되었으며, 이 동마찰계수를 같은 조립토에 대한 평면변형률시험을 통해 얻어진 최대내부마찰각으로 부터 구한 마찰계수와 비교하여 정량화하였다.

Abstract

The response of a soil-structure system subjected to dynamic loading due to earthquakes is influenced significantly by the characteristics of the interfaces and relative movement such as sliding between the soil and the structure. In this paper, the dynamic direct shear test using shaking table was performed to understand dynamic friction behavior of interfaces between granular materials and steel. It was observed that the variation of dynamic interface frictional coefficients between granular materials and steel was small in the sliding velocity range employed in this study. The influence of the mean grain size of granular materials and normal stresses on the dynamic interface friction coefficients were also investigated, and these coefficients were compared with the peak internal friction angles of the same granular materials through plane strain compression tests.

Keywords : Interface friction, Dynamic direct shear test, Shaking table, Sliding velocity

1. Introduction

Severe 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 and friction angle. For the friction angle, the numerical approaches have not used the interface friction angles between soils and construction materials

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but the internal friction angles of the soils. In order to understand the properties of interface frictional behavior between soils and construction materials, the surface roughness of the construction materials, and the size and the shape of soil particles must be taken into account. In addition, 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 materials. Potyondy (1961) proposed an expression of skin friction between various soils and construction materials 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 frictions for concrete and grout cast on a 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 in various ways such as 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 to 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 frictional properties of geomembranes and geotextiles were given by Yegian and Lahlaf (1992). They observed that there was a limitation in the amount of shear stress transmitted from one geosynthetic to another. Marone (1998) reviewed rate- and state-dependent friction laws applicable to seismic faulting.

However, few attempts have been made to investigate dynamic frictional behavior of interfaces between granular materials and steel. The purpose of this paper is to experimentally look over dynamic frictional behavior of interfaces between granular materials and steel.

2. Test Program

2.1 Selection of Variables

Dynamic direct shear tests of 21 cases were performed to obtain the dynamic frictional behavior of the interfaces. 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 Newmark's calculation (1965) overestimates the permanent displacement of sliding, the above ranges of the maximum sliding velocity for the tests are evaluated not to be so exorbitant. Normal stresses of 13.5, 45, and 75kPa were applied over the range of overburden soil pressures from the surface to a depth of 5m.

2.2 Testing Equipment

The steel plates were put on an H-beam 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 (245 N), measured shear reactions at the

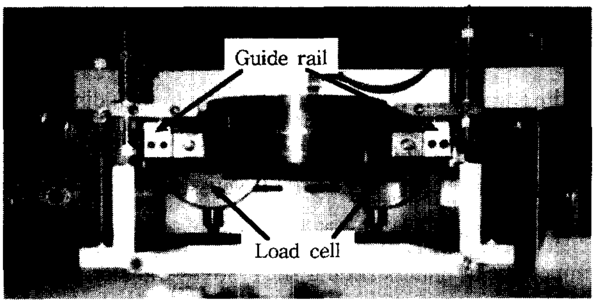


Fig. 1 Front view of the testing set-up

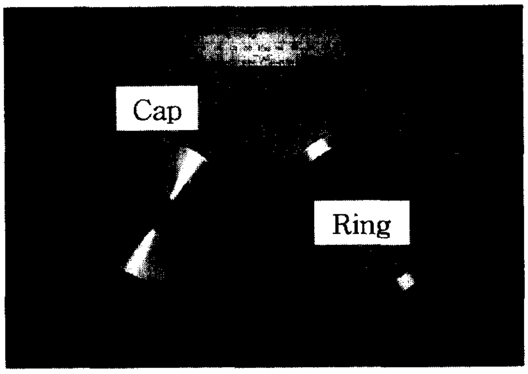


Fig. 2 The cap and the ring of the shear box

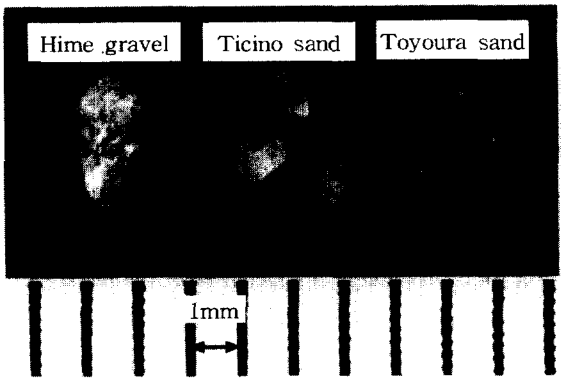


Fig. 3 Microscopic images of the granular materials

left and right wings of the ring. Two hinges were installed in front of the load cell to minimize the rotational moment caused by the 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 direct shear box was ring-shaped, 40mm high, 10mm thick, and had an inner diameter of 90mm. A 20mm-thick disk cap was used to cover the soil specimen, as shown in Fig. 2.

2.3 Properties of Granular Materials and Steel

2.3.1 Granular Materials

Three kinds of granular materials were used and their properties are shown in Table 1. Toyoura sand 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 and Hime gravel were also chosen for the tests. Fig. 3 shows their microscopic images and sizes. Dense specimens with a relative density of 95% were made to obtain the maximum interface friction coefficient that can transfer the maximum interface shear stress from the soils to the structures.

Table 1. Properties of granular materials

Properties	Granular Materials		
	Toyoura sand	Ticino sand	Hime gravel
D_{10} (mm)	0.137	0.372	1.50
D_{50} (mm)	0.206	0.527	2.01
D_{60} (mm)	0.216	0.564	2.09
Cu	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

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

2.3.2 Construction Material(Steel)

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

The surface profile was measured by means of a laser displacement sensor with $1\mu m$ spot diameter. The surface roughness along the transverse length with respect to the shearing direction of the steel plates was measured at 8

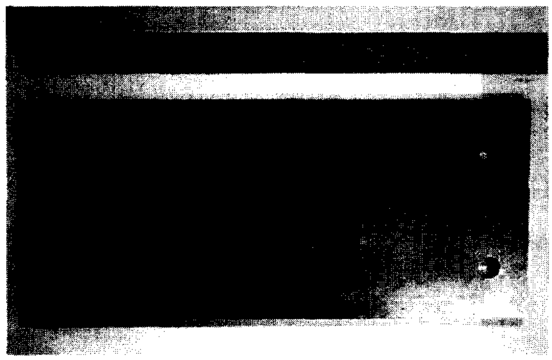


Fig. 4 Steel plate

locations. Typical examples of the surface roughness profile of the steel plates are shown in Fig. 5.

The surface roughness was described in terms of maximum height $R_{max,gagelength}$, 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 $R_{max,gagelength}$ are measured with respect to two gage lengths, 2.5*mm* and 12*mm*. The surface roughness of the steel plates ranges from 20 to 40 μm for $R_{max,2.5}$ and from 30 to 50 μm for $R_{max,12}$. The

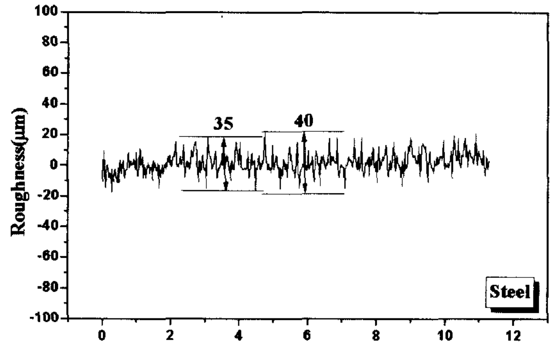


Fig. 5 Roughness of steel plate

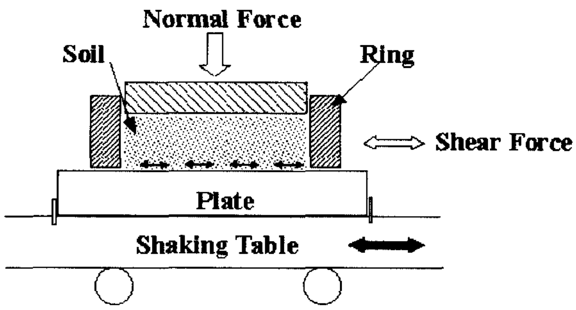


Fig. 6 Schematic diagram of the dynamic direct shear test using a shaking table

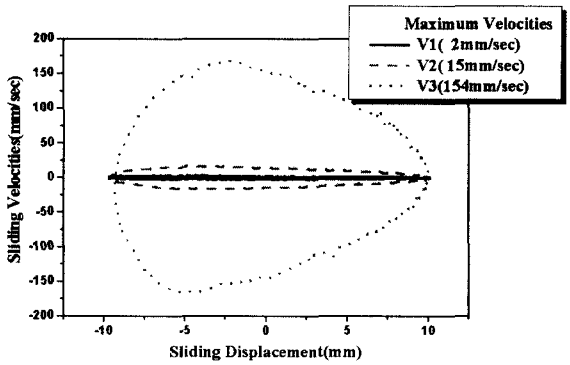


Fig. 7 Velocities of input motions

Table 2. Surface roughness of the steel plate

Gage Lengths	$R_{max,2.5}$(μm)	$R_{max,12}$(μm)
Roughness	20~40	30~50

gage length of 12mm was determined as six times of D_{50} of Hime gravel.

2.4 Test Method and Procedure

2.4.1 Test Method

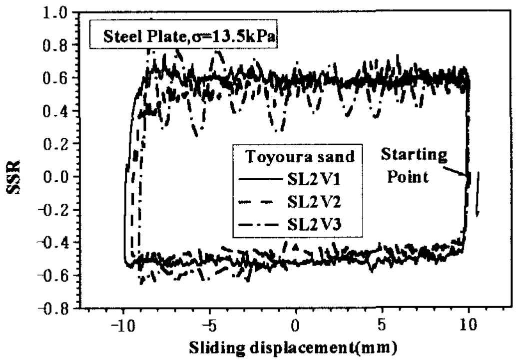
The method taken in the course of this test was, in principle, similar to direct shear testing except that a shaking table was used as an actuator to apply dynamic shear forces to the interfaces between granualr materials and steel. Fig. 6 shows a schematic diagram of the dynamic direct shear test.

The motion of the shaking table activated relative sliding displacement between granular materials and steel, 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 did not change with increase in sliding displacement. Fig. 7 shows the input motions with amplitude of 10mm.

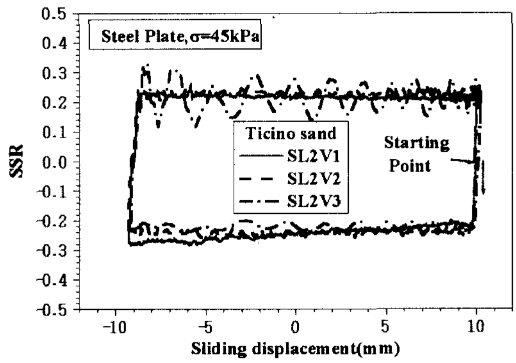
2.4.2 Test Procedure

The following preparations were made before each test:

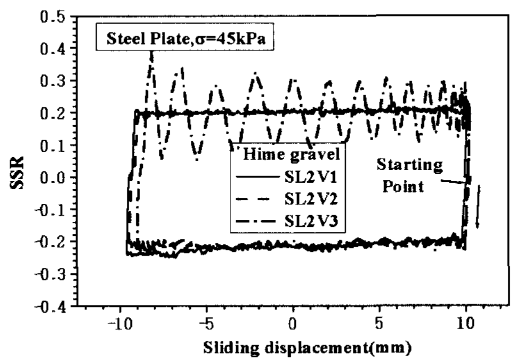
1) The steel plate to be tested was put on the H-beam.
2) Four sheets of thin plastic paper with 0.1mm in thickness were placed on the plate as spacers to keep necessary clearance between the ring and the plate.
3) A ring was put on the sheets and linked to the load cell using two long steel rods having a hinge each.
4) Granular materials were air pluviated from 5cm above the top of the ring and leveled out.
5) The soil specimen was covered up with the cap.
6) Continuous and steady taps with a wooden hammer were given to the soil specimen through the cap to achieve the desired relative density.



(a) Toyoura sand



(b) Ticino sand



(c) Hime gravel

Fig. 8 SSR versus sliding displacement

7) Guide rails, 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 carefully over the aluminum rod to measure the volume change in the soil specimen during a shear.
10) The spacers previously inserted between the ring and the plate were pulled out prior to the test.

3. Discussions of Test Results

3.1 Shear Stress-Sliding Displacement Relationship of 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 steel plates are shown in Figs. 8(a), (b), and (c), respectively. The obtained hysteresis curves showed post-peak plastic behavior in all cases. Even if the post-peak strain softening behavior was observed at the high normal stresses (75kPa), peak shear stress ratio (PSSR) was defined as the average value from the bending point to 3mm of sliding displacement because the difference between the peak and residual shear stress ratios was small. 3mm was chosen due to the fact 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 granular materials and steel plates. In the table, S represents the steel plate. 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. As shown in Fig. 9, the average values of the PSSR of Toyoura sand, Ticino sand, and Hime gravel were found to be 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 1/2 - 1/4 of the peak internal friction angle of the same soils by plane strain compression as shown in Table 4 (Yoshida, 1994). The table shows that the peak internal friction angles from the plane strain compression test are not so much influenced by the relative density.

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

Specimen	Types of Plates	Granular Materials	Toyoura sand	Ticino sand	Hime gravel
		Normal Stresses (kPa)	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)

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

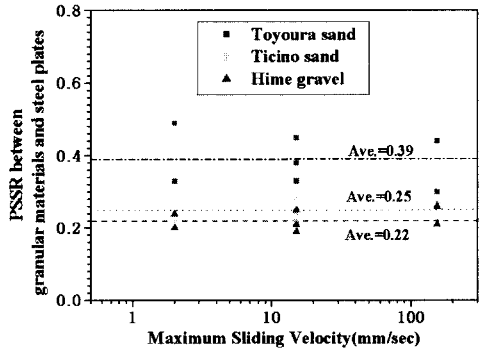


Fig. 9 PSSR between granular materials and steel plates

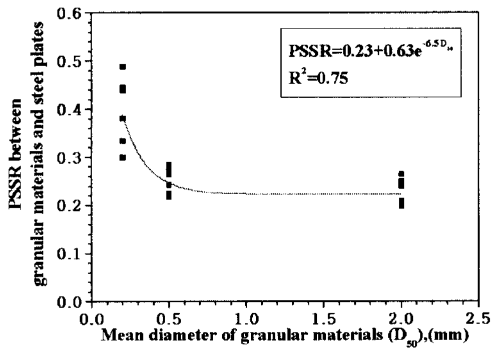


Fig. 10 Variation of PSSR with D_{50} between granular materials and steel plates

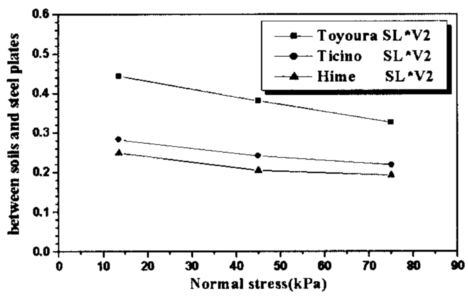


Fig. 11 Variation of PSSR with normal stress

3.2 Influence of Mean Grain Size of Granular Materials

Fig. 10 shows how the mean diameters of soil particles affect the PSSR between granular materials and steel plates. The Fig. 10 includes all the data having different velocities and normal loads except a case of SL3V2. The Fig. 5 shows that the smaller the soil particles are, the bigger the PSSR. Roundness and circularity can affect this result because angular particles are more interlocked and thus more resistant to shear than 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 slides on identical rough surfaces. The regression curve and corresponding equation showing the relationship between the PSSR and mean grain size (D_{50}) are also obtained in the figure.

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

Granular Materials	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)

3.3 Influence of Normal Stress

Fig. 11 shows decrease in PSSR with increasing 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 in PSSR with increasing normal stress.

4. Conclusions

Dynamic frictional behavior of interfaces between granular materials and construction material(steel) was investigated. The following conclusions are drawn:

(1) Dynamic direct shear tests were performed using a newly designed ring-type shear box and a shaking table. The variation of the PSSR (peak shear stress ratio) for the granular materials 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 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 the granular materials and steel plates were about 1/2 - 1/4 of the peak internal friction angle of the same soils by the plane strain compression test.

(3) The smaller the particles of the granular materials are, the bigger the PSSR in the velocity range employed in this study. To decrease the transfer of interface shear stress from the soil to the structure, it is desirable that granular materials having a large mean particle size be used for filling up the excavated area surrounding the structure.

(4) The PSSR decreases with the increasing normal stress. The relationship between shear stress and normal stress was not linear and the interface friction coefficient decreased with the depth. The granular material of small mean diameter had a tendency of relatively big decrease in PSSR with increasing normal stress.

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