INFLUENTIAL FACTORS OF FRICTION BETWEEN STEEL AND DRY SANDS

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ABSTRACT

Series of laboratory tests are carried out on the friction between steel and air-dried sands with a simple shear apparatus. The significance of factors on the frictional coefficient are examined with the use of the experimental design method by orthogonal array table. The influence of sand type (Fujigawa Sand, Fukushima Sand, Toyoura Sand and Glass Beads) and the surface roughness of steel ($R_{\max}=1.5\sim3\mu\text{m}$ and $10\sim15\mu\text{m}$) are found to be significant, while the effects of normal stress (98 kPa and 980 kPa) and mean grain size (0.55~0.62 mm and 0.15~0.19 mm) are of poor significance. The sliding displacement at the contact surface and the displacement due to shear deformation of sand mass were obtained distinctively. The shear deformation of sand mass was found to be unaffected by the surface roughness of the steel.

Key words : friction, grain size, laboratory test, particle breakage, sand, shear strength, statistical analysis, steel, test equipment (IGC : D 6)

INTRODUCTION

In soil-structure interaction problems, it often becomes important to make a good estimation of frictional resistance between ground and foundation. Among a number of studies on friction between soils and construction materials, there are some on the friction between sand and steel. Based on the extensive experimentation, Potyondy (1961) proposed to express the skin friction resistance in a similar form to that of the Coulomb failure envelope as a sum of the adhesion and the normal stress dependent

component. In a study on the uplift capacity of piles, Esashi et al. (1966) showed that skin friction coefficient between sand and construction materials, such as steel, concrete and wood, could be a function of the quantified surface roughness.

While direct shear apparatus were used in the above mentioned studies, Yoshimi et al. (1981) used a ring torsion apparatus to overcome the disadvantages of direct shear apparatus. It was found that the quantified roughness of the metal surface could be correlated with the frictional coefficient, irrespective of the sand density.

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In all the references cited previously, the significance of each influential factors on the frictional coefficient was examined independently. By these studies, it is impossible to determine whether the same effect of a factor would be preserved when the other factors changed.

With what is called minimum energy concept, the frictional coefficient could be upper-bounded by the shear strength of the sand (Uesugi et al., 1984). The results of the experiments with a ring torsion apparatus (Yoshimi et al., 1981), however, did not show upper-bounded characteristics of frictional coefficient even with a very rough steel surface.

The object of the present paper is to study the significance of multiple influential factors on the frictional coefficient between steel and dry sands as well as the upper-bounding value of the coefficient. A simple shear type apparatus is used for the experiments. With this apparatus, the sliding displacement at the sand-steel contact surface can be obtained in distinction from the displacement due to the shear deformation of sand mass.

EXPERIMENT

Figs. 1 and 2 show the simple shear type apparatus for this study. The contact surface between steel and sand is 400 mm in length and 100 mm in breadth. The contact area remains constant during the test even if sliding occurs, since the steel specimen is longer than the contact surface. Normal and tangential loads are applied by the vertical and horizontal hydraulic cylinders with steel bars. The container of sand specimen is a stack of rectangular 2 mm thick aluminium plates with 400 mm $\times$ 100 mm square space in the middle. The surface of each ring was lubricated to allow the container to follow the shearing deformation of sand with minimum friction resistance.

The applied normal load is determined by the calibrated tensile strain of steel bars (accuracy : 0.0673 kN/digit) and kept constant during the operation. The tangential

Fig. 1. Simple shear type friction test apparatus

Fig. 2. Detail of the apparatus

load is measured by a strain gage type load transducer (accuracy : 0.0245 kN/digit). Based on a preliminary calibration, the tangential load was corrected for the frictional resistance by the lubricated teflon plates supporting the steel specimen

The displacement of the steel specimen δ_a is measured with a displacement transducer of 0.005 mm/digit accuracy. The displacements of the aluminium plates (δ_b and δ_c) are measured independently (accuracy : 0.002 mm/digit). The sliding displacement (δ_1 in Fig. 3) is obtained as the difference between δ_a and δ_b , i.e. $\delta_1 = \delta_a - \delta_b$. The displacement due to the shear deformation

Fig. 3. Components of total displacement

of sand mass (δ_2 in Fig.3) is obtained as the difference between δ_b and δ_c , i.e. $\delta_2 = \delta_b - \delta_c$. Total displacement is obtained as the sum of the sliding displacement (δ_1) and the displacement due to the shear deformation of the sand mass (δ_2), i.e. $\delta_1 + \delta_2$. In most of all the previous researches, there was no distinction between the sliding displacement (δ_1) and the displacement due to the shear deformation of sand mass (δ_2), but only the total displacement ($\delta_1 + \delta_2$) has been provided. The vertical displacements of the loading plate δ_d and δ_e in Fig.2 are measured with displacement transducers (accuracy : 0.002 mm/digit). The change of the sand height was obtained as the average of these vertical displacements, i.e. $(\delta_d + \delta_e)/2$.

The experimental design method with the use of orthogonal arrays was used in order to evaluate the significance of multiple influential factors (Taguchi, 1977). Based on previous reports, four factors shown in Table 1 were considered as possibly influential. Among the sands used, Fujigawa Sand has rather angular particles, while a Glass Bead has virtually spherical particles. Toyoura Sand and Fukushima Sand have particles of intermediate angularity. Toyoura Sand is a quartz-rich sand, and Fukushima Sand contains other minerals such as Feldspar and Hornblende as well. Mean grain diameters were specified so as to be classified as fine or medium sands. The surface roughness

Table 1. Considered factors and their values

Factor	Values	
Sand Type	Toyouura Sand Fukushima Sand	Fujigawa Sand Glass Beads
Mean Grain Size D_{50}	0.55~0.62 mm	0.15~0.19 mm
Surface Roughness of steel $R_{max}(L=0.2\text{ m})$	1.5~3 μm	10~15 μm
Normal Stress	98 kPa (1 kgf/cm ²)	980 kPa (10 kgf/cm ²)

Notes :

D_{50} ; Diameter at which 50% of the sand is finer.

R_{max} ; Surface roughness in terms of a maximum height (Yoshimi et al., 1981) with gage length $L=0.2\text{ mm}$ (Yajima et al., 1984.)

Fig. 4. Example of surface roughness

of steel was quantified as a maximum height R_{max} (Yoshimi et al., 1981). They employed the gage length $L=2.5\text{ mm}$, over which the maximum height, R_{max} , was measured. In the present paper, however, the gage length was modified to 0.2 mm considering the average diameter of Toyoura Sand (Yajima et al., 1984). Fig.4 shows an example of magnified record of surface profile. R_{max} is obtained as the average of the maximum height h_i . The values of steel surface roughness covers reasonable range, since the surface roughness in R_{max} of a steel pipe pile driven into sand deposit are some 5 to 20 μm (Sumikin Weld Pipe Co. Ltd., 1983). The normal stress 98 to 980 kPa (1 to 10 kgf/cm²) covers reasonably sufficient range for ground- foundation contact surface.

Table 2 shows the properties of sands. The air-dried sands are sieved so that mean grain size, D_{50} , become some 0.2 mm or 0.6 mm and uniformity coefficient U_c less than 2. The grain size distribution of the

Table 2. Properties of sands

Sand Type	Mean Grain Size D_{50} (mm)	Specific Gravity G_s	Max. Unit Weight γ_{dmax} (kN/m ³)	Min. Unit Weight γ_{dmin} (kN/m ³)	Uniformity Coefficient U_c
Fujigawa	0.60	2.71	15.4	12.6	1.31
	0.17	2.74	15.7	12.2	1.58
Fukushima	0.56	2.66	15.3	12.7	1.34
	0.19	2.79	15.9	12.3	1.58
Glass Beads	0.62	2.49	15.4	14.4	1.37
	0.15	2.49	15.7	14.1	1.21
Toyoura	0.19	2.64	16.2	13.0	1.29

Fig. 5. Grain size distribution curves

sands are shown in Fig. 5. The sand was air-pulvitated with a multiple sieve sand rain-er so as to make a uniform sand specimen of some 90% relative density.

Low-carbon structural steel was machined to make a specimen in a rectangular plate with the base of 500 mm $\times$ 150 mm and 40 mm in thickness. The upper surface of steel plate was filed and polished by lapping on fine emery cloth to make its R_{max} ($L=0.2$ mm) less than 1 μ m. For the tests of steel surface roughness larger than 5 μ m of R_{max} ($L=0.2$ mm), it was filed in the normal direction to the shear load. For the tests of steel surface roughness smaller than 5 μ m of R_{max} ($L=0.2$ mm), it was sandpapered in the normal direction to the shear load. The roughness of each steel surface was measured in the direction in which shear load would be applied. The finished metal surface was thoroughly cleaned with acetone before each friction test.

All of the 57 tests used in the present paper are listed in Appendix A. The 26 tests of Series A in Table A-1 were carried

out mostly for the variance analyses of influential factors by experimental design method (Taguchi, 1977). The influence of the surface roughness of steel are examined further with the 12 tests results of Series B in Table A-2. The 19 tests of Series C in Table A-3 were conducted to study the effects of high normal stress of the steel-sand interface.

TYPICAL TEST RESULTS

Fig. 6 shows the typical shear stress ratios and volumetric strains as functions of total displacement of the experiments with dense Toyoura Sand. The shear stress ratio is defined as the tangential stress divided by the normal stress (τ/σ_n). The total displacement is the sum of the sliding displacement (δ_1 in Fig. 3) and the displacement due to the shear deformation of sand mass

Fig. 6. Behavior of friction between steel and Toyoura Sand (Test No. B-1, 5, 6, 9 ; See Appendix A)

(δ_2 in Fig.3). Since the sand mass was restrained by the stack of layered rectangular aluminium plates, the horizontal sectional area was kept constant. Then, the volume strain was obtained as the change of sand height divided by its initial height.

Between the origin and yield points, which is defined in Appendix B, all the shear stress lines seems to follow the same line. After passing through the yield points, the shear stress ratios tend to decrease with the increase of total displacement. The shear stress ratio seems to approach gradually to a certain value for each surface roughness.

Examples of the transition of the total displacement components are shown in Fig.7. These are the test results with Toyoura Sand. The displacement due to the shearing deformation of sand mass (δ_2 in Fig.3) exceeds the sliding displacement along the contact surface (δ_1 in Fig.3) before the yielding, while the sliding displacement would become larger than the displacement due to the shearing deformation after the yielding. The test results using other sands showed the same tendency.

Fig.8 shows the schematic diagrams of the transition of total displacement compo-

Fig. 7. Transition of displacement components (Toyourea Sand) (Test No. C-3, 14, ; See Appendix A)

Fig. 8. Schematic diagram of the friction process

nents. In Fig.8(a) the arrangement of the steel and sand mass before the start of loading is illustrated. The point "O" is fixed on the steel surface beneath the left bottom corner of the sand mass. Fig.8(b) shows the stage between the start of loading and the yield. In this stage, the major part of the total displacement is the displacement due to the shear deformation of the sand mass (δ_2). The sliding displacement (δ_1) is small compared with the total displacement. A state after the yield is shown in Fig.8(c). In this stage, the major part of the increase in the total displacement ($\delta_1 + \delta_2$) is the increase of the sliding displacement (δ_1). The increase of the displacement due to the shear deformation of sand mass (δ_2) is negligible compared with the increase of the total displacement.

The relationships between shear stress ratio and shear strain of sand mass for the tests in Fig.6 are shown in Fig.9. These are the test results with Toyoura Sand. Although the maximum value of the shear stress ratios are different, these relationships seem to follow the same line before the yielding. This figure shows that the shear strain of sand mass is not affected by the surface roughness of steel during the friction

Fig. 9. Shearing deformation of sand samples (Toyoura Sand) (Test No. B-1, 5, 6, 9; See Appendix A)

Fig. 10. Sliding displacement at the steel-sand contact surface (Toyoura Sand) (Test No. B-1, 5, 6, 9; See Appendix A)

tests. The test results using other sands showed the same tendency.

Fig. 10 shows the relationships between shear stress ratio and the sliding displacement (δ_1) corresponding to the tests in Fig. 6. These are the test results with Toyoura Sand. There seems to be no sliding displacement before yielding except for the very rough case with $22 \mu\text{m}$ R_{max} . The test results using other sands showed the same tendency. With the use of X-ray photographs, Yoshimi et al. (1981) observed the sliding and shear deformation of sand during friction tests by a ring torsion apparatus.

As the result, it was concluded that until the shear stress exceeds about 85% of the maximum value, both the shear zone in the vicinity of the contact surface and the slip distance at the contact surface remain at 0. A similar description can be obtained from Fig. 10. Then, the simple shear apparatus is satisfactory for measuring the sliding at the sand-steel contact surface without using equipments for X-ray photography.

INFLUENTIAL FACTORS

The experimental design method (Taguchi, 1977) was used in order to evaluate the significance of possible influential factors. Since a 2-level type table of orthogonal ar-

Table 3. Variance analyses of test results on frictional coefficient

(a) Glass Beads vs Fukushima Sand

Factor	Degree of Freedom	Observed F Value	Significance Level	Contribution Ratio (%)
Sand Type	1	19.46	*	42.1
Normal Stress	1	0.78		0.0
Surface Roughness of steel	1	18.44	*	39.8
Mean Grain Size	1	2.16		2.6
Errors	3	...	...	15.5

Note: Significance Levels *.....5% **.....1%
(Test No. A-10, 11, 12, 13, 15, 16, 17, 18; See Appendix A.)

(b) Fujigawa Sand vs Fukushima Sand

Factor	Degree of Freedom	Observed F Value	Significance Level	Contribution Ratio (%)
Sand Type	1	8.05	*	12.2
Surface Roughness of steel	1	40.05	**	67.5
Mean Grain Size	1	5.76		8.2
Errors	4	...	...	12.1

(Test No. A-1, 2, 7, 8, 10, 11, 12, 13; See Appendix A.)

(c) Fujigawa Sand vs Toyoura Sand

Factor	Degree of Freedom	Observed F Value	Significance Level	Contribution Ratio (%)
Sand Type	1	69.3	**	27.8
Normal Stress	1	4.7		1.5
Surface Roughness of steel	1	167.2	**	67.8
Errors	4	...	...	2.9

(Test No. A-1, 5, 6, 8, 23, 24, 25, 26; See Appendix A.)

rays was used, two kinds of sands were chosen for each set of experiments.

Table 3 shows the results of the variance analyses on the frictional coefficient at yield. In Table 3(a), glass beads and Fukushima Sand were used. Following the common practices in the experimental design method, the significance levels of 5% and 1% are used. Since the degree of freedom for errors is 3, the F values corresponding to 5% and 1% significance levels are 10.1 and 34.1 respectively. It means that if the observed F value of a factor exceeds 10.1 or 34.1, then the probability of the insignificance of the factor is less than 5% or 1% respectively. Further details on F value and significance level can be found in the textbooks on the experimental design method (e.g. Taguchi, 1977). As is shown in Table 3(a), the sand type and the surface roughness of steel are found to be influential, while the normal stress and the mean grain size are not so influential. In Table 3(b) Fujigawa Sand and Fukushima Sand were used. In a preliminary analysis of the test results, the observed F value for the normal stress was smallest and found not to be influential. Then, it was included in errors. Since the degree of freedom is 4, the F values corresponding to 5% and 1% significance levels are 7.71 and 21.2 respectively. As is shown in Table 3(b), the sand type and the surface roughness are found to be influential. The tests with Fujigawa Sand and Toyoura Sand are analyzed in Table 3(c). In a preliminary analysis, the observed F value for the mean grain size was smallest and found not to be significant. Then, it was included in errors for this analysis. Since the degree of freedom for errors is 4, the F value corresponding to 1% significance level is 21.2. As is shown in Table 3(c), the sand type and the surface roughness are found to be influential. Followings are further studies on the effects of some of the factors.

Type of Sand: There can be a number of reasons, including the shape and the major minerals of the sand particles, for the

Table 4. Major minerals of sands based on visual observation

Sand Type	Major Minerals		
Fujigawa Sand	Quartz	Feldspar	Magnetite
Fukushima Sand	Quartz	Feldspar	Hornblende
Glass Beads	(Glass)		
Toyouura Sand	Quartz		

significance of sand type on frictional coefficient. Major minerals of the sands are shown in Table 4. It was visually observed that most of the particles of Toyoura Sand in the tests were quartz. According to Miura et al. (1975), however, Toyoura Sand consists of three main mineral ingredients; quartz 79.7%, chert 3.1% and feldspar 16.7%, with a small amount of other minerals. Since the particle strength of the minerals are different, it could also be a cause of the influence by sand type. Although the influence of sand type could not be fully worked out, there is a possibility that the effects of sand type can be indirectly correlated with frictional coefficient by means of the shear strength of sand. For this purpose, the apparatus used for the friction tests was modified so as to be used as a simple shear test apparatus of the sands by preventing the sliding at the sand-steel contact surface. In Table 5, reasonable correlation can be seen between the order of the maximum shear stress ratio in simple shear tests of sands and the order of frictional coefficient. Further works, however, are required to estimate the sand type effects quantitatively.

Although the surface roughness of sand was not explicitly treated as a possible influential factor, the influence of this factor

Table 5. Shear strength of sands in simple shear tests

Sand Type	Glass Beads	Toyouura Sand	Fujigawa Sand
Maximum Shear Stress Ratio (Shear Strength)	0.58	< 0.85	< 0.90
Frictional Coefficient at $R_{\max}=20 \mu\text{m}(*1)$	0.39	< 0.61	< 0.86

Note: Relative Density 90%

Normal Stress 98 kPa (1 kgf/cm²)

*1 Inferred from the linear regressions of test results

Fig. 11. Effects of steel roughness and sand type on frictional coefficient (Test No. A-1, 4, 5, 7 to 17, 19 to 22, B-2 to 12; See Appendix A)

was considered to be included in that of the type of sand. The influence of the surface roughness of sand may include those of the shape, the mineral ingredients and the microscopic surface roughness of sand particles. The method to evaluate the components of the type of sand is currently investigated, and not treated in the present paper.

Surface Roughness of Steel: In Fig. 11, the surface roughness of steel and the types of sand are employed as the parameters in plotting the frictional coefficient by the tests. The results of B-Series experiments which are concerned about the influence of surface roughness are plotted in the figure as well as those of A-Series experiments. When the surface is smoother than the critical roughness, sliding occurs along the steel-sand contact surface. For each type of sand, the coefficient of friction is linearly correlated with the surface roughness of the steel. When the surface roughness exceeds the critical value, however, shear failure occurs within the sand mass instead of sliding along the contact surface (Yajima et al., 1984). The frictional coefficient is upper-bounded by the maximum shear stress ratio in simple shear tests of each sand. This upper-bounded characteristic of frictional coefficient is consistent with what is called minimum ener-

gy concept.

Similar relationships by Yoshimi et al. (1981), however, did not show the characteristic of frictional coefficient upper-bounded by the shear strength of sand, even with metal surface as rough as $500 \mu\text{m } R_{\text{max}}$. Among a number of possible reasons of the difference, there is one which lies in the sample preparation.

In case of the ring torsion apparatus used by Yoshimi et al. (1981), the sand sample was formed in the apparatus first (Fig. 12 (a)). After levelling the sand surface, a metal sample was placed upon the sand mass. If the metal sample has a very rough surface, the sand particles near the surface would be displaced by the projections of the metal surface. This would loosen the sand in the vicinity of the sand-metal interface, decreasing the shear strength of sand. In the tests of the present paper, on the other hand, the sand particles were pluviated upon the steel surface as is shown in Fig. 12(b). By this method, there would be no loosening of sand in the vicinity of sand-steel interface

Fig. 12. Loosening of sand specimen during sample preparation

- (a) Placing rough steel on levelled sand surface (Method used by Yoshimi et al., 1981)
- (b) Pluviating sand on steel surface (Method used in the present paper)

by contacting sand and steel.

As is shown in Fig.11, the type of sand has a significant influence on the coefficient of friction. Similar relationships by Yoshi-mi et al. (1981) showed little effect of sand type on the friction coefficient for rough metal surfaces. The reason for the difference would be the loosening of sand in the vicinity of sand-metal interface, such as shown in Fig.12(a), during the sample preparation of the ring torsion apparatus.

Since the shear strength of sand in the vicinity of the interface is influenced by its density, as mentioned above, the sand density can be considered as one of the influential factors of the frictional resistance. It must be noticed, however, that the shear strength of sand influence the frictional resistance only as the upper-bounding limit when the sand in the vicinity of the interface yields. It does not mean that the sand density influences the frictional coefficient even when the shear stress is lower than the local shear strength of sand.

Unlike what was shown in some of the previous paper (Esashi et al., 1966), the frictional coefficient does not seem to be zero even if R_{max} would be nought. This characteristic is consistent with the Adhesion Theory of Friction for Solids (Bowden et al., 1954).

Normal Stress : The significance of normal stress was not recognized in Table 3, in which the range of the normal stress was between 98 kPa (1 kgf/cm²) and 980 kPa (10 kgf/cm²). The tests of Series C in Table A-3 were carried out to extend the range of normal stress up to 3.9 MPa (40 kgf/cm²) for Toyoura Sand. Fig.13 shows the relationship between the coefficient of friction and the normal stress. The average of all the data was 0.49. The values for 95% confidence limits were 0.43 and 0.55. As is shown in the figure, there seems to be little influence of normal stress on frictional coefficient.

Fig.14 shows typical relationship between shear stress ratio (τ/σ_n) and total displacement ($\delta_1 + \delta_2$) under 2.0 MPa normal stress.

Fig. 13. Effects of normal stress on frictional coefficient (Test No. C-1 to 7, 9 to 15; See Appendix A)

Fig. 14. Typical test results under 2.0 MPa normal stress (Test No. C-9, 16; See Appendix A)

Apparent yield is observed for the case with 10.8 μm R_{max} . There is reduction in shear stress ratio just after the yield peak. After that, the shear stress ratio increased again gradually with the increase of total displacement. In case of 59 μm R_{max} , the relationship between shear stress ratio (τ/σ_n) and total displacement ($\delta_1 + \delta_2$) traces the same line as that for 10.8 μm R_{max} before yielding. The shear stress ratio for 59 μm R_{max} kept increasing to the values larger than that at yielding for 10.8 μm R_{max} . This is because of the larger shear resistance along the sand-steel interface.

The relationships between shear stress ratio

(τ/σ_n) and sliding displacement (δ_1) for the same cases are shown in Fig. 15. In case of $10.8\ \mu\text{m}$ R_{max} , apparent yield followed by the reduction of shear stress ratio is observed. Thereafter, the shear stress ratio increased again with the increase of sliding displacement. In case of $59\ \mu\text{m}$ R_{max} , the relationship between shear stress ratio (τ/σ_n) and sliding displacement (δ_1) traces the same line as that for $10.8\ \mu\text{m}$ R_{max} before yielding. The shear stress ratio for $59\ \mu\text{m}$ R_{max} kept increasing to the values larger than that at yielding for $10.8\ \mu\text{m}$ R_{max} , because of the larger shear resistance along the sand-steel interface.

Fig. 15. Sliding at the sand-steel interface under 2.0 MPa normal stress (Test No. C-9, 16; See Appendix A)

Fig. 16. Shearing deformation of sand specimens under 2.0 MPa normal stress (Test No. C-9, 16; See Appendix A)

Fig. 16 shows the relationships between shear stress ratio (τ/σ_n) and shear strain of sand mass for the cases shown in Fig. 14. The shear strain was obtained as the displacement due to the shear deformation of sand mass (δ_2) divided by the sand height. Before the yielding for the case of $10.8\ \mu\text{m}$ R_{max} , these relationship trace the same line. There is some reduction in shear strain for $10.8\ \mu\text{m}$ R_{max} caused by the reduction of shear stress just after the yield. With the re-increase of shear stress ratio, however, the relationship between shear stress ratio and shear strain for $10.8\ \mu\text{m}$ R_{max} shows the tendency to become an asymptotic curve of the relationship for $59\ \mu\text{m}$ R_{max} .

In Fig. 15, the relationships between shear stress ratio (τ/σ_n) and sliding displacement (δ_1) are apparently influenced by the difference of the steel surface roughness. On the other hand, in Fig. 16, the relationship between shear stress ratio (τ/σ_n) and shear strain of sand mass are not affected by the difference of the steel surface roughness. These relationships are consistent with the test results under 98 kPa ($1.0\ \text{kgf/cm}^2$) normal stress shown in Figs. 6, 9 and 10.

Crushed particles were observed along the contact surface after the friction tests under high normal stress. In this paper, the degree of particle crushing is indicated by the weight of particles finer than $105\ \mu\text{m}$. Since the sand had been sieved to remove the particles finer than $105\ \mu\text{m}$ before the tests, all the particles finer than that diameter collected after the tests were produced during the friction tests. Fig 17(a) shows the correlations between the degree of particle crushing and the final sliding distance. The degree of particle crushing seems to be proportional to the sliding distance, and the slope of each correlation depends on the normal stress. In Fig. 17(b), the degree of particle crushing is correlated with the energy consumed along the contact surface. The energy consumed at the contact surface is obtained as the sum of the shearing load tangential to the contact surface multiplied by the sliding displacement under the tan-

Fig. 17. Effect of plastic work of friction on particle crushing
(Test No. C-5 to 19; See Appendix A)

gential load. As is shown in the figure, particle crushing could be closely related to the energy consumed along the sliding surface.

CONCLUSIONS

A series of laboratory experiments are carried out on friction between steel and dry sands. The results of the tests are concluded as follows.

(1) It was observed that major part of the total displacement is the displacement due to the shearing deformation of sand mass before the yielding in the loading process of a test. The sliding displacement along the steel-sand contact surface would overtake the displacement due to the shearing deformation after the yielding of the contact surface.

(2) The type of sand (Fujigawa, Fukushima, Toyoura Sand and Glass Beads) and the surface roughness of steel ($R_{max}=1.5\sim3\ \mu\text{m}$ and $10\sim15\ \mu\text{m}$) have significant influences on the frictional coefficient. The influence of the normal stress (98 kPa and 980 kPa) and the mean grain size of sand (0.55~0.62 mm and 0.15~0.19 mm) are not so significant within the range of this series of experiments. Little influence of normal

stress up to 3.9 MPa was observed on frictional coefficient.

(3) If the steel surface is smooth enough, sliding occurs along the steel-sand contact surface, while shear failure of sand mass would take place when the surface is rough enough. Then, the frictional coefficient, which depends on surface roughness and sand type, is upper bounded by the maximum shear stress ratio in simple shear tests of the sand mass.

(4) Sand particles crushed during the friction were collected after the tests. The amount of the crushed particles were proportional to the sliding distance of the friction surface, and was linearly correlated to the energy consumed along the sliding surface.

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Appendix A. List of tests

Table A-1. Series A for variance analyses of influential factors

Test No.	Sand Type	50% Diam. (mm)	σ_y (kPa)	$R_{max}(\mu m)$ ($L=0.2$ mm)	$R_{max}(\mu m)$ ($L=2.5$ mm)	μ_y
A-1	Fujigawa	0.17	99	13.6	29.1	0.70
2		0.60	99	15.7	41.0	0.59
3		0.60	99	1.7	3.2	0.30
4		0.17	99	1.4	3.1	0.36
5		0.17	99	13.6	29.1	0.75
6		0.17	99	2.6	—	0.41
7		0.60	960	1.5	1.9	0.41
8		0.17	902	1.6	3.2	0.45
9		0.17	99	21.8	44.3	0.89
10	Fukushima	0.19	1088	16.0	38.1	0.64
11		0.56	99	1.3	3.5	0.33
12		0.56	943	11.3	24.5	0.46
13		0.19	99	1.4	2.8	0.33
14		0.56	995	1.4	3.6	0.36
15	Glass Beads	0.62	967	1.6	2.9	0.18
16		0.15	99	21.8	43.3	0.36
17		0.15	977	1.5	3.2	0.18
18		0.62	99	20.3	46.3	0.29
19		0.15	99	21.8	43.3	0.43
20	Toyoura	0.15	99	11.3	24.5	0.28
21		0.15	99	12.6	—	0.29
22		0.15	970	2.0	—	0.22
23		0.19	980	10-15	—	0.53
24		0.19	98	1.5-3	—	0.33
25		0.19	980	10-15	—	0.51
26		0.19	98	1.5-3	—	0.29

Note : μ_y ; Frictional coefficient at yield defined by Appendix B

Table A-2. Series B for influence of surface roughness

Test No.	Sand Type	50% Diam. (mm)	σ_n (kPa)	$R_{\max}(\mu\text{m})$ ($L=0.2\text{ mm}$)	$R_{\max}(\mu\text{m})$ ($L=2.5\text{ mm}$)	μ_y
B-1	Toyoura	0.19	78	0.6	2.4	0.14
2		0.19	78	3.4	5.9	0.33
3		0.19	78	3.3	5.7	0.29
4		0.19	78	6.8	35.0	0.31
5		0.19	78	6.8	35.0	0.33
6		0.19	78	9.8	20.5	0.45
7		0.19	78	11.0	22.0	0.52
8		0.19	78	21.0	46.0	0.58
9		0.19	78	22.0	46.0	0.71
10		0.19	78	22.0	46.0	0.64
11		0.19	78	33.0	47.0	0.78
12		0.19	78	33.0	47.0	0.94

Table A-3. Series C for influence of normal stress

Test No.	Sand Type	50% Diam. (mm)	σ_n (kPa)	$R_{\max}(\mu\text{m})$ ($L=0.2\text{ mm}$)	$R_{\max}(\mu\text{m})$ ($L=2.5\text{ mm}$)	μ_y	W_{105} (N)	Slide (mm)	Plast. Work (kN·m)
C-1	Toyoura	0.19	78	11.3	21.8	0.52	—	9.15	—
2		0.19	78	11.0	22.0	0.52	—	9.21	—
3		0.19	78	9.8	20.5	0.45	—	9.34	—
4		0.19	970	11.3	21.8	0.50	—	8.72	—
5		0.19	1029	11.7	22.9	0.53	0.018	8.10	0.182
6		0.19	1088	11.1	21.7	0.51	0.027	13.26	0.305
7		0.19	1078	9.6	20.0	0.52	0.007	4.14	0.089
8		0.19	1950	11.0	21.8	—	0.002	0.21	0.008
9		0.19	1970	10.8	21.5	0.47	0.031	8.50	0.334
10		0.19	1950	10.1	21.4	0.46	0.010	3.98	0.136
11		0.19	1980	9.6	21.1	0.45	0.014	5.99	0.209
12		0.19	2009	10.5	22.0	0.48	0.017	4.85	0.190
13		0.19	3920	9.5	20.4	0.45	0.057	7.83	0.629
14		0.19	3920	11.5	22.5	0.46	0.121	13.21	1.16
15		0.19	3910	10.6	20.6	0.47	0.034	3.81	0.296
16		0.19	2029	59	100	0.71	0.003	0.54	0.027
17		0.19	2038	59	100	0.67	0.002	0.83	0.041
18		0.19	3989	59	100	0.71	0.012	1.18	0.117
19		0.19	4078	59	100	0.65	0.014	2.09	0.206

Notes: W_{105} ; Amount of crushed particles as the weight of particles finer than 105 μm collected after the tests

Slide; Slide displacement (δ_1) of friction surface at the end of the tests

Appendix B. Definition of “yield” in this paper

The word “yield” used in this paper is defined here in connection with frictional coefficient as follows.

If there is an apparent peak in the relationship between shear stress ratio and sliding distance, such as the Line A in Fig. A-1, the peak value of the shear stress ratio is treated as the frictional coefficient at “yield”. If there is not an apparent peak in the relationship, such as the Line B in Fig. A-1, the frictional coefficient at “yield” is rep-

Fig. A-1. Definition of “yield” in this paper in connection with frictional coefficient

resented by the shear stress ratio when the steel-sand contact surface started to slide. If shear failure of sand mass occurs, instead of sliding along the interface, the maximum

value of shear stress ratio throughout the test is used as the frictional coefficient at "yield".