SAND-STEEL INTERFACE FRICTION RELATED TO SOIL CRUSHABILITY

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ABSTRACT: A ring shear apparatus is used to evaluate the interface behaviour between sand and steel up to an interfacial critical state. Four kinds of sands having a different mean particle size and crushability were sheared along the steels with various surface roughness at a given normal stress level. Further, the individual particle strength tests were also conducted to investigate the degree of soil crushability. Test results are discussed in the context of the normalized surface roughness and soil crushability index. As a conclusion, it is indicated that, depending on the relative roughness, the crushability has a strong influence on the friction behaviours between sand and steel, particularly in the large deformation state.

INTRODUCTION

Friction between soil and construction materials is of major significance in soil-structure interaction problem, including retaining structures, deep foundation, earth reinforcement and so on. A current study attempts to evaluate friction based on the micromechanism between individual grains and the grains/solid interface using theoretical and experimental approach. In European and North American countries, the foundation design codes tend to move from an allowable stress based design to a performance based design which is strongly related to the deformations of the foundation. In such situations, it is important to clarify the frictional characteristics related to the relative slip between soils and construction materials.

The interface friction behaviour of sand is strongly dependent on the surface roughness of solid interface, the size and shape of the particles, the particle strength which is related to the soil crushability, the grading and the shear deformation level

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FIG. 1 Influenced factors in the interaction behaviours

up to an interfacial critical state. A general equation for estimating the pile skin friction is given as a function of the friction angle $\delta'$ between pile and soils surrounding the pile:

$$f_s = K \sigma' \tan \delta' \tag{1}$$

where, $f_s$: pile skin friction, $K$: coefficient of lateral effective stress and $\sigma'$: overburden pressure at arbitrary depth. The purpose of this study is to provide a realistic view of a sand-solid interface shear mechanism over a wide shear deformation range from the pre-peak to the post-peak state, and its relation to the soil crushability. Particularly, $\delta'$ at large shear deformation is to be characterized in relation to soil crushability and steel roughness mainly based on the experimental considerations.

A newly developed ring shear apparatus is used to evaluate the interface behaviour between sand and steel up to the interfacial residual deformation state. Four kinds of sands characterized by different mean particle size and crushability were sheared along the steels with various surface roughness at a given normal stress level. Further, a series of individual particle strength tests were conducted to clarify the degree of soil crushability. The test results are discussed in the context of the normalized surface roughness and soil crushability. A better choice of a representative angle of sand-steel interface friction in the field is also argued from comparison with the characteristics of the internal friction angle of sand.

INFLUENCED FACTORS CONCERNED WITH INTERACTION BEHAVIOURS

The influenced factors concerned with the interaction behaviours between sand and steel are generally divided in two parts, that is, the external factors such as the given stress conditions and the inner factors. Figure 1 shows the inner factors that influence interfacial friction properties between sands and steel. The inner influenced
factors are classified as "the features of steel" such as surface roughness and rust, "the type of sand particles" such as particle diameter, particle hardness and particle shape and "the state of sand" such as water content, density and grading (e.g., Uesugi and Kishida 1986; Kishida and Uesugi 1987). Among those, in this study, it is focused on the steel surface roughness, the mean particle diameters and the particle strength of sands.

KEY PARAMETERS USED

Relative roughness
As mentioned by many researchers, the frictional characteristics between sand and steel are strongly linked to the particle size and surface roughness of steel. Uesugi and Kishida (1986) have clarified that the mutual relationship between the mean particle diameter of sand and maximum surface roughness of steel is sufficient to rationally understand the interaction behaviours. They defined a parameter R_{max}/D_{50} as an index for representing the mutual relationship, which is named as "relative roughness", where the definition of R_{max} is given by the maximum height between top and bottom of steel surface within 2.5mm standard length of steel shown in Figure 2. In this study, R_{max}/D_{50} is used as a key parameter to discuss the experimental data obtained.

Relative crushability index
Crushability is known to be strongly dependent on the effective normal stress σ_n’ as an outer source and the particle fragmentation strength σ_{sf} as an inner source (Yasufuku and Kwag 1999). In this study, a simple parameter σ_n’/σ_{sf} is used to quantify the degree of crushability. Particle fragmentation strength σ_{sf} is defined as a representative particle strength at the mean particle diameter of sand D_{50}, i.e. measured fragmentation force divided by the area calculated using corresponding mean particle diameter of sand. Note that crushability is increasing function of σ_n’/σ_{sf}. This parameter is easily determined by single particle fragmentation tests.
FIG. 4 Typical fragmentation mode of silica sand

FIG. 5 Typical fragmentation mode of carbonate sand

which have already reported by Kwag et al., (1998).

**Basic characteristics of sand particle fragmentation strength**

The particle size of one group is defined by the mean value between upper and lower sieve sizes, and 50 particles are tested for each group to determine the mean value of the particle fragmentation force $P_{fl}$. The most widely used method of assessing the particle force was devised by Marsal et al. (1975). This method requires three similarly sized particles placed roughly at the apexes of an equilateral triangle between two steel plates. However, a simpler point-load set-up has been adopted here as an index test for particle strength. It is believed that the testing of individual particles simplifies the procedure to investigate the single particle strength, and yields as much information (Lee, 1992). Individual particles were loaded to destruction between highly polished platens shown in Figure 3.

Individual particles fragmentation mode depend on the soil component, the particle shape and the particle size. The typical fragmentation modes for different kinds of soil components and particle shapes are shown in Figures 4 and 5. The soil components are divided into largely two types, the hard particles of silica sand and
FIG. 6 Fragmentation strength related to particle size

the weak particles of carbonate sand. The particle shapes are here selected as round. Figure 4 shows the typical fragmentation mode of round particles of silica sand named as Toyoura sand, together with the picture of the particle before and after the crushing. It is noted from this figure that the round silica sand reaches the peak force without any bearing fragmentation.

The weak carbonate sand with round particle shape, as shown in Figure 5, has shown the bearing fragmentation at the peak force and subsequent force increase with the increasing displacement. In addition, the particle shapes before and after the crushing are shown on Fig.5. According to these results, the peak force of $P_{sp}$ is not clearly shown. Therefore, the values of the force at the first particle fracture, $P_{fl}$, see Figs. 4 and 5 is used in this study to determine the single particle fragmentation stress related to the material particle crushing.

**Representative fragmentation stress for particle crushing**

The first fracture force $P_{fl}$ depends on the size of the particles and their tensile strength. Data of the mean of $P_{fl}/A$ for each sand against the mean particle size “$D_{m}$” are plotted in Figure 6, where $A = \pi D_{m}^2/4$. It is found that despite a considerable amount of scatter in the data, the strength characteristics of the materials can be identified. Both the carbonate sands and the silica sand exhibit near linear decline in strength with increasing particle size in the full-logarithmic plot. It is only logical that larger particles tend to contain larger internal flaws, and hence exhibit lower tensile strength than those that were created by the disintegration of their parents. The following relationship is hypothesized by Griffith (1921):

$$\sigma_f \propto \frac{1}{\sqrt{d}} \quad (2)$$

From the linear regression lines in Figure 6, the first fragmentation stress can be written as:
FIG. 7 Ring shear apparatus used

\[ \frac{P_{t}}{d^{2}} = Zd^{b} \]  

where, \( Z \) is a material constant which represent the value of \( P_{t}/A \) (MPa) at \( D_{m}=1.0 \) (mm), and \( b \) is the size index that represents the slope of the plot, which is negative.

Interpolation on the linear regression line may be necessary at times to produce the parameter, \( P_{t}/A \), using the diameter of \( D_{50} \) (mm) which is obtained by the grain size distribution curves. The values of \( P_{t}/A \) at \( D_{50} \) are representative of the single particle fragmentation stress of each material, and therefore, are useful to reasonably evaluate the soil crushability. Note that the smaller are the above values, the smaller is the crushability.

TEST PROCEDURES AND MATERIALS

Ring shear apparatus and sands used

All the frictional tests between steel and sand were carried out by using a ring shear apparatus shown in Figure 7, which is suitable to apply large shear deformation up to the residual stress state. The vertical load is applied to the specimen through the loading disk, where the additional friction between the wall of the ring and the specimen during compression and shearing can be measured by the upper load cell. Thus, the net vertical load \( L \) acting on the shear zone of the specimen can be estimated by the difference between the applied vertical load and the measured additional friction. A lower cylindrical ring is rotated to produce the shear force while an upper cylindrical ring is fixed to the loading frame with a load cell, where the torque \( T \) reflecting the shear force due to the rotation of the lower ring is measured by the load cell (see Figure 7). When assuming that the stress is uniformly distributed in the radial direction, the vertical stress \( \sigma_{n} \) and shear stresses \( \tau \) on average are given by the following equations:
Table 1 Physical properties of sands used

<table>
<thead>
<tr>
<th></th>
<th>$\rho_s$ (g/cm$^3$)</th>
<th>$e_{max}$</th>
<th>$e_{min}$</th>
<th>$D_{50}$ (mm)</th>
<th>$U_c$ (%)</th>
<th>CaCO$_3$ (%)</th>
<th>$\sigma_{sf}$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Toyoura sand</td>
<td>2.640</td>
<td>0.985</td>
<td>0.606</td>
<td>0.16</td>
<td>1.6</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Amami sand</td>
<td>2.753</td>
<td>1.114</td>
<td>0.711</td>
<td>0.22</td>
<td>2.2</td>
<td>50</td>
<td>45</td>
</tr>
<tr>
<td>Dogs Bay sand</td>
<td>2.717</td>
<td>1.720</td>
<td>1.080</td>
<td>0.60</td>
<td>2.3</td>
<td>93</td>
<td>13.5</td>
</tr>
<tr>
<td>Quiou sand</td>
<td>2.697</td>
<td>1.303</td>
<td>0.786</td>
<td>0.61</td>
<td>4.3</td>
<td>81</td>
<td>6.3</td>
</tr>
</tbody>
</table>

\[
\sigma_n = \frac{L}{\pi (r_0^2 - r_{in}^2)} \tag{4}
\]

\[
\tau = \frac{3T}{2\pi (r_0^3 - r_{in}^3)} \tag{5}
\]

where, $r_0$ and $r_{in}$ are outer and inner specimen diameters, respectively. The outer and inner diameter are roughly 300mm and 200mm, respectively, which are considered to be effective in order to maintain uniform strain distribution. The height of each ring is approximately 20mm. The vertical deformation due to shearing is measured by two dialgauges which are set up on the upper loading plate.

Four sands with different crushability are used in this study. Their basic characteristics are shown in Table 1. Soil density $\rho_s$, maximum and minimum void ratio, $D_{50}$, uniformity coefficient $U_c$, calcium contents and representative single particle fragmentation strength $\sigma_{sf}$ are summarized in the table. Refereeing to the magnitudes of $\sigma_{sf}$ at $D_{50}$ (see Table 1), it is found that Quiou sand with $\sigma_{sf}$ of 6.3MPa is the most crushable, and then Dogs Bay sand with $\sigma_{sf}$ of 13.5MPa, Amami sand with $\sigma_{sf}$ of 45MPa, and Toyoura sand with $\sigma_{sf}$ of 100MPa are less crushable.

**Test conditions**

All the tests were conducted under the constant vertical stress of 100kPa and the constant shear deformation rate of 3.0mm/min. The gap between lower and upper rings was kept as 0.15mm during the shearing by carefully pushing up the upper ring and then the space was covered by a thin film of 0.1mm to protect from the leakage of sand particles. In all of the cases of frictional tests between sand and steel, a steel plate with 20mm in height was set up into the lower part of the ring shear box. Figure 8 shows the situation of setting up a steel plate to the lower part of the ring shear box. As shown in Figure 8, in order to change surface roughness of steel plate, an artificial groove in the plate was created in the direction perpendicular to the ring shearing direction. The surface roughness is evaluated as the maximum height of the groove within the standard length of 0.25mm in Figure 2, which is defined by Japanese standard (JIS-B0601). Five steel plates with various maximum surface roughness $R_{max}$ from 0.01 to 1.0mm were prepared in this study. The initial relative density of sand samples on the steel plate was controlled to be $50\% \pm 5\%$, and the height was around 20mm. For comparison, the general ring shear tests of sand were also carried
out under the test conditions similar to the sand-steel frictional tests.

INTERACTION BEHAVIOURS DUE TO RING SHEARING

Friction behaviour between sand and steel

Typical mobilized friction angle $\delta'$ and vertical displacement $V$ against horizontal displacement $H$ obtained in the frictional tests between Toyoura sand and steel plates with different roughness, in which the normal stress $\sigma_n$ was kept at 100kPa, are shown in Figure 9. Toyoura sand is a representative of non-crushable one, where the relative crushability index $\sigma_n'/\sigma_{sf}$ is given as 0.001. Based on the Coulomb frictional law, $\delta'$ is calculated as:

$$\delta' = \tan^{-1} \left( \frac{\tau}{\sigma_n'} \right) \tag{6}$$

Figures 9(a-b) show the $\delta'$-$H$ relationships, and Figures 9(c-d) show the $V$-$H$ relationships. It is noted that Figures 9(b) and (d) show the results up to the relatively small horizontal displacement of 20mm during the ring shearing. The circle and triangle plots represent the results given by the relatively smooth steel plate with $R_{max}/D_{50}=0.06$ ($R_{max}$=0.01mm) and the rough steel plate with $R_{max}/D_{50}=6.25$ ($R_{max}$=1mm), respectively. In addition, the ring shear test results of Toyoura sand with Dr=50% are also depicted by a solid line. Similarly, the typical $\delta'$-$H$ relationship for Quio sand with high crushability are shown in Figure 10. The interaction behaviour observed when relative roughness or crushability increases is shown in matrix form in Figure 11.

Tests for smooth surfaces with low crushability show no significant peak stress and mobilize more or less a constant angle of friction, whereas very rough surfaces with low crushability show that a higher peak strength can be mobilized and that this is associated with dilatancy at low displacements (see Figures 9 and 14). A completely different response is found for very smooth surfaces for particles with high crushability in that a small peak or yield value of interface friction angle is mobilized before particle degradation becomes significant. This is accompanied by a
FIG. 9 Typical tests results for Toyoura sand categorized as a representative of non-crushable sands

FIG. 10 Typical tests results for Quiou sand categorized as a representative of crushable sands

erginal increase of friction angle with horizontal displacement as shown in Figure 10. Thus, we can see that the characteristics of the mobilized $\delta'$ and dilative behaviours are strongly dependent on the relative roughness and crushability, especially, the effect of crushability on the mobilized angle of friction becomes more significant when the relative roughness is smaller. Such phenomenon can be found only by
FIG11 Sketch of typical d-H relationship related to relative roughness and crushability

FIG12 Image of friction mechanism for relatively smooth steel surface

FIG13 Image of friction mechanism for relatively rough steel surface

investigating the shearing behaviours up to the large deformations beyond the peak or yield state.
FIG. 14 Friction angles at peak state related to dilatancy angles

**Brief consideration of frictional mechanism**

Figure 12 shows the schematic $\delta'$-H relationship and interaction behaviours close to slip surface between steel and sand for the case that the relative roughness is very smooth, together with a photo which shows the state of the slip surface after shearing up to 100 mm displacement. It is considered that a direct shear mode is dominant up to the yield point $H_y$, and then interface slip occurs beyond $H_y$. Similar results for the case when the relative roughness is large are depicted in Figure 13. In this case, a direct shear mode is also dominant up to a peak point $H_p$, and then a clear slip line within sand is developed and becomes dominant beyond the displacement at peak point $H_p$. The mobilized characteristics of interfacial friction angle $\delta'$ between sand and steel is therefore considered to be similar to those of the internal friction angle of sands when the relative roughness becomes greater than a certain value.

Figure 14 shows the friction angles at peak state $\delta_p$ against the dilatancy angles at peak state $\omega_p$, obtained by the frictional tests between steel and Toyoura sand with various normal stresses and relative densities. The dilatancy angle at peak state $\omega_p$ is defined as

$$\omega_p = \tan^{-1}(dV/dH)_{\text{at peak state}} \quad (7)$$

It is clear that when $R_{\text{max}}/D_{50}$ becomes greater, in this case roughly greater than 0.5, $\delta_p$ has an unique relationship to $\omega_p$, irrespective of the test conditions. However, in the case of being $R_{\text{max}}/D_{50}$ is relatively small, the values of $\delta_p$ tend to be out of an unique line as shown in this figure. This tendency may reflect the failure mechanism just mentioned above. It means that at least in the range $R_{\text{max}}/D_{50}>0.5$, which can be categorized as a rough zone, the interfacial dilatancy properties are similar to those obtained by shearing a sand sample.
FIG. 15 Friction angles against relative roughness for Toyoura sand as a representative of non-crushable sand

FIG. 16 Friction angles against relative roughness for Quiou sand as a representative of crushable sand

FRICTION PROPERTIES AT PEAK AND RESIDUAL STATES

Figure 15 shows the interface friction angles of Toyoura sand with hard particles at peak and residual state against the relative roughness $R_{\text{max}}/D_{50}$ defined by Uesugi and Kishida (1986). Similarly, Figure 16 also shows the interface friction angles of Quiou sand with high crushability at peak and residual states against the $R_{\text{max}}/D_{50}$. The expected rough, intermediate and smooth zones by Paikowsky et al. (1995) are also depicted in these figures for categorizing the interactional friction properties at peak and residual states.

The mobilized interface friction angle of sand with low crushability is found to
increase as the relative roughness increases for both peak and residual states, and these converge towards a steady state value. The state values are found when the relative roughness is greater than around 0.5, which is roughly consistent with the value which separates the dilatancy behaviour due to sand-steel shear mode from that due to sand-sand shear mode as shown in Figure 14. The results at both peak and residual state give a good agreement with the classification of intermediate and rough zones by Paikowsky et al. (1995). A different response is found for residual state for very crushable sand as shown in Figure 16. A steady interface friction angle is mobilized even though the relative roughness becomes smaller. One of the reasons might be the particle crushing due to shearing up to the residual state with large deformation.

Figure 17 shows the relationship between $\delta_r$ normalized by $\phi_r$, which is defined as
residual friction angle of the corresponding sand material, and the relative roughness relevant to soil crushability. The results of five types of granular materials with different crushability indices are included in this figure. It should be emphasized that the decreasing rate of $\delta_r/\phi_r$ with the decreasing relative roughness may become smaller when the crushability index increases. The decreasing rate for each granular material against the crushability index are shown in Figure 18. The decreasing rate of $\delta_r/\phi_r$ to the decreasing relative roughness in the intermediate zone decreases linearly with the increasing crushability at log scale, and in this figure, when the crushability index $\sigma_n'/\sigma_s'$ becomes roughly higher than 0.02, the decreasing rate is apparently zero, which means that $\delta_r/\phi_r$ becomes constant, independent of the relative roughness even in the intermediate zone. In addition, when looking at Figure 17, the constant values of $\delta_r/\phi_r$ at steady state for each sand are approximately equal to 0.9, although some scatter can be found.

CONCLUSIONS
1. Relative roughness and crushability index presented here are useful to understand the interaction behaviour between steel and sands not only in the peak state but also in the residual state.
2. Interfacial friction angles at peak and residual states in the rough conditions, approximately defined by $R_{\text{max}}/D_{50}>0.5$, can be strongly linked with the measured dilatancy angle, which is found to be similar to the dilatancy properties of sands.
3. Friction properties are generally classified into three parts, that is, rough, intermediate and smooth zone. The rough and intermediate zone were confirmed not only in the peak state but also in the residual state. In the intermediate zone where $R_{\text{max}}/D_{50}$ is roughly smaller than 0.5, the interface friction angles decreases with the decreasing relative roughness.
4. Crushability strongly influences the friction behaviours between sand and steel particularly in the large deformation state of the intermediate zone. The decreasing rate of interface friction angle normalized by the internal friction angle at residual state $\delta_r/\phi_r$ to the relative roughness decreases linearly with the increasing crushability index in log scale.
5. In this study, when the crushability index $\sigma_n'/\sigma_s'$ becomes approximately higher than 0.02, the decreasing rate of the normalized interface friction angle at residual state $\delta_r/\phi_r$ to the decreasing relative roughness converges to zero. It means that in this case, $\delta_r/\phi_r$ becomes constant, independent of the relative roughness even in the intermediate zone.
6. In addition, the constant values of $\delta_r/\phi_r$ at the steady state for sands with different crushability, which are measured in the rough zone, are approximately equal to 0.9 although some scatter can be found.

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