BEHAVIOR OF SAND PARTICLES IN SAND-STEEL FRICTION

Morimichi Uesugi\(^i\), Hideaki Kishida\(^i\) and Yasunori Tsubakihara\(^{ii}\)

ABSTRACT

This paper describes a method for observing the particle behavior near the interface in sand-steel friction tests. A friction testing apparatus was modified to allow the observation of sand particles. Close-up photographs were taken of the sand particles at specified timing in sand-steel friction tests. The change in particle coordinates gives the displacement of particles during the friction test. The sand-steel interface showed a small amount of sliding before the peak in the frictional resistance. The sand on a smooth steel surface slid without large shear deformation. The sand particles on a rough steel surface rolled as well as slipped along the interface. These movements caused the formation of a shear zone within the sand along a rough interface. The displacement of stacked aluminum frames provides approximate displacement of the sand particles. The relative displacement between the bottom frame and the steel specimen gives the sliding displacement at the sand-steel interface.

Key words: friction, laboratory test, sand, steel, test equipment, slip surface, dilatancy

(IGC: D6)

INTRODUCTION

The behavior of sand particles has an important role on the friction at sand-steel interfaces. Measuring the displacement of sand particles is a useful method for understanding the mechanism of the interface behavior.

The measurement of particle movement has provided important contributions to the understanding of sand deformation. Butterfield et al. (1970) introduced a stereophotogrammetric method for measuring displacement field in sand. Andrawes and Butterfield (1973) and Murayama and Inoue (1981) applied the method for measuring the displacement of sand particles. De Pater and Nieuwenhuis (1986) used a double-exposure photograph to obtain the displacement of sand particles. They calculated the displacement from the interference pattern formed by directing a laser beam through the negative.

As for the sand-metal friction, Yoshimi and Kishida (1981 a) used X-ray photography.

\(^i\) Research Associate, Graduate School at Nagatsuta, Tokyo Institute of Technology, 4259 Nagatsuta, Midori-ku, Yokohama.

\(^{ii}\) Professor of Geotechnical Engineering, Tokyo Institute of Technology, Yokohama.

\(^{iii}\) Graduate Student, Tokyo Institute of Technology.

Manuscript was received for review on June 5, 1987.

Written discussions on this paper should be submitted before October 1, 1988, to the Japanese Society of Soil Mechanics and Foundation Engineering, Sugayama Bldg. 4 F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.
to measure the deformation of sand mass. The tangential displacement of the interface consisted mostly of slip for smooth surfaces. For rough surfaces, the displacement consisted mostly of shear zone distortion along the interface. Until the shear stress exceeded about 85% of the maximum value, the slip distance and the shear zone displacement remained at 0. The sand deformed uniformly throughout its height. The embedded lead balls were, however, larger than the maximum particle diameter of the sand. Placing the balls in the sand sample can cause disturbance of the sand fabric. It was impossible to observe the particle rolling with the use of virtually spherical lead balls.

This paper describes a method to observe the behavior of sand particles near the sand-steel interface. This method requires neither embedded markers nor special equipment. The measurement of particle displacement enables us to separate the tangential displacement into the shear deformation of sand mass and the interface sliding. The measurement of the normal displacement enables us to see the volume change in the sand mass along the sand-steel interface. This method is applied to a series of friction tests between dry sand and mild steel with various interface roughness. Along a smooth interface, the sand mass slipped without large deformation. A shear zone formed within the sand mass along a rough interface.

**MEASUREMENT OF DISPLACEMENT**

Fig. 1 shows the simple shear type apparatus used in the present study. This apparatus is the same as the one used by Uesugi and Kishida (1986a). The sand-steel interface was 400 mm in length and 100 mm in breadth. The sand mass was about 30 mm in thickness. The container of sand specimen is a stack of rectangular 2 mm thick aluminum frames with a 400 mm × 100 mm hollow square in the middle. The surface of each frame was lubricated to allow the container to follow the deformation of sand mass with minimum friction resistance. Normal and tangential loads are applied by vertical and horizontal hydraulic cylinders. The interface area remains constant even if sliding occurs, since the steel specimen is longer than the sand-steel interface.

The displacement was measured in the directions tangential and normal to the sand-steel interface. In the present experiments, the interface was horizontal. The tangential displacement was in the horizontal direction and the normal displacement was in the vertical direction. In contrast, a soil-pile interface is vertical unless the pile is inclined. In such a case, the tangential displacement is in the vertical direction and the normal displacement is in the horizontal direction. It is preferable to use the words tangential and normal displacement rather than horizontal and vertical displacement.

Tangential displacement was measured at the steel, at the bottom aluminum frame and at the top aluminum frame. Total tangential displacement $\delta$ is the relative displacement between the steel and the top aluminum frame. Sliding displacement $\delta_s$ is the relative displacement between the steel and the bottom aluminum frame. The change of the sand mass thickness was measured as the normal displacement at the both ends of the loading plate. Volumetric strain is the ratio of the change to the initial value of
the thickness of the sand mass.

The apparatus was newly equipped with a glass window for observing the particle movement near the interface. The window was 19.5 mm in height and 100 mm in length. The glass was 19.5 mm in height, 200 mm in length and 5 mm in thickness. The photographs were taken with a 35 mm single-lens reflex camera, fitted with a 200 mm macro objective. The lens was about 800 mm distant from the glass window. A color reversal film (ASA 100) used in the test was developed by a standard processing. The image on the negative film was about 0.38 times the actual size.

Photo 1 shows a typical photograph taken during a test. The photograph print was enlarged to about 4 times the actual size for reading the coordinates of sand particles. The ratio of the print to the actual size was determined by measuring the distance of points marked on the window glass. The deformation of the sand mass was evaluated from the displacement of 40 sand particles.

Fig. 2 shows how to determine the coordinates of a sand particle. The coordinate axes were determined by the marker on the top aluminum frame and the sand-steel interface. The coordinate measuring machine has the sensibility of 0.02 mm. The magnification of photo print was about 4 times the actual size. Then, the sensibility of coordinate reading was 0.02/4 = 0.005 mm. The center of a particle, however, was determined on the photograph print by naked eyes. This method limited the accuracy of coordinates reading to 0.1 mm or about 1/20 of a particle diameter.

The other source of the error is the refrac-
tion by the window glass shown in Fig. 3. Consider the case when a particle moves from \(A_a\) to \(A_b\) over the distance of \(\Delta A\). Because of the refraction, this movement is observed as the displacement from \(B_a\) to \(B_b\) over the distance of \(\Delta B\). The error is \((\Delta B - \Delta A)\).

From Snell’s law, the error is expressed as:

\[
\Delta B - \Delta A = A_bB_b - A_aB_a = t_g \times \left( (\tan \alpha_b - \tan \beta_b) - (\tan \alpha_a - \tan \beta_a) \right) \tag{1}
\]

where

\[
\begin{align*}
\alpha_a &= \tan^{-1}(r_a/d) \\
\alpha_b &= \tan^{-1}(r_b/d) \\
\beta_a &= \sin^{-1}(\sin \alpha_a/n) \\
\beta_b &= \sin^{-1}(\sin \alpha_b/n)
\end{align*}
\]

\(n\) = refractive index of window glass

\(r_a, r_b, d\) : shown in Fig. 3.

The glass thickness was \(t_g = 5\, \text{mm}\) and the refractive index was \(n = 1.52\) (Jenkins and White, 1976). The distance between the lens and the window was \(d = 800\, \text{mm}\). The largest displacement in a single step was about \(40\, \text{mm} = r_b - r_a\). Substituting these values into Eq. (1), the largest error by the refraction was \(\Delta B - \Delta A = 0.09\, \text{mm}\).

The overall accuracy of the coordinate reading is \(0.1 + 0.09 = 0.19\, \text{mm}\), or \(0.5\%\) of the largest total displacement in a single step. This is much less accurate than the stereophotogrammetric method or the method with interference pattern. It was not intended, however, to make very accurate measurements of particle displacement. Instead, the sand particles were tracked over a very long distance within minimum number of measuring steps. For this purpose, the above mentioned accuracy is satisfactory.

**TEST CONDITIONS**

Table 1 shows the list of tests. A low-carbon structural steel was machined into a rectangular specimen with the base of 500 mm \(\times\) 150 mm and 40 mm in thickness. The surface of each specimen was finished to a specified surface roughness (Uesugi and Kishida, 1986 a). Fig. 4 shows typical surface profiles of steel specimen measured by a roughness gage with a stylus.

Air-dried Seto sand was sieved so that the sand diameter ranges between \(1.68\, \text{mm}\) to \(2.00\, \text{mm}\). Table 2 shows the properties of the sand. The sand was rained into the testing apparatus by multiple sieving pluviation method (Miura and Toki, 1982). This method enables us to make a dense sand mass

<table>
<thead>
<tr>
<th>Test No.</th>
<th>(R_{\text{max}}(\text{mm}))</th>
<th>(R_s(10^{-7}))</th>
<th>(p_s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28</td>
<td>15</td>
<td>0.43</td>
</tr>
<tr>
<td>2</td>
<td>46</td>
<td>25</td>
<td>0.56</td>
</tr>
<tr>
<td>3</td>
<td>84</td>
<td>46</td>
<td>0.72</td>
</tr>
<tr>
<td>4</td>
<td>124</td>
<td>68</td>
<td>0.76</td>
</tr>
<tr>
<td>5</td>
<td>193</td>
<td>106</td>
<td>0.81(^a)</td>
</tr>
</tbody>
</table>

**Notes:**
1) Sand-steel interface did not slide in Test No. 5
2) \(R_s = (R_{\text{max}}(L = D_{95})/D_{95})\)
3) Gage length \(L = 2.0 \text{mm}\) was used as the round figures for \(L = D_{95}\)
4) Relative density of sand \(D_r = 90\%\) for all the tests

---

NII-Electronic Library Service
PARTICLE BEHAVIOR ALONG INTERFACE

\[ R_{\text{max}}(L=2\text{mm})=28\mu\text{m} \]

\[ R_{\text{max}}(L=2\text{mm})=124\mu\text{m} \]

**Fig. 4. Typical surface profiles of steel specimen**

<table>
<thead>
<tr>
<th>Table 2. Properties of Seto sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G_s )</td>
</tr>
<tr>
<td>( e_{\text{min}} )</td>
</tr>
<tr>
<td>( e_{\text{max}} )</td>
</tr>
<tr>
<td>( D_{50} )</td>
</tr>
<tr>
<td>( U_c )</td>
</tr>
<tr>
<td>( w )</td>
</tr>
</tbody>
</table>

\[ \sigma_n=98\text{kN/m}^2 \]

**Fig. 5. Relationship between yield coefficient of friction and steel roughness**

of \( D_r=90\% \).

Normal stress was kept constant at 98 kN/m\(^2\). Tangential load was applied by load control until the interface yield. After the yield, the tangential load was applied by displacement control.

The coefficients of friction at yield are shown in Table 1. In the tests No.1 to 4, the sand–steel interface sliding occurred at the yielding. In No.5 test, however, the sand–steel interface did not slide. Instead, shear failure took place within the sand mass. The maximum shear stress ratio in test No.5 was 0.81. This value is much higher than the coefficient of sand–glass friction 0.16 obtained in preliminary tests. Fig. 5 shows the relationship between coefficient of friction and the interface roughness. Solid triangles are the results of present tests with glass window. Open marks are the test results without the window (Uesugi and Kishida, 1986b). The coefficients of friction at yield are in good agreement with those by the apparatus without a glass window. The newly equipped glass window caused negligibly small influence on the frictional resistance.

**ROUGH INTERFACE**

Fig. 6 shows the load–displacement relationship in friction test No.4 in Table 1 with a rough interface \((R_n=68 \times 10^{-3})\). Also shown is the volumetric strain during the test. Photographs were taken at the start (O), at the peak (A\(_1\)), at \( \delta \approx 20 \text{ mm} \) (B\(_1\)), and at \( \delta \approx 40 \text{ mm} \) (C\(_1\)). By comparing these photographs, it was noticed that particles did not only slip but also rolled along the interface. This is consistent with the behavior of rod assemblies with oval cross-section in biaxial–axial compression tests (Oda et al., 1982). Particle rolling was the major microscopic deformation mechanism of the rod assemblies.

Hata and Muro (1968) studied friction and wear of a steel plate against sandy soil. The frictional resistance was attributed to the plowing of steel plate by sand particles. This assumption, however, does not coincide with the experimental realities for rough sand–steel interfaces. The rolling of the particle has an important role in the friction along a rough sand–steel interface.
placement was $\delta = 39.9 \text{ mm}$. The tangential displacement of particles was much smaller than the total displacement. The sand particles moved not only in the tangential direction but also in the direction normal to the interface.

The sand mass was partitioned into 8 layers on the photograph prints. Each layer contained five tracked particles. Fig. 8 shows the averages and the standard deviations of the increase in tangential displacement of the particles. Fig. 9, on the other hand, shows the increase in normal displacement.

From the start (O) to the peak (A), the sand deformed uniformly (Fig. 8(a)). There was not a large increase in the sand volume (Fig. 9(a)). Between A and B, there was large shear deformation of sand near the sand–steel interface (Fig. 8(b)). Clear increase was observed in the sand volume near the interface (Fig. 9(b)). Between B and C, there was large shear deformation of sand near the sand–steel interface (Fig. 8(c)). The volume increase of sand was smaller than the previous stage (A to B). During A to C, there are large standard deviations in the tangential displacement of particles near the interface. It is typical of the particles to move randomly in a shear zone of sand mass (e.g., Murayama and Inoue, 1981). A shear zone formed within the sand mass.

Fig. 6. Load-displacement relationship with a rough interface (Test No. 4)

Fig. 7. Particle displacement with a rough interface (Test No. 4)
along the sand–steel interface during the interface sliding.

A shear zone has a maximum shear stress ratio \(\tau/\sigma_n\) lower than that of the same sand in a dense state. When \(\tau/\sigma_n\) of the shear zone is lower than \(\mu\), \(\tau/\sigma_n\) becomes the upper-limiting value of the coefficient of friction. Thus, the shear stress ratio becomes lower with the progress of shear zone formation.

In the present study, the shear zone thickness was visually determined by particle displacement. The particle displacement in a shear zone exceeds the value expected by extrapolating the displacement due to the shear deformation of sand mass. A shear zone is also characterized by the large deviation of particle displacement.

Table 3 shows the shear zone thickness \(t_s\) obtained in sand–steel friction tests and shearing tests of sand. The value of \(t_s/R_{max}\) in the present study is much larger than the value by Yoshimi and Kishida (1981b). The sensibility to the shear zone thickness in Yoshimi and Kishida (1981b) was no less than 0.8 mm owing to the diameter of lead markers for X-ray photography. The value of \(t_s/D\) is a little smaller than those obtained in the shearing tests of sand. In general, the shear zone thickness is about 5 times the
Table 3. Shear zone thickness

<table>
<thead>
<tr>
<th>Reference</th>
<th>$t_z$ (mm)</th>
<th>$t_z/D$</th>
<th>$t_z/R_{max}$</th>
<th>Test type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Present study</td>
<td>5-8</td>
<td>3-4</td>
<td>46-65</td>
<td>Friction test $R_{max}(L=2.0\text{mm})=124\ \mu\text{m}$ $R_s=68\times10^{-3}$</td>
</tr>
<tr>
<td>Yoshimi &amp; Kishida (1981 b)</td>
<td>1.5-2.5</td>
<td>5-8</td>
<td>3-5</td>
<td>Friction test $R_{max}(L=2.5\text{mm})=510\ \mu\text{m}$</td>
</tr>
<tr>
<td>Roscoe (1970)</td>
<td>(=9)</td>
<td>=10</td>
<td></td>
<td>Simple shear test of sand</td>
</tr>
<tr>
<td>Cornforth (1964)</td>
<td>1.5-5</td>
<td>(6-20)</td>
<td></td>
<td>Plane strain test of sand</td>
</tr>
<tr>
<td>Vardoulakis et al (1978)</td>
<td>3-5</td>
<td>(4-6)</td>
<td></td>
<td>Plane strain test of sand</td>
</tr>
</tbody>
</table>

Notes
1) Values of $t_z$ and $t_z/D$ in blankets are estimated from available data in the corresponding reference papers
2) For present study, $L=2.0\text{mm}$ was used as the round figures for $L=D_b$ in evaluating $R_s$

Photographs were taken at the start (O), at the peak (A$_1$), at $\delta\approx20\ \text{mm}$ (B$_1$) and at $\delta\approx40\ \text{mm}$ (C$_1$). In contrast to rough interface, there was no rolling of sand particles. The major factor of interface sliding was slipping of particles on the steel surface.

Fig.11 shows the displacement of particles tracked in this test. Open circles indicate the particle positions at O. Solid circles indicate the particle positions at C$_1$. Between O and C$_1$, the total tangential displacement was 41.5 mm. The displacement of particles was much smaller than the total displacement. It was also smaller than that in a test with a rough interface (Fig.7).

Fig.12 shows the average and the standard deviation of the increase in the tangential displacement of particles. The shear deformation of the sand was much smaller than that with a rough interface (Fig.8). Fig.13 shows the increase in the normal displacement. The volume increase in the sand was negligibly small. The sand slipped along the smooth interface without large deformation. This behavior is in good agreement with the observation by Yoshimi and Kishida (1981 b).

Fig.10 shows the load–displacement relationship in friction test No.1 with a smooth interface ($R_s=15\times10^{-6}$). Also shown is the volumetric strain during the test. The volume increase in this test was much smaller than that with a rough interface (Fig.6).

Fig.10. Load–displacement relationship with a smooth interface (Test No.1)

**SMOOTH INTERFACE**

Fig.10 shows the load–displacement relationship in friction test No.1 with a smooth interface ($R_s=15\times10^{-6}$). Also shown is the volumetric strain during the test. The volume increase in this test was much smaller than that with a rough interface (Fig.6).

**DISPLACEMENT OF ALUMINUM FRAMES**

A stack of aluminum frames contained the sand mass in the present tests. The tangential coordinates of the frames were measured in the photographs by the same method as particle coordinates. Fig.14 shows the in-
crease in tangential displacement of aluminum frames in test No.4 with a rough interface \((R_e=68 \times 10^{-3})\). Between A₁ and B₁, the dilatant sand in the shear zone pushed up the aluminum frames about 1.5 mm. In Fig. 14(b) and (c), the distance from the sand-steel interface was corrected according to the normal displacement of aluminum frames.

Also plotted are the average increase in particle displacement. The distance from the sand-steel interface was corrected according to the average normal displacement of the particles (Fig. 9). As shown in Fig. 14, the displacement of the aluminum frames is somewhat smaller than the displacement of the sand particles. The difference, however, is rather small compared with the increase in the total displacement \(\delta\).

Fig. 15 schematically illustrates the factors of the tangential displacement in a sand-steel friction test such as shown in Fig. 14. The total displacement \(\delta\) consists of the interface sliding \(\delta_1\) and the displacement due to the shear deformation of sand mass \(\delta_2\). Strictly speaking, \(\delta_1\) consists of the net interface slid-
Fig. 13. Normal displacement of particles with a smooth interface (Test No.1)

Fig. 14. Tangential displacement of sand particles and aluminum frames with a rough interface (Test No.4)

ing and the displacement due to the shear zone distortion along the interface. The displacement due to the shear zone distortion, however, is dependent on the local behavior of sand particles along the interface. This is in contrast to the displacement due to the shear deformation of the sand mass dependent on the sand layer thickness. Therefore, the value of $\delta_1$ can be considered as the nominal sliding displacement usable for engineering purposes.

Fig. 16 shows the increase in the tangential displacement of aluminum frames in test No.1 with a smooth interface ($R_s=15 \times 10^{-3}$). Also plotted is the average increase in the particle displacement. There is little difference between the displacement of the particles and the displacement of the frames. The interface sliding is nearly equal to the relative displacement between the bottom aluminum frame and the steel specimen.
CONCLUSIONS

The behavior of sand particles was observed near the sliding interface of sand-steel friction tests.

1) Before the peak of frictional resistance, there was little sliding at the interface. The sand mass deformed uniformly. At the peak, the interface started sliding. Along a rough interface, the particles slipped, rolled and moved up and down. Along a smooth interface, on the other hand, sand mass slipped without large deformation.

2) A shear zone formed in the sand along a rough interface during the sand-steel sliding. A shear zone formation explains the reduction in frictional resistance during the interface sliding. When the interface was smooth, there was no formation of shear zone.

3) The sliding displacement can be evaluated as the relative displacement between the steel and the bottom aluminum frame. This value includes the net interface sliding and the shear zone distortion in the sand along a rough interface. When the interface is smooth, the displacement of steel relative to the bottom frame is nearly equal to the net interface sliding.

ACKNOWLEDGMENTS

This research is partly funded by the Japanese Ministry of Education, Science and Culture as a Grant-in-Aid for Developmental Scientific Research, 1987-1988. The experi-
ments were carried out in the final year project of the third author (Ref.11).

NOTATIONS

\[ d = \text{distance from camera lens to window glass} \]
\[ L = \text{gage length of } R_{\text{max}} \]
\[ n = \text{refractive index of window glass} \]
\[ R_{\text{max}} = \text{maximum height over the gage length } L \]
   (See Uesugi and Kishida (1986 a) for details)
\[ R_n = \text{normalized roughness} = \frac{(R_{\text{max}} \cdot L = D_{00}) \cdot D_{00}}{D_{00}} \]
   (See Uesugi and Kishida (1986 b) for details)
\[ t_w = \text{thickness of window glass} \]
\[ t_t = \text{thickness of shear zone} \]
\[ \delta = \text{total tangential displacement} = \delta_1 + \delta_2 \]
   (See Uesugi and Kishida (1986 a) for details)
\[ \delta_1 = \text{sliding displacement of sand-steel interface evaluated as the relative displacement between the steel and the bottom aluminum frame} \]
\[ \delta_2 = \text{tangential displacement due to the shear deformation of sand mass} \]
\[ \mu_y = \text{coefficient of friction at yield} \]

REFERENCES