Experimental Study of Static and Dynamic Friction Between Sand and Typical Construction Materials


ABSTRACT: The limiting contact friction between sand and steel, cement mortar, graphite, and teflon surfaces was measured in the laboratory. The coefficients of (wall) friction were obtained using static and dynamic loadings with particular reference to conditions at the time slip was initiated. The coefficient of friction increases with the surface roughness and angularity of the sand grains, and as the roughness of the contact surface increases with respect to the size of the sand particles. For steel and mortar surfaces dynamic friction was greater than static friction by about 20 percent unless the surface was sufficiently rough that sand/sand slip was approached. The (static) angle of shearing resistance was the upper limit of the coefficient of friction for all static and dynamic tests where slip was initiated from 1-2 ms to 5 min (loading rates from $5 \times 10^5$ to 0.5 psi/min). Under static loading conditions teflon and graphite reduced wall friction by one-half to one-third; at high loading rates graphite was a more effective lubricant than teflon.

KEY WORDS: friction, dynamic loads, sands, shear tests, soil mechanics

The limiting friction between soil and construction materials such as steel and concrete has an important bearing on the stability of retaining walls, piles, weirs and other similar structures. On the basis of the previous studies of Suklje and Brodnik [1], Potyondy [2], Horn and Deere [3], it is generally assumed that available data are satisfactory for practical purposes if loads are applied gradually. For loadings induced by vibrating machinery, earthquakes, blasting, and the like, no data on the coefficient of (wall) friction has come to the writers' attention. Consequently, a preliminary investigation was conducted using specially designed but simple laboratory equipment [4-6].

Experimental Concept

Static Coefficient of Friction, $\mu_s$

The static coefficient of friction, $\mu_s$, is defined as:

$$\mu_s = \frac{F_s}{N_s}$$

where $F_s$ is the static friction force and $N_s$ the normal force on the slip surface at slip. The test configuration used for this study is shown schematically in Fig. 1a. It consisted of a cylinder of sand encased in a rubber membrane with a 1 1/2 in. diameter, 14 in. long rod located along its axis. Some selected tests were performed using a 2 in. diameter rod. By evacuating air from within the membrane, a normal stress was applied to the sand/rod interface that ranged from 1.25 to 12.5 psi. The rod was then caused to slip relative to the sand by gradually applying "static" forces to the rod in the axial direction. The membrane encased sand sample had a diameter of 5 in. and a length of 10 in. The static tests were run in a stress controlled device with the axis of the sample horizontal so that slip occurred in approximately 5 min.

Two independent auxiliary tests indicated that the actual pressure at the sand/rod interface was equal to the vacuum induced membrane pressure [4, 5], and this assumption was made in interpreting all test results. Kennedy [7], using a larger sample, concluded that the normal pressure at the sand/rod interface was equal to 1.4 times the pressure on the membrane.

Dynamic Coefficient of Friction, $\mu_d$

The dynamic coefficient of friction, $\mu_d$ is defined as:

$$\mu_d = \frac{F_d}{N_d} = \frac{F_s - ma}{N_s + \Delta N_s}$$

FIG. 1—Schematic diagram of experimental concept.

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1 Assistant professor of Civil Engineering, Georgia Institute of Technology, Atlanta, Georgia.
2 Professor of Soil Mechanics, Purdue University, Lafayette, Indiana.
where, at slip

\[ F_d = \text{dynamic friction force on the slip surface} \]
\[ N_d = \text{dynamic normal force on the slip surface} \]
\[ F = \text{dynamic force applied to the rods} \]
\[ m = \text{mass of moving rods} \]
\[ a = \text{acceleration of the moving rods} \]
\[ N_s = \text{static normal force} \]
\[ \Delta N_s = \text{change in static normal force due to application of the dynamic force} \]

The dynamic test set-up, shown schematically in Fig. 1b, used the same size membrane and rods as in the static tests. The dynamic input force, \( F \), was applied using a shock tube; by means of a piston assembly, the shock wave was transferred to the test rod. The shock tube applied essentially a step-type forcing function to the rod, producing slip in 1 to 2 milliseconds. The dynamic normal force, \( N_n \), was composed of the static normal force, \( N_s \), plus any change in the normal force, \( \Delta N_n \), that occurred at the time of slip during the dynamic test. Small piezoelectric stress gages were placed in the sample next to the test rod to detect these pressure changes.

Test Materials

Sand

Two types of sand were used. One type was a uniformly graded quartz sand, hereafter called “20-30” sand, 100 percent of which passed the 20 and was retained on the 30 U. S. standard sieve. The specific gravity of the solids of this sand was found to be 2.65. A “raining” technique for sand placement resulted in a void ratio of 0.49, or an (air) dry density of about 110 lb/ft\(^3\), which corresponds to a relative density of about 90 percent. Constant strain rate, vacuum triaxial tests gave an angle of shearing resistance, \( \phi' = 48 \) deg.

The other sand used was a crushed quartz sand, hereafter referred to as “60-80” sand, because 70 percent of the particles was retained between the 60 and 80 U. S. standard sieves. Table 1 gives the grain size distribution of this sand.

The specific gravity of solids was found to be 2.66. The “raining” method of sand placement resulted in a void ratio of 0.75, or an (air) dry density of about 95 lb/ft\(^3\), which corresponds to a relative density of about 90 percent. Constant strain rate, vacuum triaxial tests gave an angle of shearing resistance, \( \phi' = 48 \) deg.

Because the “60-80” sand was crushed, the particles were angular and the fracture surfaces were smooth. The “20-30” sand, because of its aeolian deposition, had well rounded particles with “pitted” or “frosted” surfaces. These differences in size, angularity, and surface texture had a pronounced effect on the test results.

Test Rods

Three types of rods were used: steel, smooth mortar, and rough mortar. Graphite and teflon were applied to some of the test rods to act as friction reducers. The various surfaces that were tested are listed below.

1. Plain steel
2. Teflon coated steel
3. Graphite coated steel
4. Plain smooth mortar
5. Teflon coated smooth mortar
6. Graphite coated smooth mortar
7. Plain rough mortar

The steel test rod used was machined from a mild (low carbon) steel bar and was finished with a very fine emery cloth producing a smooth test surface.

The mortar rods were made using the “20-30” sand (ASTM C190-59) and Type III Portland Cement (ASTM C150-61) in the following proportions (by weight):

- Water-cement ratio, 0.45
- Aggregate-cement ratio, 0.45
- Wetting agent (Plastiminct) 1 percent of cement weight

The mix was placed in a plexiglass mold, thoroughly rodded, and then cured for 8 h. The mortar rods fabricated in this manner had very smooth surfaces. Some of the rods were roughened by successive immersion in weak hydrochloric acid, washing, and scrubbing with a stiff brush until about 15 percent of the diameter of the sand grains was exposed above the level of the cement paste.

In some of the tests, graphite or teflon was applied to the above rods to reduce the friction. A thin (less than 0.0001 in.) graphite coating was applied to the test surfaces with a soft pencil and Dixon No. 2 graphite flakes. The surface flakes were rubbed on with a cotton applicator. The teflon coating was applied to the rods by covering them with \( \frac{1}{2} \) in. wide by 0.006 in. thick Teflon “Temp-R-Tape.” Two layers of tape were applied to the rod, care being taken so that no two of the longitudinal butted joints occurred in the same place.

Results

Static Friction Tests

Table 2 summarizes the values of \( \mu_s \), obtained for the two types of sands on the variety of surfaces tested in this study. The tests performed using a 2 in. diameter rod (contact area approximately 63 in.\(^2\)) showed no appreciable difference in computed values of coefficient of friction compared to the values obtained using the 1\( \frac{1}{2} \) in. diameter rod (contact area approximately 35 in.\(^2\)). Consequently all the values were averaged and are presented in Table 2.

The ranges in \( \mu_s \) values for most tests reported in Table 2 was \( \pm 0.05 \) and often times substantially less. However, for the rough mortar surface on the “20-30” sand and for the rough mortar, teflon coated steel, teflon coated smooth mortar, and graphite coated smooth mortar surfaces on “60-80” sand the range in \( \mu_s \) was as high as \( \pm 0.10 \).

Examination of Table 2 shows that the coefficient of wall friction depends not only on the nature of the surface involved but also on the angularity and roughness of the sand grains in relation to the roughness of the surface itself. In the case of the
TABLE 2—Average values of static coefficients of friction, \( \mu_s \).

<table>
<thead>
<tr>
<th>Rod Surface</th>
<th>Number of Tests</th>
<th>Average ( \mu_s )</th>
<th>Number of Tests</th>
<th>Average ( \mu_s )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished steel</td>
<td>8</td>
<td>0.34</td>
<td>7</td>
<td>0.30</td>
</tr>
<tr>
<td>Teflon coated steel</td>
<td>29</td>
<td>0.33</td>
<td>11</td>
<td>0.59</td>
</tr>
<tr>
<td>Graphite coated steel</td>
<td>4</td>
<td>0.24</td>
<td>4</td>
<td>0.39</td>
</tr>
<tr>
<td>Smooth mortar</td>
<td>34</td>
<td>0.60</td>
<td>3</td>
<td>1.05</td>
</tr>
<tr>
<td>Teflon coated smooth mortar</td>
<td>21</td>
<td>0.33</td>
<td>4</td>
<td>0.57</td>
</tr>
<tr>
<td>Graphite coated smooth mortar</td>
<td>28</td>
<td>0.32</td>
<td>4</td>
<td>0.61</td>
</tr>
<tr>
<td>Rough mortar</td>
<td>32</td>
<td>0.76</td>
<td>4</td>
<td>1.11</td>
</tr>
</tbody>
</table>

\( a \tan \phi' = 0.84 \)
\( b \tan \phi' = 1.11 \)

TABLE 3—Effect of lubricants on static friction.

<table>
<thead>
<tr>
<th>Rod Surface</th>
<th>Friction Reduction for “20-30” Sand, %</th>
<th>Friction Reduction for “60-80” Sand, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Graphite coated steel</td>
<td>29</td>
<td>22</td>
</tr>
<tr>
<td>Graphite coated smooth mortar</td>
<td>47</td>
<td>42</td>
</tr>
<tr>
<td>Teflon coated smooth mortar</td>
<td>45</td>
<td>46</td>
</tr>
<tr>
<td>Teflon coated steel</td>
<td>3</td>
<td>-18</td>
</tr>
</tbody>
</table>

TABLE 4—Comparison of \( \mu_s \) values.

<table>
<thead>
<tr>
<th>Rod Surface</th>
<th>“20-30” Sand</th>
<th>“60-80” Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Density, %</td>
<td>Potyondy</td>
<td>Sand</td>
</tr>
<tr>
<td>Normal Stress, psi</td>
<td>66</td>
<td>90</td>
</tr>
<tr>
<td>( \tan \phi' )</td>
<td>7.0</td>
<td>7.5</td>
</tr>
<tr>
<td>( \mu_s ), Smooth Steel</td>
<td>0.98</td>
<td>0.84</td>
</tr>
<tr>
<td>( \mu_s ), Smooth Mortar</td>
<td>0.45</td>
<td>0.34</td>
</tr>
<tr>
<td>( \mu_s ), Rough Mortar</td>
<td>0.82</td>
<td>0.60</td>
</tr>
</tbody>
</table>

TABLE 5—Comparison of average static and dynamic coefficients of friction.

<table>
<thead>
<tr>
<th>Rod Surface</th>
<th>Sand</th>
<th>Average ( \mu_s )</th>
<th>Average ( \mu_d )</th>
<th>( \frac{\mu_d - \mu_s}{\mu_s} ) \times 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polished steel</td>
<td>60–80</td>
<td>0.50</td>
<td>0.63(22)(^a)</td>
<td>26</td>
</tr>
<tr>
<td>Smooth mortar</td>
<td>20–30</td>
<td>0.60</td>
<td>0.67(18)(^a)</td>
<td>12</td>
</tr>
<tr>
<td>Rough mortar</td>
<td>20–30</td>
<td>0.76</td>
<td>0.82(14)(^b)</td>
<td>6</td>
</tr>
<tr>
<td>Teflon coated smooth mortar</td>
<td>20–30</td>
<td>0.33</td>
<td>0.58(3)(^a)</td>
<td>76</td>
</tr>
<tr>
<td>Teflon coated steel</td>
<td>20–30</td>
<td>0.33</td>
<td>0.56(13)(^a)</td>
<td>70</td>
</tr>
<tr>
<td>Graphite coated smooth mortar</td>
<td>20–30</td>
<td>0.32</td>
<td>0.44(20)(^a)</td>
<td>38</td>
</tr>
</tbody>
</table>

\( a \tan \phi' = 0.84 \)
\( b \) Numbers in parenthesis indicate number of individual dynamic tests.

"60–80" sand sliding on the rough mortar rod the angle of wall friction equalled the angle of shearing resistance of the sand, which implies that sand/sand slip occurred.

Table 3 shows that graphite was effective in reducing friction for both surfaces tested. Teflon was equally effective when applied to the smooth mortar surface; however, when applied to the plain steel surface the reduction in \( \mu_s \) for the “20–30” sand was insignificant, and in the case of the “60–80” sand, the coefficient of friction increased because the angular particles of this sand tended to dig into the teflon coating.

Suklje and Brodnik [7] performed static friction tests with several flat concrete plates 20 cm in width and either 60 cm or 30 cm long on beds of two types of cohesionless material. Their test results show that the coefficient of static friction between a smooth concrete plate and gravel is less than between the same plate and sand, and that \( \mu_s \) for a rough concrete plate sliding on gravel is greater than a smooth concrete plate sliding on the same gravel. Since details of the nature of the cohesionless materials or the roughness of the concrete plates were not given, direct comparison of numerical values with those obtained in this study is not possible. However, the order of magnitude of the results obtained, and their general trends, are compatible.

Potyondy [6] performed skin friction tests with steel, concrete, and wood on various soils. The tests were run in a stress controlled shear box having an area of 12.4 in\(^2\). The steel test surface was very similar to the one used in this study; the smooth concrete surface was prepared by placing a concrete mix with 2.5 mm maximum aggregate in a plywood form. The rough concrete surface was made by pouring a mix with 7.5 mm aggregate on “flat rough ground.” Among the soils tested by Potyondy was a well graded dry (water content = 0.8 percent) sand having a uniformity coefficient of 3.8 and a median size corresponding to the “20–30” sand. The results are compared in Table 4.

Dynamic Friction Tests

Data from the piezoelectric pressure gages measuring \( \Delta N \) [5, 6] indicated that its value just prior to actual slippage of the rod was too small to influence the computed values of dynamic coefficient of friction, \( \mu_d \), significantly. Accordingly, the values of \( \mu_d \) reported herein were computed assuming \( \Delta N = 0 \). The rough surface concrete was made by pouring a mix with 7.5 mm aggregate on “flat rough ground.” Among the soils tested by Potyondy was a well graded dry (water content = 0.8 percent) sand having a uniformity coefficient of 3.8 and a median size corresponding to the “20–30” sand. The results are compared in Table 4.

Table 5 summarizes the average values of \( \mu_d \) obtained for various test surfaces and compares them with the corresponding values of \( \mu_s \). The range in dynamic coefficients of friction were about the same as those reported for the static tests. The results show that the dynamic wall friction is greater than the static friction. In the case of unlubricated surfaces, the increase is of the order of 20 percent unless sand/sand slip occurs. For teflon and graphite surfaces the increase is much greater. The data in Table 5 offer further evidence [8] that \( \phi' \) dynamic essentially equals \( \phi \) static; thus tan \( \phi' \) is an upper limiting value for the coefficient of wall friction in dry sands.

Table 6 shows that graphite is nearly as effective in reducing dynamic friction as it was for static friction.

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Teflon is much less efficient than graphite under dynamic conditions due, perhaps, to viscosity effects.

Conclusions

The following conclusions are based on laboratory tests in which the coefficient of friction between dry sands and steel, cement mortar, teflon, and graphite surfaces with a contact area of 35 to 63 in.\(^2\) was measured at contact pressures up to 12.5 psig and for loading times to initiate slip of 5 min and about 1 ms:

1. The static coefficient of friction is markedly affected by the size, angularity, and surface texture of the sand grains, regardless of the nature of the surface against which slip is occurring.

2. When the sliding surface is rough in comparison to the grain size of the sand, the angle of wall friction exceeds the angle of shearing resistance of the sand and sand/sand slip occurs. Since the angle of shearing resistance, \(\phi'\), of dry sands is practically uninfluenced by the rate of loading, tan \(\phi'\) is an upper limiting value for the coefficient of wall friction regardless of the rate at which slip is initiated.

3. In the case of unlubricated surfaces, the dynamic coefficient of friction is about 20 percent greater than the static coefficient, unless the conditions for sand/sand slip are approached.

4. For static loading rates, graphite is an excellent lubricant for both steel and mortar surfaces; teflon was effective in the case of mortar surfaces but did not reduce friction significantly in the case of a smooth steel surface.

5. For dynamic loading rates, both teflon and graphite act as lubricants when compared to the plain surfaces; however, teflon is less effective than graphite, possibly due to viscosity effects.

References


