Side friction of piles in calcareous sands

Friction latérale des pieux dans les sables calcaires

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SYNOPSIS Steel piles driven in calcareous sands develop considerably less side resistance than those driven in silica sands. This paper describes an investigation of the strength behavior and soil-steel friction of two noncemented calcareous sands, with particular emphasis on the effects of grain crushing on these properties. Results indicate that calcareous sands have very high friction angles, and average soil-steel friction angles. Grain crushing does not appear to reduce these properties. It is concluded that low side friction of steel piles driven in calcareous sands is caused by low effective soil-pile interface stresses rather than small soil-pile friction angles.

INTRODUCTION

Calcareous sands are composed primarily of calcium carbonate ($CaCO_3$) and are abundant in coastal zones and continental shelves of the warm equatorial regions of the ocean. They are composed of shells and skeletal remains of benthos (bottom dwelling) organisms such as corals, molluscs, and calcareous algae. Coral sands are products of erosion and slumping around coral reefs and atolls. Coral reefs are formations of calcium carbonate laid down by living plants (coraline algae) and animals (corals). They develop in shallow waters between 30 degrees south and 30 degrees north latitude (McClelland, 1974). Because calcareous sands are biogenic in origin, and are derived from mechanical erosion and breakdown of coral reefs and shells by wave action (a mechanism similar to the process of erosion of clastic rocks), they are referred to as bioclastic sediments (Seibod and Berger, 1982; Noorany, 1983).

During the past decade, it has been recognized that the geotechnical properties of calcareous sands are different from those of silica sands (McClelland, 1974 and 1980; Datta, et al., 1979; several papers in Demars and Chaney, 1981; Nauroy and Le Tirant, 1983; and Dutt and Cheng, 1984). In particular, experience with pile foundations driven in uncemented and partially cemented calcareous sands indicates that friction resistance on the sides of these piles is considerable lower than that in silica sands. (Angemeer, et al., 1973 and 1975; McClelland, 1974 and 1980; Agarwal, et al., 1977; Sullivan and Squire, 1980; Cottrill, 1982; Puyuelo, et al. 1983, Dutt and Cheng, 1984 among others). When this phenomenon was first noted, it was attributed to the relative softness of calcium carbonate compared to quartz. However, it was later realized that some calcareous sands develop higher interparticle friction than most terrestrial soils (McClelland, 1980; Beringen, et al., 1981; Noorany, 1982; Dutt and Cheng, 1984), indicating that factors other than soil friction might be responsible for the abnormally low side resistance of piles driven in calcareous sands.

SCOPE OF STUDY

The objective of this study was to investigate the internal friction and soil-steel friction of two noncemented calcareous sands, and to evaluate the influence of particle crushing on these properties. The sands were taken from two beaches: one on the island of Guam and the other in southern Florida. Isotropically consolidated-drained (ICD) triaxial compression tests were run on each soil to measure the stress-strain behavior and the effective friction angle, ϕ', in loose and dense states. The effective confining pressure varied from 100 kPa to 400 kPa. The loose condition was obtained by pouring (raining) the soil in the specimen mold. The dense condition was obtained by placing the soil in five layers and tamping. The controlling factor for each set of specimens was void ratio. The tests on crushed soil were run on the material which was partially crushed to obtain a finer grained soil with the same coefficient of uniformity as the natural soil shown in Figure 1. A few tests were also run on thoroughly crushed (ground) soil samples.

Soil-steel friction was measured in direct shear mode by sliding a 9cm x 9cm steel plate on the surface of compacted soil. The effect of particle crushing on soil-steel friction angle, δ, was also measured.

For comparison, a silica sand having a grain-size distribution similar to the two calcareous sands, was also tested. The test results were analyzed to evaluate the influence of soil crushing on shear behavior, and on soil-steel friction angle of calcareous sands.

SOIL DESCRIPTION AND PROPERTIES

The calcareous sand from Guam was a uniformly graded material with a carbonate content of more than 90%. The grain-size distribution curves for this soil, in natural, crushed and ground states, are shown in Fig. 1. The soil had both rounded and elongated particles with rough texture, and

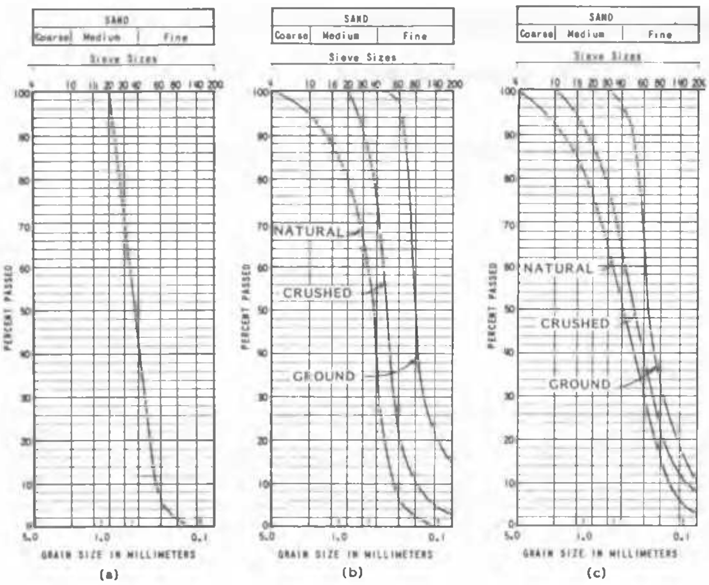

Fig. 1 Grain Size Distribution Curves for (a) Silica Sand, (b) Calcareous Sand from Guam and (c) Calcareous Sand from Florida

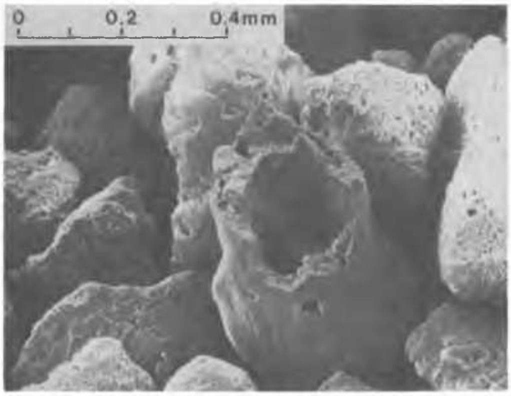

Fig. 2. Electron Photomicrograph of Calcareous Sand from Guam

it also included some hollow particles as shown in Fig. 2. The specific gravity of solids was 2.80. The grain-size distribution curves for the calcareous sand from Florida are shown in Fig. 1. The specific gravity of solids was 2.84. The soil contained some flat pieces of broken shells as well as bulky particles with rough texture. The percentage of calcium carbonate was about 92.

The silica sand tested was a uniformly graded sand with a grain size distribution shown in Fig. 1. The soil consisted of bulky particles with smooth surfaces. The specific gravity of solids was 2.61.

RESULTS OF STRENGTH TESTS

The stress-strain and volume change characteristics of each sand under loose and dense conditions were measured in ICD triaxial compression tests. Tests were run both on dry and fully saturated samples. Back pressures of 400 to 500 kPa were used to obtain B values over 97%. To study the effect of particle crushing on the strength properties, tests were run at equal soil densities on natural, crushed and ground soil conditions.

Typical stress-strain and strain-volume change data measured on the calcareous sand from Guam are shown in Fig. 3, and a typical p-q plot is shown in Fig. 4. Similar results were obtained from a large number of triaxial tests on both calcareous sands; complete data can be seen in Noorany, 1982. A summary of the soil friction data is given in Table I.

The salient points of the triaxial test results are summarized below:

a. When compacted in identical manner, the calcareous sands tested had considerably higher void ratios than the silica sand (Table I). However, because a significant part of the voids were intraparticle voids they did not affect soil shearing resistance, especially at low stress levels. As stresses built up, some grain crushing occurred, but the amount of crushing in triaxial samples loaded to failure was very minor. This was determined from a comparison of grain size distribution curves before and after testing.

b. Despite a higher void ratio and crushability, calcareous sands possess very high internal friction angles. The friction angles of the two calcareous sands tested (44° to 49°) are significantly higher than those for most silica sands. The high values for loose condition are particularly surprising, although the limited data available support this finding (Datta et al., 1979 and 1980; Beringen et al., 1980; and Dutt and Cheng, 1984).

c. The high friction angles of the calcareous sands tested were not due to dilatational behavior during shear. In loose states both soils exhibited volume decrease, yet they had friction angles in the range of 44 to 46 degrees. Surface roughness at grain contact points, and the reinforcing effects of elongated flat particles in the soil matrix, might be responsible for high frictional resistance of calcareous sands.

d. The friction angle of the calcareous sands tested decreased with increase in confining pressure (Fig. 4). The decrease in ϕ' was noticeable at confining pressures higher than 300 kPa; at a confining pressure of 400 kPa, the amount of reduction in ϕ' value for both sands was from 2 to 4 degrees.

e. At equal void ratios, the friction angles of crushed calcareous sands were essentially the same as those of natural soil.

TABLE I

Results of Triaxial and Soil-Steel Friction Tests

Soil Type	Specific Gravity, G_s	Soil Condition	Void Ratio, e	Friction Angle, ϕ, Degrees	Soil-Steel Friction Angle δ, Degrees
Silica Sand	2.61	loose	0.90	35	21
		dense	0.73	40	20
Calcareous sand from Guam	2.80	loose	1.36	46	18
		dense	1.18	49	18
		loose,crushed	1.32	46	21
		loose,ground	1.32	46	--
		dense,crushed	1.12	48	22
Calcareous sand from Florida	2.84	loose	1.44	44	20
		medium	1.30	45	20
		dense	1.19	47	23
		medium,crushed	1.30	45	23
		medium,ground	1.30	45	--
		dense,crushed	1.06	49	23

Even when a thoroughly crushed (ground) soil was tested at the same void ratio as the natural soil, it had the same friction angle (Fig. 4).

RESULTS OF SOIL-STEEL FRICTION TESTS

The results of soil-steel friction tests are summarized in Table I. These results indicate that unlike ϕ' values, δ values for calcareous sands appear to be comparable to those of silica sands. The test results also indicate that the soil-steel friction angle, δ, did not change significantly with soil density. Also, as was the case for ϕ', the δ values for the natural and crushed soils were about the same. This finding was similar to the test results reported by Beringen et al. (1981), but Dutt and Cheng (1984) have reported higher δ values for another calcareous soil.

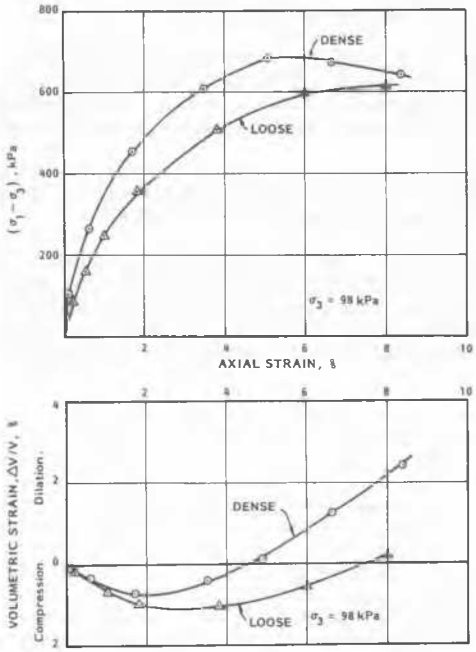

Fig. 3. Typical Results of Triaxial Compression Tests on Calcareous Sand from Guam

CONCLUSIONS

The side resistance developed on the surface of a pile driven in a soil can be expressed as:

$$f = \sigma_n' \tan\delta = K\,\sigma_v' \tan\delta \qquad (1)$$

where f is side friction; σ_n' is effective normal stress; σ_v' is effective vertical stress; K is coefficient of lateral pressure; and δ is soil-pile friction angle.

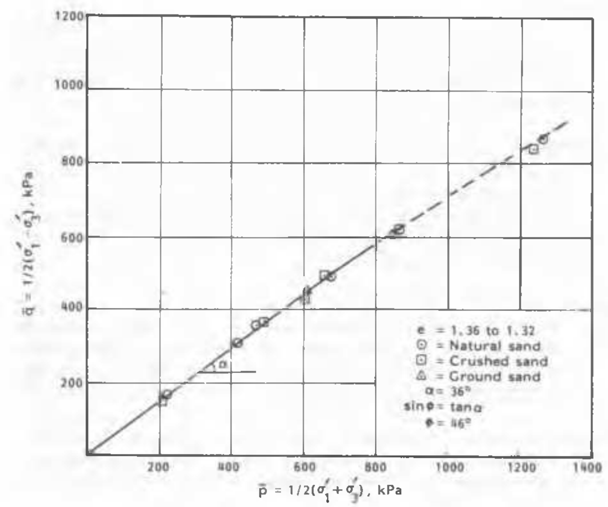

Fig. 4. p-q Diagram and Failure Line for Loose Calcareous Sand from Guam

The results of this study have eliminated the possibility that the frictional characteristics of calcareous sands are responsible for the low shaft resistance of piles. Therefore, by eliminating this factor, and on the basis of effective stress principles applied at the pile-soil interface, it appears that the only remaining cause of the observed low capacities of driven straight steel pipe piles in calcareous sands is that the effective normal stress, σ_n' acting perpendicular to the pile surface is much lower than expected. The possibility that the soil-pile interface stress is abnormally low was suggested by McClelland (1980), Nauroy and LeTirant (1983), and Dutt and Cheng, (1984).

The soil-pile interaction mechanism in calcareous sands is different from silica sand. When a pile is driven in a silica sand, the soil packs tightly around the pile and builds large soil-pile interface stresses. In calcareous sands, however, the soil is naturally very loose and pile driving vibrations are not very effective in densifying this type of soil which is composed of many flat particles and some bulky hollow particles. A driven pile causes the soil grains to crush rather than displace laterally. Consequently, the soil-pile interface stresses will be small.

Soil cementation can further influence the soil-pile interface stress. In a partially cemented soil, pile vibration during driving may create a small gap between the soil and the pile, decreasing the soil-pile interface stresses to very small values. The combination of these factors appears to be responsible for the low side resistance of piles in calcareous sands.

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