Centrifuge 88, Corté (ed.)
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Scale effects arising from particle size

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ABSTRACT: A Chatelet flint grit and a silica flour of similar particle shape and grading were selected to display a factor of 50 difference in particle size. Footing tests were conducted on the soils both in a centrifuge and at 1 g using equivalent surcharge.

The centrifuge and surcharge tests were found to give compatible results. There was no evidence that reduced particle size encouraged "premature" failure through shear ruptures. Indeed the dominant effect, proved in triaxial tests, was the greater capacity of the silica flour to maintain large angles of shearing and rates of dilation at high effective stresses. This caused the footing tests on silica flour to exhibit greater stiffness and strength than those in flint grit. If particle scaling is carried out for the purposes of satisfying scaling problems related to ruptures or permeability, it must be appreciated that the relative invulnerability to crushing of smaller particles may influence results.

1 BACKGROUND

Dimensional analysis reveals that the use of identical soils at field and model scales carries with it a distortion D/L due to the particle size D in relation to a typical boundary dimension L. It is well known that shear rupture propagation (Scarpelli and Wood, 1982) is affected by particle size. A given soil may be less vulnerable to post-peak softening on rupture bands in a small model with reduced displacements. Furthermore, fast softening to a critical state was inferred by Bolton and Steedman (1985) in the analysis of retaining walls subject in a centrifuge to sliding during a model earthquake. It is therefore necessary to consider the possibility of reducing particle size in conformity with the model scale factor, and to categorise the various classes of boundary problem with regard to the importance of rupture propagation. This can best be done by comparing model tests whose only difference is the particle size of soils which display identical continuum properties.

2 MODELLING THE SOIL AGGREGATE

Two silica soils were modified to produce sand-sized and silt-sized aggregates with similar grading curves, figure 1, which differed by a factor of 50 in particle size. Micrographs of the Chatelet flint grit and the silica flour at appropriate magnification show that both soils consist of highly angular particles of similar shape: figure 2. Their maximum packing density, e = 0.55, was found to be identical and this was used as a target state in all the tests.

Since the mineralogy of the soils was similar, their unit weight was identical at identical void ratios. Mechanical properties of the aggregate additionally depend on the stiffness and strength of the particles. Stiffness is an intrinsic property which depends only on mineralogy. Crushing strength of grains is, however, an extrinsic material property depending on such parameters as the spacing of flaws. Figure 3 shows the results of drained high pressure triaxial compression tests on the two soils close to their densest condition. It will be seen that the angle of shearing resistance ϕ'_{max} of the silica flour is 4 to 5 degrees more than that of the flint grit at the same void ratio and confining pressure. Figure 4 confirms this, and shows that the extra strength is due to extra dilatancy.

Both direct shear box tests and stress-dilatancy plots indicated that the two soils possessed identical critical state angles $\phi'_{crit} = 37.5°$. This high value, according to Norris (1977) is typical for angular soils. Whereas the strength and dilatancy of the flint grit tests fell close to the Bolton (1986) empirical correlations for sands, the silica flour was much more strong and dilatant at a given effective stress. The separation in figure 4 can be described either as a strength increment of about 4.5° or as a reduction in stress-sensitivity by a factor of about 4.5. It is logical that the

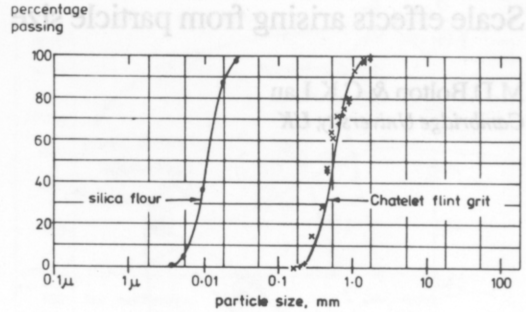

Figure 1 Grading curves

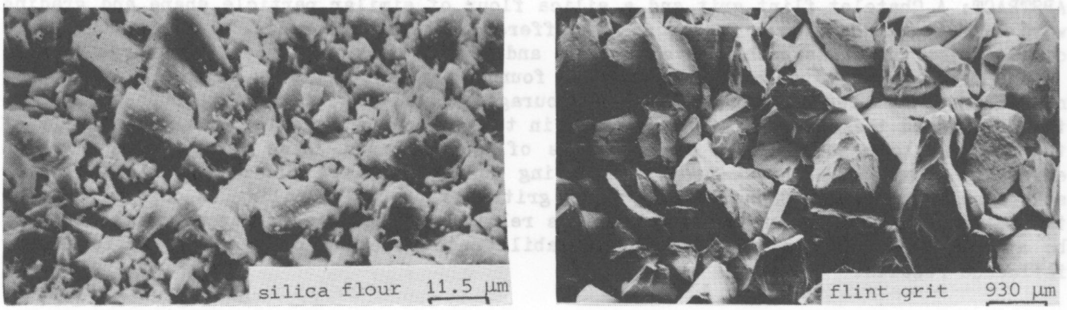

Figure 2 Micrographs

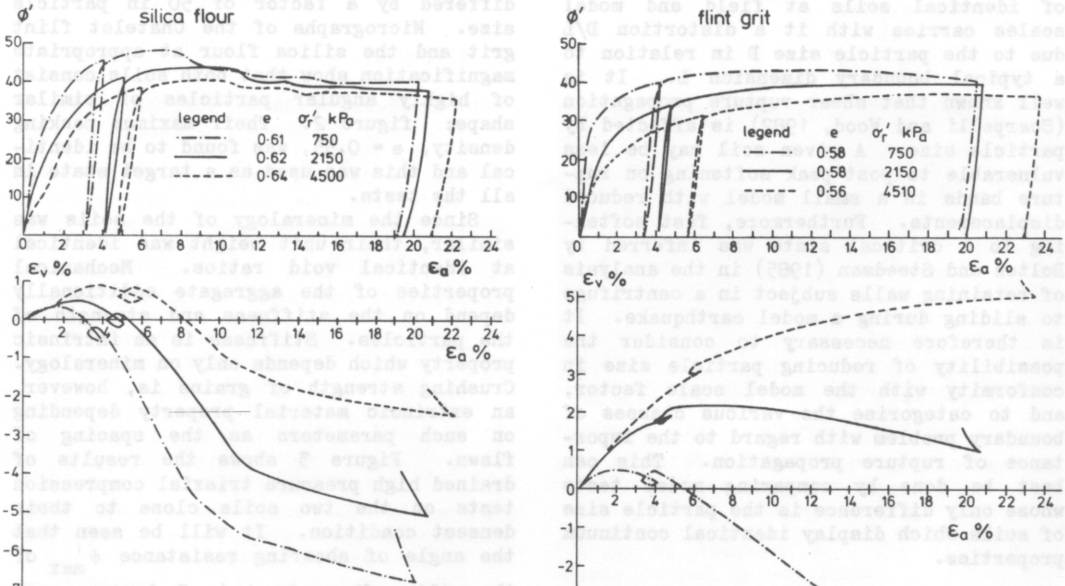

Figure 3 High pressure triaxial tests

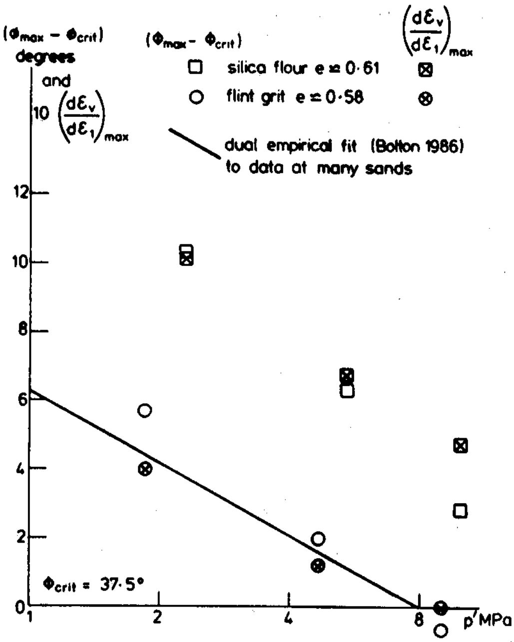

Figure 4 Strength and dilatancy versus mean effective stress

crushing strength of small silica particles should be greater, since they have precisely been derived through the crushing of larger particles (Marachi et al, 1969).

3 CENTRIFUGE TESTS

Figure 5 shows a schematic arrangement of tests conducted on the Cambridge Geotechnical Centrifuge, in which circular punches were driven slowly into the surface of dense, saturated beds of the two soils. The grit was produced by slow pluviation and subsequently saturated by upward percolation. The silica flour was mixed in a saturated condition and densified by vibration to the same void ratio. Figure 6 shows at prototype scale the development with time of bearing pressure, penetration, and surface movement when a 100 mm footing was forced at 50 g into silica flour. Pore water pressures were measured at various locations and found to be negligible. Two unload reload cycles were performed. The capacity of the loading frame prevented the application of bearing pressures in excess of 8 MPa, and it seemed that the soil still had a reserve of strength. Failure was eventually provoked only be reducing the acceleration to 30g. The footing then continued to "creep" at constant load. Vertical lead threads which had been inserted by hypodermic needle in the model around and beneath the location of the footing showed no evidence of dislocation when radiographed after the test. Figure 7, in contrast, shows the same test repeated on flint grit. A clear bearing failure had occurred by 80 minutes, at which the bearing pressure was about 6 MPa at a settlement ratio w/B = 0.15. There followed clear evidence of plastic indentation and surface heave, causing extra punch capacity due to the extra overburden of sand lying above the punch interface. The final deformations were displayed by excavation revealing the specially coloured layers which had been introduced during pluviation. The excavation was made possible by introducing sugar solution which was then evaporated so that the grit skeleton became lightly cemented with sugar grains. There was no evidence of shear ruptures: figure 8.

4 1-g SURCHARGE TESTS

There is some advantage in supplementing the data of relatively expensive centrifuge tests by conducting analogous tests at 1g in a conventional laboratory.

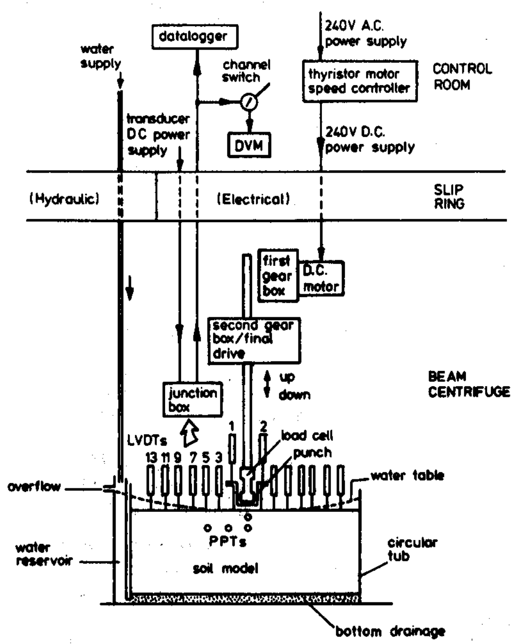

Figure 5 Schematic layout of centrifuge package

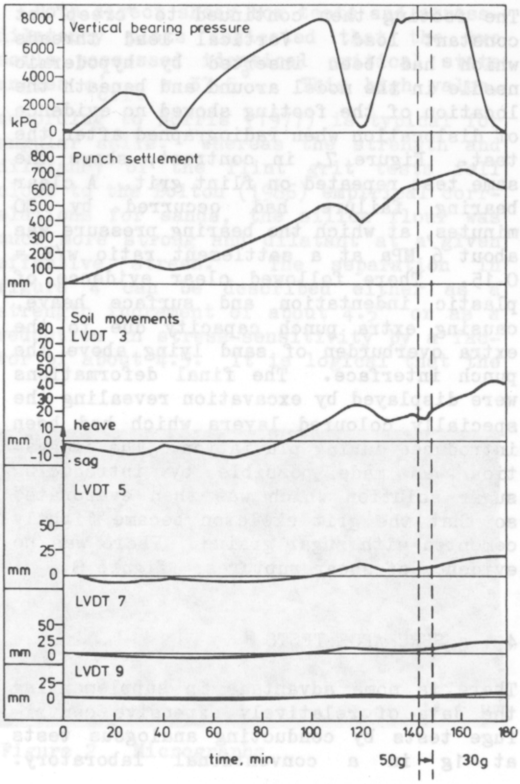

Figure 6 100 mm footing at 50g/30g: silica flour

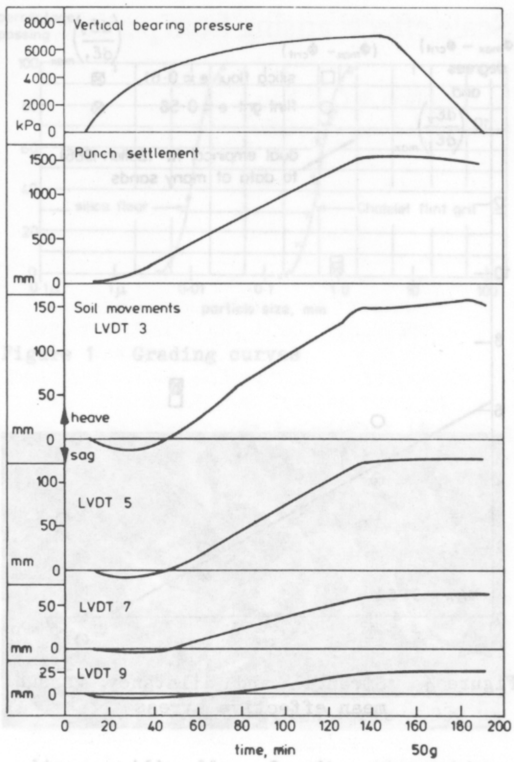

Figure 7 100 mm footing at 50g: flint grit

Terzaghi's bearing capacity equation

$$\sigma'_f = \sigma'_o N_q + \frac{1}{2}B\gamma' N_\gamma$$

can be used to draw an equivalence between the terms $\frac{1}{2}B\gamma'$ and σ'_o, bearing in mind that N_γ and N_q are approximately equal over a wide range of ϕ' values. Such an equivalence, bearing in mind the variation of ϕ' with p' for example, is bound to be approximate.

The footing apparatus was modified so that an annular balloon could apply an effective surcharge σ_o around the footing. Figure 9 compares the data of 1g tests of the 100 mm diameter footing on silica flour with the centrifuge data shown in figure 6.

The footing stress σ_f is non-dimensionalised by dividing by the "equivalent surcharge" defined as the effective vertical stress at a depth B/2 beneath the footing of diameter B. The extra surcharge caused by settlement is accounted for (approximately) in the centrifuge tests but is negligible at 1g. It will be seen that data at corresponding surcharge levels is quite similar. The extreme dependence of bearing stiffness and

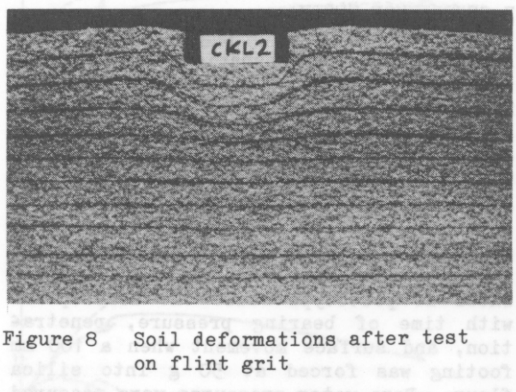

Figure 8 Soil deformations after test on flint grit

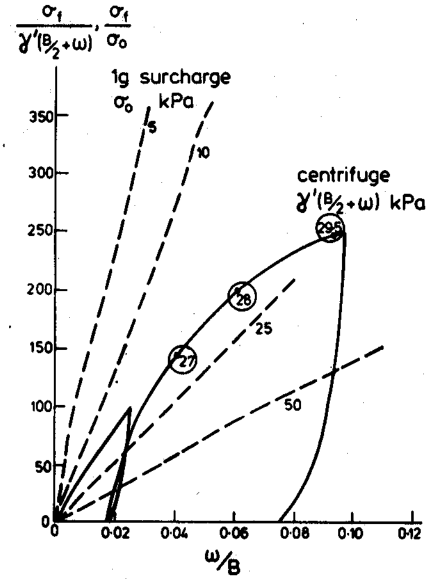

Figure 9 50g test compared with 1g tests: 5 m prototype on silica flour

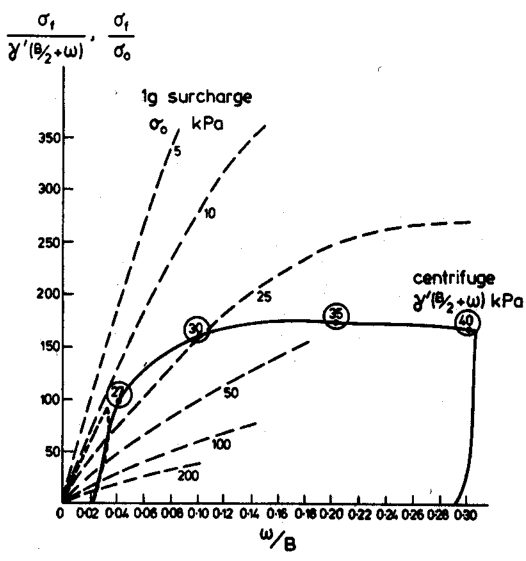

Figure 10 50g test compared with 1g tests: 5 m prototype on flint grit

strength on the stress magnitude is now obvious.

Figure 10 shows a similar non-dimensional plot for the 100 mm footing on flint grit. The reduced strength of flint grit compared with silica flour is evident from a comparison of figures 9 and 10, where there is a factor of about 1.6 between pressures developed at larger settlement ratios. Inspection of charts of bearing capacity coefficients reveals roughly parallel log-linear relationships between N_q (and N_γ) and ϕ' . A factor of 1.6 on bearing capacity corresponds to a differential angle of shearing of about 3°. A similar factor was observed in the bearing capacities of 14 mm footings tested under surcharge on the two soils.

5 CONCLUSIONS

1. It was possible to construct two soils - a silica flour and a flint grit - which differ in grain size by a factor of 50 and which are otherwise similar.

2. Silica flour is effectively a crushed sand, and it exhibits an unusual degree of strength and dilatancy even under large confining stresses. Any attempt to scale down soil particles must account for the tendency of smaller particles to be less crushable.

3. Large footings (e.g. > 1 m prototype) develop large bearing capacities on granular soils. The progressive loss of strength and dilatancy under increased stresses dominates behaviour. Ruptures were not observed.

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