Interpretation of the rapid load test for foundation piles

I. Luker
University of the Witwatersrand, Johannesburg, South Africa

ABSTRACT: Surface shear stress on a 93 mm diameter pile was measured in laboratory load tests done at a very slow speed, equivalent to a standard maintained load ("static") test, and at velocities seen in "rapid" load tests. The unloading point method was used to predict the slow speed stresses from the rapid loading stresses. An empirical factor is used in practice to adjust the predicted to actual stresses. The effect of soil type on this factor is shown.

1 INTRODUCTION

There are two methods of quickly doing a load test on piles: the "dynamic" and the "rapid" tests. In the dynamic test, a large mass is dropped onto stiff padding (e.g. a wooden board) on the head of the pile. This sends a compression force wave down the pile, of duration and length approximately 5 milliseconds and 20 m. The wave's energy is damped by friction with the soil on its way down and at the toe reflects as a tension wave. Acceleration and strain are measured at the head of the pile and are interpreted into the force v. displacement relationship that would have been seen if a standard maintained load ("static") load test had been done instead. This interpretation requires special computer software and much experience.

In the rapid test, force is applied over a longer time (approximately 50 to 200 ms) either by dropping a mass onto a spring or by accelerating a mass up from the pile head. Because of the longer time of force application, all the pile is in compression throughout the test and there are no wave effects, so that interpretation to get the static behaviour does not require complex computing.

Calculation of the static behaviour from measurements done in the rapid test has been done in two ways (Rausche et al. 2018): (i) the unloading point method (UPM) described by Middendorp et al. (1992); (ii) direct conversion of the rapid test's force v. displacement relationship to that of a static test, using a soil behaviour model incorporating soil velocity. In both cases empirical factors are needed to adjust the theoretical result to match reality. These have been found by previous researchers from on-site tests on full size piles, and recommended values vary. For example, the following are applicable to the UPM.

Table 1. Results applicable to UPM

Authors	Sandy soils	Clay soils
Weaver and Rollins (2010)	1.1	2.1
Holscher et al. (2012)	1.0	1.52

To improve the precision of interpretation of the rapid test using the UPM, a 93mm diameter pile was tested in the laboratory in a wide range of soil types.

2 APPARATUS AND PARAMETERS MEASURED

Figure 1 shows a section through the apparatus.
Salient features are: (i) the 93mm diameter pile is a steel tube with glued-on sand, separated into three lengths by loadcells measuring longitudinal force; (ii) acceleration is measured by two instruments in one of the loadcells; (iii) when soil is compacted between the pile and the container, a "ramming block" is placed under the pile; (iv) when the pile is being tested, a soft expanded polystyrene block with a hole in its centre supports the soil while allowing free downward movement of the pile. Hence only side shear resistance is present.

It was decided to investigate only the shaft resistance component because: (i) the soil mechanics of side shear are very different from end bearing; (ii) Holscher et al. (2012) have said that the velocity of the pile during the test influences side shear more than end-bearing; (iii) it was desirable to limit the complexity of the testing arrangement and concentrate on one aspect of pile resistance at a time.

The South African and USA specifications for the static test state that the next load increment may be applied when the rate of settlement has reduced to less than 0.2 and 0.25 mm/hr respectively. Rausche et al. (2018) refer to tests of Coyle and Gibson (1970) and suggest that no further reduction in resistance occurs if a test is carried out slower than 0.005 m/s in sand or 10^{-5}m/s in clay. Therefore, in the present slow tests, the rate of movement was kept below 0.5 mm/hr ($1.4x10^{-7}$ m/s).

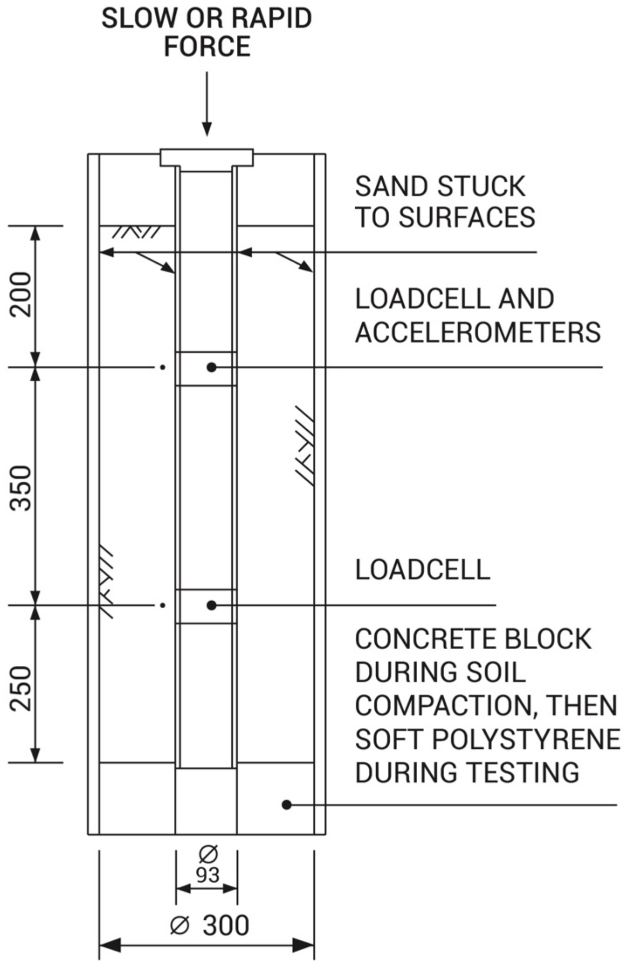

Figure 1. Section through the pile in its soil

Middendorp and Daniels (1996) have reported that for wave effects to not occur in a quick test - that is for it to be a "rapid" test - the length of time over which the force is applied must be greater than 12 times the time that a stress wave would take to travel from one end of the pile to the other. The model pile was 910 mm long, made of steel having a stress wave velocity of 5000 m/s, so the travel time is 0.18 milliseconds. In all the fast tests done in this study, the time of force application was not less than 20 ms, therefore they satisfy this criterion to be rapid tests.

Rapid loading was applied by dropping a 100 kg steel mass onto a plastics polymer spring on top of the pile, causing velocities of displacement of the pile up to 2.2 m/sec. Rausche et al. (2018) report that velocities in rapid tests vary up to 6 m/s. The higher values would occur when, to have enough energy to produce the required force, a small mass was dropped from a sufficiently large height.

3 CHOICE OF TESTS FOR COMPARING "STATIC" AND "RAPID" BEHAVIOURS

Ideally one would set up the pile in a bed of a particular soil then do (say) a slow (i.e. "static") test on it. One would then set up the pile in an identical bed of the same soil and do a rapid test on it. However, because the side shear behaviour of the soil is dominated by the condition of a thin annulus adjacent to the pile surface, it is difficult to get identical soil conditions in sequential tests.

To investigate whether sufficiently consistent test results could be obtained from different (though nominally identical) beds of soil in the present apparatus, the pile was set up three times in a bed of clayey sand. Slow tests taking 18 hours each were performed. Figure 2 shows the resulting graphs of shear stress v. displacement.

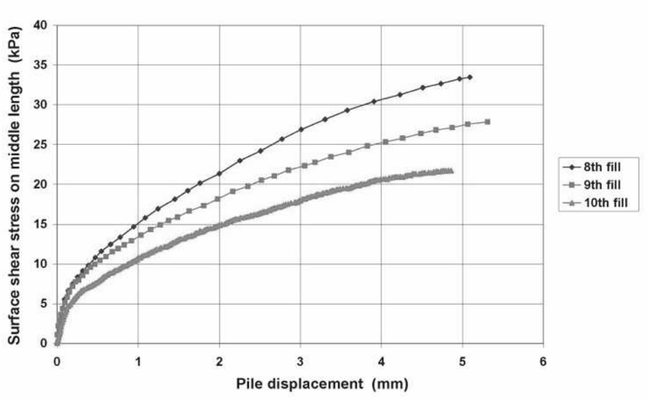

Figure 2. Shear stress v. displacement in slow tests on the pile in nominally identical beds of an SC soil

The differences between the graphs shows the variation in the soil conditions. It was considered to be excessive, as it would probably produce inaccurate comparisons between slow and rapid tests and obscure the effect of soil type on these comparisons.

A strategy to reduce the scatter in the results of nominally identical tests is to do multiple tests and take the average of them. However, because of the long time needed for each test in this case, and the desire to investigate as wide a range of soils as possible, the total amount of time would be great even if the average of only three tests was obtained.

An alternative strategy is to do both the slow and rapid tests on the same pile set-up in a soil bed, but this produces another problem. Consider the series of slow load; unload and re-load tests in clayey sand shown in Figure 3.

The shape of the initial loading graph is significantly different from the subsequent re-loads' graphs. Also, the maximum stress reached, and the shape of the re-load graphs progressively change with each subsequent test. If a rapid test had been done after (say) the initial slow loading, it would be unreasonable to compare its result to that preceding slow test.

The strategy adopted was to utilise the similarity of the re-load graphs in the following manner.

i. Load the pile at the slow rate until the shape of the shear stress v. displacement graph is horizontal or close to it. Slowly unload.
ii. Slowly re-load until the shape of the shear stress v. displacement graph is horizontal or close to it. Slowly unload.
iii. Do a rapid re-load test.
iv. Do a slow re-load and unload test. I.e. repeat step (ii).
v. Repeat steps (iii) and (iv) twice more.

An illustration of this sequence of tests is shown in Figure 3, in which the gaps between the slow re-load tests are where rapid tests were done. The logic of this pattern of tests is that the average of the conditions for the slow tests on either side of a rapid test can reasonably be considered to represent the state of the pile and soil when the rapid test is done. The effect of type of test (slow or rapid) on the pile's shear stress v. displacement behaviour can then be expected to be seen by comparing the average of the slow tests' results to the rapid test done between them.

Furthermore, three such comparisons of slow test to rapid test behaviour can come from the sequence of testing described in (i) to (v) above, so averaging can also be done of the results of the tests in a single soil bed. Six different soils were used and the results as described for a single bed were obtained for each soil.

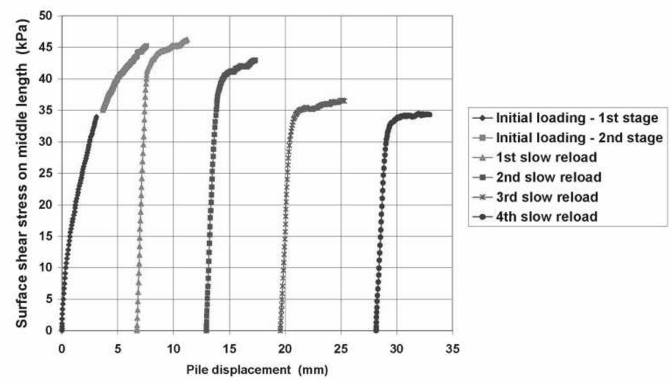

Figure 3. Shear stress v. displacement in a typical series of slow tests on a pile set-up

4 TEST RESULTS

Figure 4 shows a typical graph of surface shear stress v. pile displacement for a rapid test. The engineer's problem is that they will have such a rapid test graph and needs a way of getting the slow test graph from it.

The shear stress in the rapid test comes from three things:

i. the soil resistance if the pile were statically loaded;
ii. additional soil resistance from the rate of shearing of the soil caused by the velocity of the pile;
iii. inertia force.

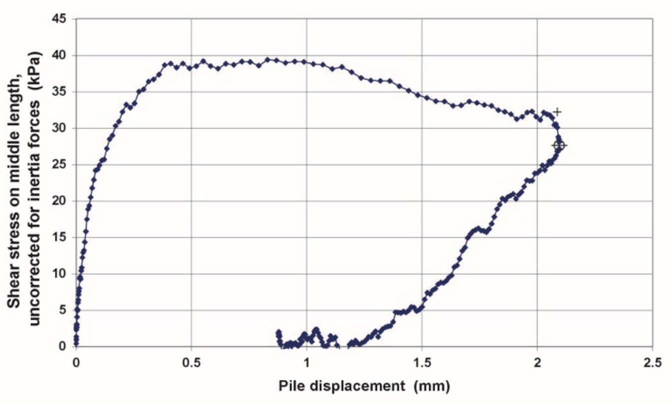

Figure 4. Shear stress v. displacement in a typical rapid test

At the unloading point (marked by a cross on a circle on Fig. 4) the velocity is zero, so item (ii) above is zero. The inertia contribution to the force difference between the ends of the pile's middle length at the unloading point (and hence the shear stress) is the mass of the middle length times its acceleration at that point. However, as the pile approaches its stationary point it is, of course, decelerating, therefore, to get the soil resistance, the stress generated by the inertia force must be added to that calculated from the measured forces in the pile. On Figure 4 the point marked + gives this value of soil resistance, which is then theoretically a point of maximum shear stress on the static stress v. displacement graph.

Note that it is assumed that during a rapid test on a real pile the acceleration of the pile will be measured, enabling the inertia force adjustment to be done. The mass consists of the sum of the pile, which can be accurately estimated, and the soil that moves with it, which is difficult to estimate because the extent of the moving soil varies with soil type and the degree of development of the shear stress v. pile displacement curve. In practice the soil's inertia is usually ignored and its effect included in the inevitable empirical correlation factors that are used to relate rapid to static behaviour.

Several methods for the completion of the graph between the origin and the unloading point have been suggested and are described by Holscher et al. (2010). They are not reviewed in the present paper because of (i) space limitation and (ii) the critical value to obtain from a pile load test is the maximum load that can be carried, e.g. point + on Figure 4. For the present tests, Figure 5 plots the ratio of: (shear stress at the unloading point) / (actual value of shear stress from the slow test) v. the six soils' Unified Soil Classification, laid out (arbitrarily) as a horizontal scale of "sandiness to clayeyness ".

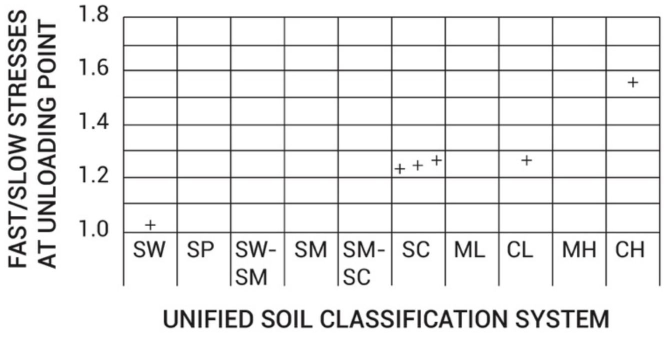

Figure 5. Effect of soil type on the ratio of shear stress at the unloading point in a rapid test to the actual shear stress in a slow test

5 CONCLUSIONS

An empirical factor is needed to adjust the side shear stress result of the unloading point method of interpretation of a rapid test to give the maximum shear stress in a static test. Accurate determination has been made of the factor for a wide range of soil types.

6 REFERENCES

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