Proceedings of the 16th International Conference on Soil Mechanics and Geotechnical Engineering

doi:10.3233/978-1-61499-656-9-2125

Influence of loading rate on the bearing capacity of piles in sand
L'influence de la vitesse de chargement à la capacité portante de pieux dans le sable

N.Q. Huy[1], J. Dijkstra[1], A.F. van Tol[1,2]
(1) Delft University of Technology, Delft, the Netherlands

P.Hölscher[2]
(2) GeoDelft, Delft, the Netherlands

ABSTRACT: Laboratory experiments have been performed to study the rate effect on sandy soil in order to improve the application of quasi-static pile load tests. Firstly, remolded Itter-beck sand specimens are statically and dynamically tested in hydraulic triaxial apparatus. The rate effect on stress – strain behavior and strength of the sand are examined. Secondly, model piles (scale 1:10) are tested in a large calibrated sand chamber with several loading rates. The rate effect on point resistance and shaft resistance of the model pile is point out. Both tests will be performed in dry and saturated soil condition but, up to now, only the tests on dry condition were done at this moment. Results from triaxial tests clearly show the rate effect on shear strength parameter and slightly on the stress – strain behavior of the sand. The magnitude of rate effect depends on the relative density of sand specimen. Results from model pile tests show slight rate effect on the pile resistance

RESUME : Des expériences de laboratoire ont été exécutées pour étudier la vitesse de mobilisation sur le sol sableux afin d'améliorer l'application des essais de chargement quasi-statique sur le pieu. Premièrement, des spécimens de sable Itter-beck remoulés sont statiquement et dynamiquement examinés dans un appareil hydraulique triaxial. La vitesse de mobilisation du comportement contrainte-déformation et de la résistance du sable sont examinés. Deuxièmement, des modèles de pieu (échelle 1:10) sont examinés dans une grande chambre d'étalonnage avec plusieurs vitesses de chargement. La résistance en pointe et le frottement latéral du modèle de pieu sont examiné. Les deux essais seront réalisés dans la condition de sol sec et saturé mais, jusqu'à maintenant, seulement les essais sur la condition sèche ont été faits à ce moment. Les résultats des essais triaxials montrent clairement une légère influence de la vitesse de mobilisation sur la capacité portante de pieu.

1. INTRODUCTION

Quasi-static pile load tests, such as Statnamic and pseudo-static tests are considered as economic alternative for static test due to the lower costs and faster execution of these tests compared with ordinary static load tests. In practical interpretation of quasi-static tests rate effects in clay are taken into account, but in sand both rate effects and pore water pressure are generally neglected. Measurements made by Hölscher (1995) at a test site in Delft (the Netherlands) showed that the soil is loaded dynamically and pore water pressures are generated during quasi static tests. In order to facilitate the usage of quasi-static pile load tests to improve the quality of design in the Netherlands, the influence of dynamic effects such as rate effect and excess pore water pressure must be understood. Therefore, a research project has been started. Because the pleistocene sand layer is essential for the bearing capacity of almost all piles in the Netherlands, the project firstly focuses on sand.

The final result of this project will be a guideline for interpretation of quasi-static tests. The project started with two studies to resolve the two fundamental questions:

- an empirical study on the influence of rate effects on the behaviour of dry, unsaturated and saturated sand;
- a numerical study on the effects of pore water pressure on soil strength during quasi-static loading.

This paper presents the results of two empirical studies on the rate effects in dry and unsaturated sand.

Two types of tests are carried out. Firstly, sand specimens are tested in a triaxial cell statically and dynamically at the rate correlated to quasi-static test to look for the rate effect in sand. Secondly, model piles (scale 1:10) are tested at different rates to look for the rate effect on point and shaft resistance.

From literature no clear relationship can be derived. Many authors found a slight increase of the strength or bearing capacity with increasing loading rate. This is partly due to the different interpretations of the rate effect and also due to the limited amount of tests available in literature. The rate effect is a relative measure, an increase in strength from an arbitrary chosen static situation to the dynamic situation. Two types of tests are reported:

- Tests on soil samples are reported by Casagrande and Shannon (1948), Seed and Lundgren (1954), Whitman and Healy (1962), Schimming et al. (1966), Lee et al. (1969), Luong (1980), Ibsen (1994). Schimming et al. (1966) applied a direct shear test of which only the time to failure is documented.
- Tests on model pile. Most authors who reported model pile tests, performed the tests at several constant loading velocities and measured only the resulting pile capacity (Eiksund & Nordal (1996), Al-Mhaidib (1999), Kimura (2002)) Other authors also studied both the point resistance and shaft resistance (Dayal and Allen (1974), De Gennaro et al (2001)) or only the shaft resistance or interface strength between two different materials (Brumund et al. (1973), Heerema (1979)).

Comparison of the results of soil tests with the results of (model) pile tests is difficult, because during model pile tests which study the rate effect no strains are measured a proper method for comparison is needed, see literature reviews of Huy (2004) and Dijkstra (2004).

Dijkstra (2004) has compiled a comparison graph for the results of the model pile tests. It is noted that each author has a different static reference situation and also the maximum applied loading velocity varies greatly. Therefore, the pile behaviour due to an increasing loading velocity can be compared for a large velocity range, see Figure 1. For each author two points are plotted the bearing capacity at the lowest loading velocity (F_0) and the bearing capacity during the test at the highest loading velocity (F). On the vertical axis a normalized force (F/F_0) is plotted. The horizontal axis shows the pile velocity normalized to the pile diameter, this is needed to incorporate the scale differences of the tests. The cumulative curve is also given, a 10 % increase in bearing capacity per decade increase of velocity is found for pile velocities > 0.08 D_{pile} [1/s].

The large increases which are found by Al-Mhaidib (1999) and De Gennaro (2001), are still in the domain where no waves are travelling in the pile or radiate into the soil. The tests of Al-Mhaidib and De Gennaro at (what they call) high velocity are still at very low velocity when compared to the other results. In this velocity range, considered as static because of the absence of propagating waves, the largest variations are introduced. We are wondering whether these variations are induced by the soil or by the measurement system. It seems that with decreasing velocity it is harder to control the load and to do proper measurements.

Out of Figure 1 it becomes apparent that the rate effect varies with the absolute normalized velocity. For comparison static and quasi-static tests, the range from $0.001D_{pile}$ to $0.01D_{pile}$ per second are of interest.

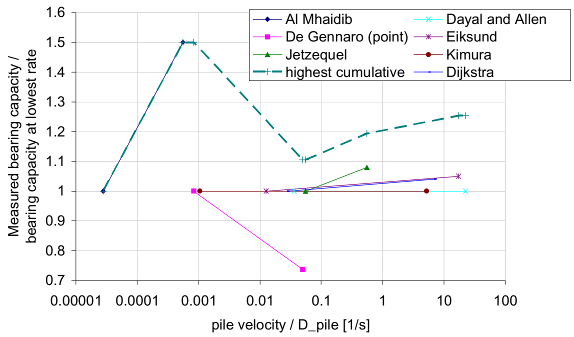

Figure 1 Influence of loading velocity on bearing capacity, normalized arbitrarily on the lowest velocity/pile diameter

2. TRIAXIAL TESTS

The tests have been done in a triaxial apparatus with a hydraulic loading system, which can perform both static and dynamic tests. All tests are strain controlled. During the tests the applied stresses, the resulting axial strain and pore pressure are measured. All tests are performed on dense specimen with different relative densities from 60% up to 85%. The sand and preparation method of the dry specimens is introduced first. Then the measured rate effect on internal friction angle of dry sand is discussed.

2.1. *Sand and specimen preparation*

The sand used in this study is Itter-beck sand. It has a specific gravity of 2613 kg/m^3. The maximum and minimum densities are 1731 kg/m^3 and 1415 kg/m^3, respectively. The sieve curve is shown in Figure 2 (the figure includes the sieve curve of the sand in calibrated chamber). The mean grain size, d_{50} is 0.165 mm, the uniformity coefficient, D_{60}/D_{10} is 1.7.

The specimens are prepared in a split mold by a tamping and vibration technique. The dimension of the mold is 6.6 cm in diameter and 15 cm in height. The rubber membrane has the thickness of 0.5 mm. Before deposition into the mold, the sand is dried in an oven for at least 12h. The amount of sand is predetermined. During deposition the mold is kept full of sand. Dimensions of the specimen are measured at the vacuum pressures of 100 kPa (i.e. equivalent to cell pressure). The deviation in density from uncertainty analysis is about 4% ($I_D \pm$ 4%).

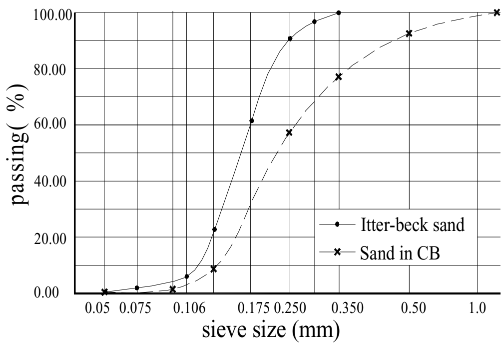

Figure 2 Grain size distribution curve

2.2. *Testing program*

The tests are strain controlled. All tests are run by control the downward velocity of the loading piston. In the static tests, the velocity is 0.0125 mm/s. In the dynamic tests the velocities are 0.2 m/s and 0.55 m/s. All tests are performed till the axial strain reaches about 15%. The cell pressure of 100 kPa is applied by air and kept constant in all tests. At each velocity of deformation some specimens of different density are tested. Total 19 dry specimens were tested, of which 9 tests are static; 6 tests are dynamic with rate of 0.2 m/s; 4 tests with rate of 0.55 m/s.

2.3. *Test results*

The results from triaxial tests on dry Itter-beck sand show the appearance of rate effect for dry sandy soil and the rate effect depends on the density state of soil. Since all 19 tests are performed in the same condition, i.e. 100 kPa confining pressure, drainage valve opened so any different in the results is caused by the difference of loading rate.

Figure 3 displays the measured deviator stresses a function axial strain in static and dynamic tests with three different velocities. All specimens had the same relative density (≈ 83%). The following issues can be observed:

- No change in stiffness of the deviator stress vs. strain curves. At the beginning of compression (strain ≤ 1%), no rate effect is observed.
- The peak deviator stress increases as the strain rate increases. The increase is about 15% and 20% compared to static value for the rate of 0.195 m/s and 0.590 m/s, respectively. This is due to the rate effect.

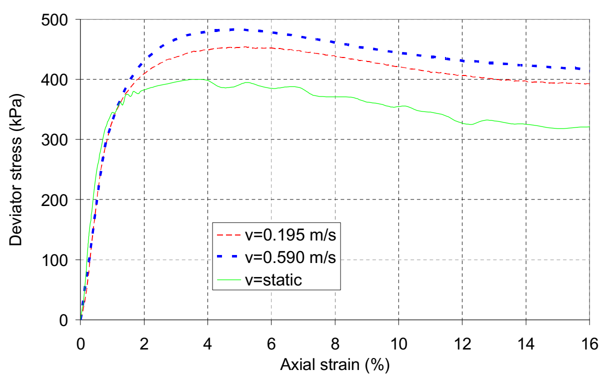

Figure 3 Measured stress-strain relationship

Figure 4 shows the pore air pressure on axial strain for three loading rates. During static test no change in pore air pressure is observed so the static tests are in drained condition. During dynamic tests, some negative excess pore air pressure is observed. The excess increases as strain increases (maximum ≈

-12 kPa at 16% of train). This confirms the finding from Seed and Lundgren (1954) that during the dynamic test even the air does not have enough time to drain so the test is not in drained condition.

It is unknown why the pore pressure at 0.59 m/s is lower than at 0.195 m/s. We expect the opposite. This deviations might be due to the failure mode of the sample.

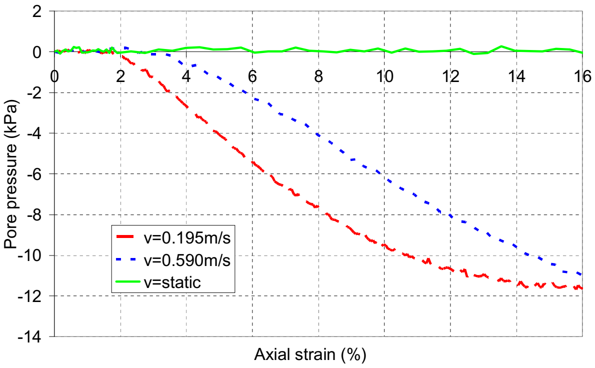

Figure 4 Excess pore pressure on axial strain

This measured pore pressure has no influence on the strength of the sample. Its' value (about -3 kPa at 5% axial strain) is small compare to the increase in isotropic stress due to the loading (about -30 kPa at 5% strain). Therefore, the increase in deviator stress in Figure 3 is not caused by the pore pressure. It must be caused by the strain rate effect.

Figure 5 shows the influence of the loading rate on angle of internal friction for several densities. The trend lines are static tests; dynamic v = 0.2 m/s tests and v = 0.55 m/s tests. The results in Figure 5 show that the rate effect increases as the relative density of specimen increases.

At this moment, the study is continued with saturated sand and further results analysis to quantify the dynamic effects in sandy soil. Excess pore water pressure may play an important role in interpretation the quasi–static test results and is generally disregarded.

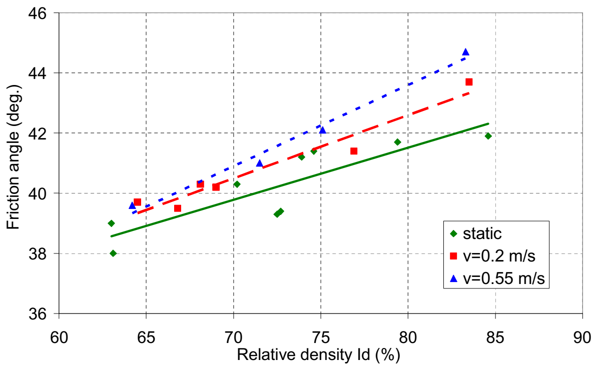

Figure 5 Measured friction angle – relative density relation

3. MODEL PILE TESTS

A series of model pile tests (scale 1:10) in unsaturated sand is carried out in order to investigate the loading rate effect on the pile capacity.

3.1. *Test setup*

The tests are performed in the calibration chamber of the Geo-Engineering section of Delft University of Technology. The dimensions of the soil sample in the chamber are: diameter 1.9 m, height 1.6 m. The calibration chamber is equipped with a fluidization system and some vibration engines to prepare the soil. Each preparation cycle consists of: 1.5 hours fluidization, vibration for 10 min. and finally drainage of the sample for 40 hours.

The chamber is filled with quite coarsely grained river sand. Figure 2 shows the sieve curve of the sand. The maximum and minimum densities are 1788 kg/m^3 and 1467 kg/m^3.

The model pile is actually a Dutch standardized CPT cone: 36 mm in diameter, the point surface is 10 cm^2 and the friction sleeve is 150 cm^2. The total length is 2.65 m of which 1.3 m is embedded in the sand. The rod above ground level is equipped with strain gauges, an acceleration transducer and a displacement sensor (linear stroke potentiometer). The following quantities are measured: Tip resistance, shaft resistance, displacement of the pile head, acceleration of the pile and the force on the pile head.

A hydraulic rig is used to install the piles in the sand with a constant rate of 20 mm/s (normal rate used for CPT in the Netherlands), the end value of the tip resistance and local shaft resistance is recorded. The same rig is used to perform static tests with a constant velocity of 1 mm/s. The displacement during these tests is 20 mm or 55 % D_{pile} during these tests also the force on the pile head is registered.

During the high speed tests or dynamic tests the model pile is loaded with a drop mass of 70 kg with a drop height up to 30 cm. Between the pile head and the drop mass a series of disc springs is installed to extent the duration of the blow. A guiding tube guides the mass during the drop. Figure 6 shows a schematized view of the test setup.

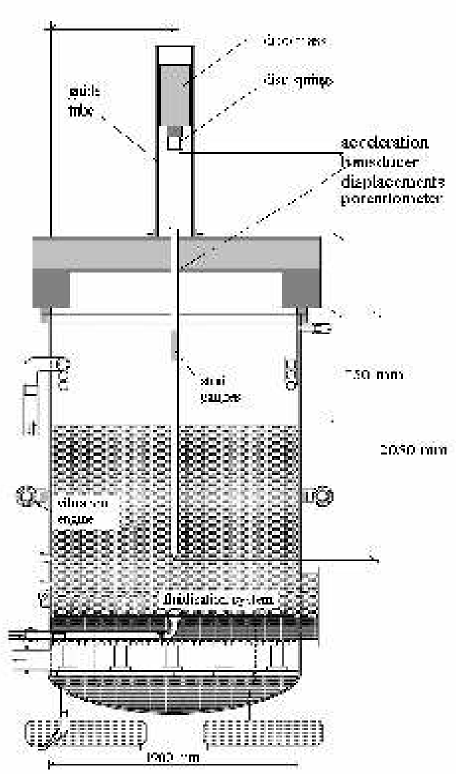

Figure 6 Schematized view of the test setup

3.2. *Test regime*

The following test regime is applied during the test:

- first installation of the model pile with a constant rate of 20 mm/s with a typical displacement of 1.3 m,
- second a constant rate test of 1 mm/s with a typical displacement of 20 mm (called static),

- third a dynamic test (typical rate 0.25 m/s ≈ 250 mm/s, typical displacement of ~6 mm) and
- finally again a static constant rate test of 1 mm/s.

During the dynamic test also the spring stiffness is varied to obtain variations in pile velocity. All tests reached plastic failure.

3.3. *Results*

The tests showed a slight increase in tip resistance and shaft friction with increasing loading rate. Figure 7 shows the results of the tip resistance. Figure 8 shows the shaft resistance. The results of both the tip resistance and the local shaft resistance are normalized to the resistance found during the static case (1 mm/s). On the horizontal axis the pile velocity (m/s) is listed. By measuring the soil reactions the inertia of the model pile is already accounted for, therefore only the rate effect of the soil is in the comparison.

The increase is statistically not significant. The measuring data is normal distributed. Figure 7 and Figure 8 shows the mean and the 5 % and 95% confidence limits.

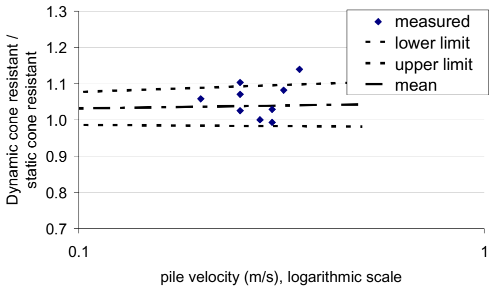

Figure 7 Loading rate tip resistance

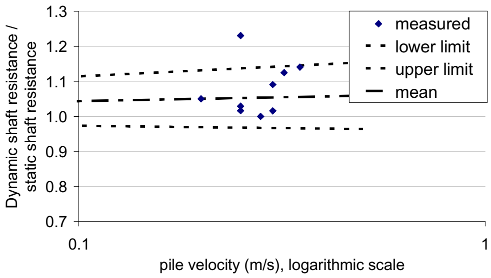

Figure 8 Loading rate local shaft resistance

4. CONCLUSIONS

The triaxial tests show that the rate effect appears in dry sand. Compression strength of dry sand increases as the testing rate increases and the rate effect is stronger in denser sand. During the dynamic tests, the soil behavior is not in drained condition.

The pile model tests shows that in non-saturated sand

- an increase in tip resistance of 4 %
- an increase for local shaft resistance of 6 %

This holds for an increase of velocity from 1 mm/s to ~250 mm/s. Both increases are non-significant with 95 % reliability. These results are in line with e.g. Dayal & Allen (1975) and Eiksund & Nordal (1996) who also didn't find a rate effect in dry sand.

REFERENCES

Al-Mhaidib, A. I. 1999. *Bearing Capacity of Model Pile in Sand under Different Loading Rates*. Proc. 9th International Offshore and Polar Engineering Conference Brest, France. pp. 724-730.

Brumund, W.F. and Leonards, G.A. 1973. *Experimental study of static and dynamic friction between sand and typical construction materials*. Journal of testing and evaluation, Vol. 1, No. 2, pp. 162-165.

Casagrande and Shannon 1948 *Strength of soils under dynamic loads.* Proceeding of the American Society of Civil Engineering, Vol. 74, No.4, pp. 591-608.

Dayal, U. & Allen, J. H. 1975. *The Effect of Penetration Rate on the Strength of Remolded Clay and Sand Samples*. Can. Geotech. J., 12, 336, pp. 336-348.

Dijkstra, J. 2004. *Influence of loading rate on pile capacity in sand.* MSc. thesis, Delft University of Technology.

Eiksund, G. and Nordal, S. 1996. *Dynamic model pile testing with pore pressure measurements*. Proc. 5th Int. Conf. Appl. Stress-Wave Theory to Piles, Orlando, Sept. 1996, Gainesville, Univ. Florida, Dep. Civ. Eng., pp. 1-11.

Gennaro, V. De et al. 2001. *Effet de la vitesse de chargement sur le comportement mecanique de pieux modele en chambre d'etalonnage*. Proc. 15th Int. Conf. Soil Mech. Geotech. Eng., Istanbul, Aug. 2001", Lisse, Balkema, 2001, Vol.2, pp.885-888.

Gibson, G.C. & Coyle, H.M. 1968. *Soil damping constants related to common soil properties in sands and clays (Bearing Capacity for Axially Loaded Piles)*. Texas Transportation Institute Research Report 125-1 (Study 2-5-67-125). Texas: Texas A&M University.

Heerema, E. P. 1979 *Relationships between wall friction displacement velocity and horizontal stress in clay and in sand for pile driveability analysis.* Ground Engineering, Vol. 12, No. 1., pp. 55-61

Hölscher, P. 1995. *Dynamical response of saturated and dry soils*. Ph.D thesis, Delft University of Techno-logy.

Huy, N.Q. 2004. *Literature review of quasi – static pile load tests*. Report Delft University of Technology.

Ibsen, L.B. 1994. *The static and dynamic strength of sand.* Proc. 11th European Conf. Soil Mechanics and Foundation Engineering, Copenhagen, Vol. 6, pp. 69-76.

Kimura, M. & Boonyatee, T. 2002 *Statnamic load tests on model piles and their 3D elasto-plastic FEM analyses*, Soils and Foundations vol. 42 No. 1, pp. 71-87

Lee et al. 1969. *Effect of transient loading on the strength of sand.* Proceedings of the 7th Int. Conf. on soil mechanics and foundation Eng., Vol. 1, pp. 239-247.

Luong, M.P. 1980. *Stress-strain aspects of cohesionless soils under cyclic and transient loading*. Int. Symp. On soils under cyclic and transient loading. pp. 315-322.

Schimming et al. 1966. *Study of Dynamic and Static Failure Envelopes*. Journal of the soil mechanics and foundations division, ASCE, Vol.92, No. SM2, pp. 105-124.

Seed and Lundgren. 1954. *Investigation of the effect of transient loadings on the strength and deformation characteristics of saturated sands*. Proceedings of the American Society for Testing and Materials, Vol. 54, pp. 1288-1306.

Whitman and Healy. 1962. *Shear strength of sands during rapid loading*. Journal of the soil mechanics and foundations division, ASCE, Vol.88, No. SM2, pp. 99-132.