Compressive resistance of piles, an update

Résistance à la compression des pieux, une mise à jour

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ABSTRACT: The research consortium Delft Cluster/CUR recently published the results of a study of axial pile capacities. It emerged that the capacity of displacement piles calculated using the Dutch method considerably overestimates the actual capacity measured in static pile load tests. The identification and quantification of any concealed safety factor is a possible way of preventing the reduction of the pile capacity factors that could follow from the test results at least in part. This paper presents the results of a study of concealed safety factors. The conclusion of the study is that it is useful to examine time effects in greater detail, primarily focusing on the quantification of the effect and the determination of the impact of load variations. It is recommended to continue with research into the impact of compaction on pile-base capacity in combination with the sequencing of installation of displacement piles.

RÉSUMÉ: Le consortium de recherche Delft Cluster/CUR a récemment publié les résultats d'une étude sur la capacité axiale des pieux. Il est apparu que la capacité des pieux de déplacement calculée à l'aide de la méthode néerlandaise surestime considérablement la capacité réelle mesurée lors des essais de chargement statique. L'identification et la quantification des facteurs de sécurité cachés est un moyen de prévenir la réduction des facteurs de capacité dans la méthode NEN, du moins en partie. Cet article examine les résultats d'une étude des facteurs de sécurité cachés. La conclusion de l'étude est qu'il est utile d'examiner les effets du temps plus en détail, en se concentrant principalement sur la quantification de l'effet et la détermination de l'impact des variations de charge. En outre, nous recommandons la poursuite des recherches sur l'impact de la compaction sur la capacité de la base du pieu en combinaison avec le séquençage de l'installation de pieux de déplacement.

KEYWORDS: pile capacity, displacement pile, set-up, group effect.

1 INTRODUCTION

Research looking at the axial capacity of foundation piles (van Tol et al., 2010) has shown that calculating the capacity using the method set out in the Dutch standard (NEN 9997-1, 2012) results in a considerable overestimation of the capacity as compared to measurements in load tests. The study referred to properly equipped load tests conducted in France, Belgium and the Netherlands in which it was possible to distinguish between pile-base capacity and shaft capacity. It emerged that adequate tests for the reliable validation of the design rules (French, Belgian and Dutch) were available only for driven, soil-displacement, prefabricated piles (concrete and close-ended tubular piles). Calculations of the shaft capacity in accordance with the NEN standards proved to be a good match for the values generated by load tests, although the coefficient of variation is large at approximately 30%. The measured pile-base capacities, however, proved on average to be only 70% of the predicted values. The overestimation of capacity increased with the depth driven in the sand, see Figure 1. Piles located at a depth of more than 8 D in the sand layer were found to have a pile base capacity of 60% of the predicted value.

Since the capacity calculation is too optimistic, and since no failures have been observed in practice, it is thought that there must be concealed safety factors in the system. The identification and quantification of those factors may prevent a future reduction of the installation factors in the Dutch standard in whole or in part.

This paper will focus primarily on the results of the literature study looking at concealed safety factors. It will discuss the following areas: *i* the improvement in capacity over time *ii* residual stresses in the pile *iii* limit values *iv* group effects and *v* wind load in relation to negative skin friction.

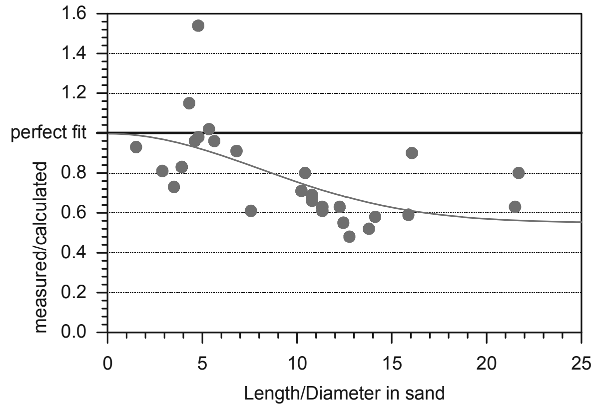

Figure 1. Comparison of measured and calculated pile-base capacities as a function of penetration in the sand (Stoevelaar et al. 2011).

2 IMPROVEMENT OF CAPACITY IN TIME

Extensive research has been conducted into the increase of pile capacity over time. In the past, it was mainly thought that this phenomenon was a factor related to piles in clay, but it has also emerged that the capacity of piles in sand increases with time. Most research involved steel tubular piles and the load tests were usually conducted under tension loading. Axelsson (2000) conducted a study of time effects in prefabricated concrete piles loaded in compression. This study will be discussed further here.

In predominantly silty sand, an instrumented prefabricated concrete pile with a cross-section of 235 x 235 mm was driven to a depth of 13 m below ground level. The pile was equipped with a pressure sensor at the pile base, and pressure sensors at the shaft. Static load tests were conducted 1, 5, 8, 141 and 667 days after the installation of the pile. Figure 2 shows the load-displacement curves for the load tests. This shows that the total capacity of the pile increases substantially over time. The increase in the pile-base capacity is at maximum approximately 10%. The increase in capacity is therefore mainly caused by an increase in the shaft capacity.

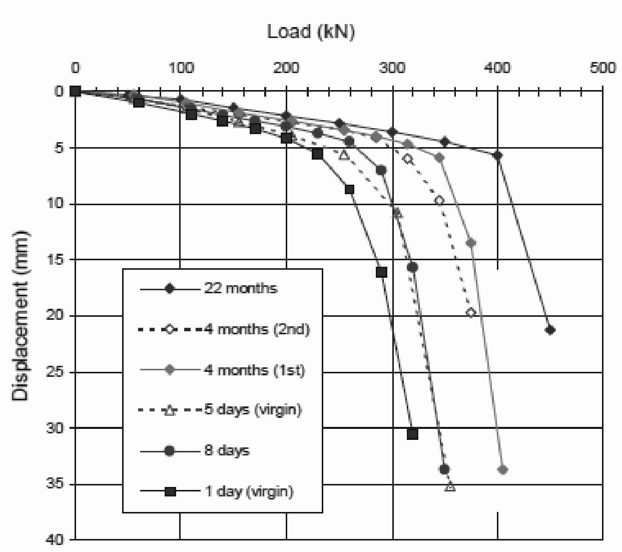

Figure 2. Head displacement, static tests, Axelsson (2000)

This is confirmed by the horizontal effective stress on the pile shaft. A distinction is made between the horizontal stress on the pile in loaded and unloaded conditions. The difference between the contact pressure in loaded and unloaded conditions is caused by dilatant behaviour. The increase over time of the horizontal stress during loading is primarily a result of increasing dilatant behaviour, which indicates a change in particle structure where the pile and the soil meet (Axelsson, 2000).

The increase in capacity over time is expressed by a range of authors as an increase with the logarithm of time in line with the equation below (Skov and Denver, 1988):

$$Q_t = Q_0\left(1 + A.\log_{10}\frac{t}{t_0}\right) \quad (1)$$

Where:
- Q_t is the pile capacity at time t
- Q_0 is the pile capacity at t_0
- A is a factor – dependent of the type of soil
- t_0 is the time for Q_0

The values for A used in the literature for clay and sand respectively are 0.6 and 0.2. This means that capacity increases by 60% per decade in clay and by 20% in sand. The lower limit generally used for piles in sand is 15%. However, Axelsson's study stated a much higher value of A=37.5% for a driven concrete pile in silty sand, see Figure 3.

The literature relating to set-up, the usual term for the phenomenon of increasing capacity over time, shows that the following factors are important in determining the set-up level (Axelsson, 2000; Sobolewsky; 1995, Chow & Jardine, 1997; Joshi et al., 1995; Baxter & Mitchell, 2004):

- Relative density and stiffness of the soil: set-up increases with density
- Particle-size distribution: set-up in silty sand is higher than in coarser sand
- Particle strength: set-up is higher in strong sands
- Particle structure and form: angular particles result in higher set-up
- Soil humidity: very high set-up is observed in unsaturated sand
- Stress level: at high stress levels, dilatant behaviour is a more significant factor
- Installation process determines the stress conditions after installation and therefore set-up
- Diameter of pile: higher set-up with smaller diameter

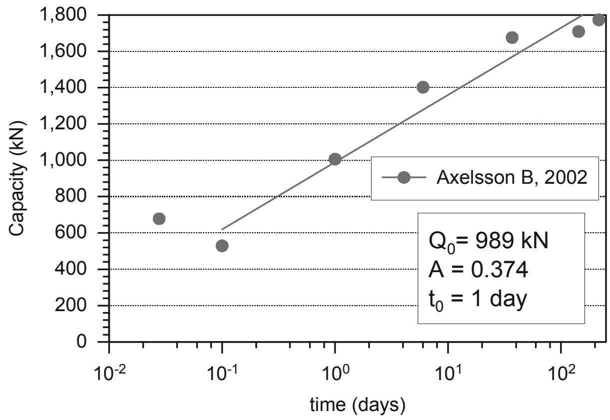

Figure 3. Measurements from Axelsson, 2000, fitted with equation (1)

Before the positive effect of time can be included in the regulations, the most important of these factors will have to be investigated. Another important question is the extent to which the increase in capacity persists after varying loads have been imposed. A study by Jardine et al. (2006) demonstrated that the repeated testing of piles in sand resulted in lower capacity measurements than tests on piles that have not been subjected to loads in the past. Tensile capacity in repeat testing approximates the trend line of Chow at al. (1997) which corresponds, according to their findings, with A is approximately 27.5%.

Subsequent research will, then, have to take this into account, as well as the effects of varying loads.

3 RESIDUAL STRESSES

In loading tests with driven piles, the strain gauges used to measure the forces in the pile are normally reset to 0 after the installation of the pile or installed as a string of gauges cemented into a tube in the pile, also after installation. That means that any residual stresses present in the pile base (after pile-driving) are not included in the measurement of the base capacity in pile load tests. This could explain why the pile-base capacity in the load tests was low (and lower than the value resulting from the design rule). However, any increase in the base capacity resulting from this consideration will be at the expense of the shaft capacity.

Xu et al. (2008) showed that the residual stress at the pile base is negligible in the case of piles when penetration is less than 20D; substantial residual stresses occur only when the driven depth exceeds 30D in the load-bearing layer. This phenomenon does not therefore explain the low pile-base resistance as shown in Figure 1, where the penetration depth of all the piles is less than 25D.

4 LIMITING – LIMIT VALUES

Another explanation for the lack of problems with the capacity of driven piles in practice could therefore be that the limit values prescribed in the Dutch standard (15 MPa for pile-base resistance and 150 kPa for shaft resistance) are too conservative. On the basis of a comparison between foreign standards and research looking at measured pile-base stresses in sand layers with very high cone resistances, it can be concluded that:

- The literature that was examined confirms the current limit value for base resistance (API, 2007; Foray et al., 1998).
- The limit value for shaft friction seems to be on the low side. Higher shaft resistances have been measured and also approved in other, foreign, standards (Foray et al., 1998; Bustamente et al., 2009).

5 GROUP EFFECTS

Group effects include both the effect of the installation and the consequences of the higher load in the ground as a result of the loading of the piles. Both effects are taken into account when calculating the capacity of tensile piles according to the Dutch standard. The installation effect of soil-displacement piles with factor f1 and the effect of the load (in the case of tensile piles, this is a negative effect) with factor f2.

Factor f1 (NEN 9997-1, 2012) is determined by converting the volume of the piles into compaction combined with an empirical relationship that, at a constant vertical stress, links density to cone resistance qc.

Factor f1 is the ratio of increased to initial qc, and it is included in the Dutch standard calculation method of the shaft capacity of a tensile pile. In principle, this factor should also be included when calculating the compressive shaft capacity of jacked or driven piles. It is under discussion whether compaction also occurs to this extent below the level of the pile base and to what depth, and therefore whether this factor can be included in the calculation of the pile-base capacity. For this purpose, the depth to which compaction extends must be determined, as must the effect of the pile-driving sequencing. Upward pile movement has been noted during the driving of piles close to piles that have already been installed; the piles in place move upward. This could have a negative effect on the pile-base capacity.

The compaction factor f1 determined as described above may result in a considerable increase in cone resistance and consequently of shaft capacity.

Figure 4 shows, for a symmetric pile field, factor f1 as a function of the centre-to-centre distance between the piles. For a symmetrical pile field with a centre-to-centre distance s of, for example, 4Deq, f1 is approximately 1.5, with a small variation due to differences in initial density. The compaction percentage expressed as pile surface to total surface is 5% here, which is not an extreme value.

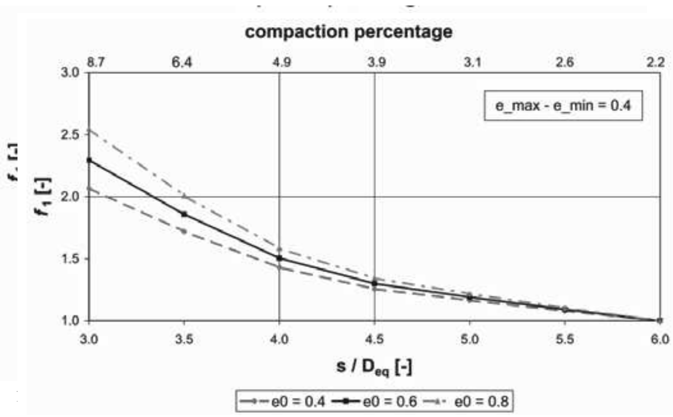

Figure 4. Compaction factor f_1 for a pile in a symmetrical pile field

The densification was checked in several projects by conducting CPTs before and after the installation of the displacement piles, (van Tol & Everts, 2003). It emerged that the value f1, as determined in NEN 9997-1 (2012) is a safe estimate of the installation effect; the compaction found in practice is usually higher than the predicted value. This is advisable in a design guideline, particularly because any over-estimate of the effect will only be noticed during the execution of the work, with all the associated consequences.

It should be pointed out that the actual installation effect with soil-displacement (driven) piles is much more complex than in an approach complying with NEN 9997-1 (2012).

- In addition to compaction, there is also an increase of stresses. If the initial density is already high, the increase of stresses will actually be dominant with respect to compaction.
- Not the full volume of the pile is involved in compaction; soil is also moved upwards.
- In the immediate vicinity of the pile shaft, in stead of compaction there is also dilatant behaviour. However, in the immediate vicinity of the shaft, there may also be relaxation, which is known as "friction fatigue" as a result of the up-and-down movement of the shaft during the pile-driving.
- Particularly in dense sands, crushing occurs, and the increase of stresses is therefore limited.

The conclusion with respect to the group effect is that, in principle, the compaction factor f1 can also be used for driven piles loaded in compression.

The following, more specific, topics must therefore be studied in more detail related to the factor f1:

- Does f1 also apply to the pile-base capacity and, if so, down to what depth below the pile base does compaction occur and what role is played by pile-driving sequencing?
- Does f1 also apply to small, highly compact, groups of piles?
- Is the value of f1 affected by the properties of the sand such as particle-size distribution, form, strength and the silt concentration?

6 WIND LOAD AND NEGATIVE SKIN FRICTION

In the current design approach, wind load is transferred to the load-bearing sand layer. In the western part of the Netherlands, where the Pleistocene sand is covered by a thick layer of Holocene clay and peat layers, piles are subjected to negative skin friction. The loads generated by negative skin friction can be very considerable, rising to more than 30% of the total pile load. Wind load is another major, temporary, component of the total load, particularly in the case of high-rise buildings. In the case of piles in which negative skin friction is fully developed, wind load will initially result in the pile being pushed downwards, decreasing the amount of negative skin friction. A number of calculations have been conducted for this phenomenon using an interaction model. Figure 5 shows a calculated result for the fluctuation of forces in a pile shaft, first when the pile is subjected only to a permanent load of 1000 kN and 550 kN negative skin friction. Then there is an additional temporary wind load of 600 kN. Negative skin friction drops from 550 to 300kN. In other words, (550-300) / 600 = approximately 40% of the wind load is transferred to the upper Holocene layers.

This factor can therefore certainly not be neglected and, in this case, represents a concealed safety factor in current design practice.

However, it should be kept in mind that wind load makes a significant contribution only when the height of the building exceeds 40 m. The contribution in the total load in that case is approximately 10% (so much smaller than in the example of figure 5). This means that the wind load transferred to the upper layers is therefore only a concealed safety factor in specific conditions of high buildings.

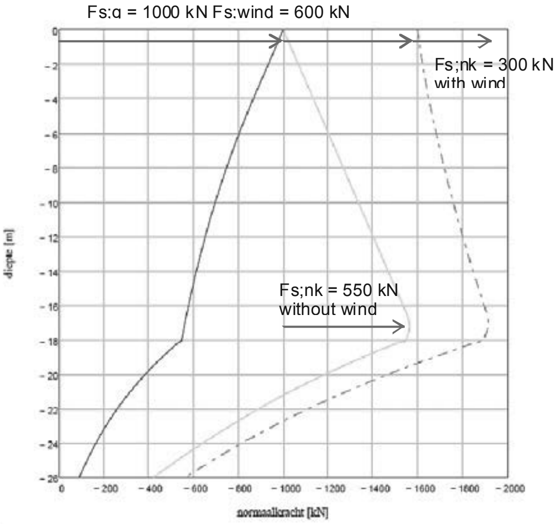

Figure 5. Normal forces as function of depth and a wind load of 600 kN

7 CONCLUSIONS AND FOLLOW-UP

The conclusion of the study of concealed safety factors is that the time effects and the pile group effects are the two effects most likely to contribute to concealed safety. It will therefore be useful to look at time effects more closely. The primary focus should be on quantifying and understanding the effect, determining the impact of load variations and identifying the applicable limitations. Furthermore, it is recommended to continue with research into pile group effects of displacement piles: the impact of compaction, focusing in particular on the impact on pile-base capacity in combination with the sequencing of installation.

7.1 *Pilot tests in geotechnical centrifuge*

The follow-up research will include pilot testing in a geotechnical centrifuge looking at concealed safety factors. This test will look at the time and the group effect. The design of this pilot test will focus primarily on determining whether the phenomena in question can be studied in the centrifuge. It is generally thought that creep (the process underlying set-up) cannot be modeled in a centrifuge because time cannot be scaled during testing. However, longer centrifuge testing can lead to the determination of the size of factor A in equation 1. If this is the case, research can be conducted in the centrifuge, precluding the need for more expensive field studies and allowing controlled conditions.

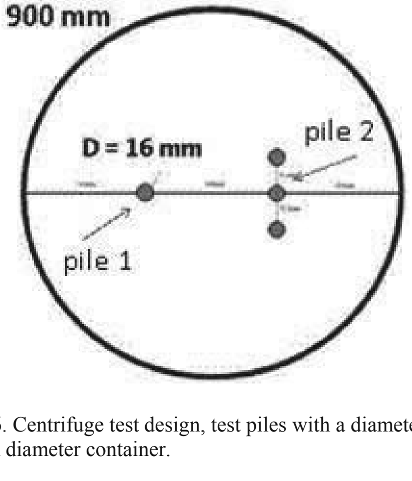

Figure 6. Centrifuge test design, test piles with a diameter of 16 mm in a 900 mm diameter container.

The test set-up is shown in Figure 6. Two instrumented test piles will be installed in a single sample preparation in the container, one single pile and a pile in a group of 3 piles. The two test piles and the other piles in the group will be installed in flight. To study the time effect, pile1 will be test loaded at 1, 10, 100 and 1000 minutes after installation. Then pile 2 will be loaded in the group using the same time schedule. The centrifuge will continue to operate from the start of the installation until the final load test.

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