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A critical review of field testing of helical steel piles

Un examen critique des essais sur le terrain de pieux hélicoïdaux

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ABSTRACT: In this paper, an initial appraisal of the existing body of knowledge contained in the records of full-scale axial maintained load tests on helical steel piles (HSP) is presented. There are numerous case studies on full-scale testing of HSP which cover a variety of configurations (no. helices, helix spacing, depth of installation, etc.), ground conditions, testing procedures and definitions of failure. This data base is being critically reviewed by the authors and in this paper, the procedures employed in the review are outlined and illustrated through a selection of the case studies. The review involved examining the time-displacement and time-load data (when available), to confirm the reliability of the test stages from a given test and then applying a uniform failure condition across all studies. It is shown that the short loading stage durations employed in most studies (so-called quick test) and not imposing a creep criterion, especially in the latter stages of the test, means that the ultimate capacity is often overstated. This revised and updated database will be used to critically appraise resistance calculation methods used in practice and develop reliability-based design procedures for HSP that are compatible with Eurocode 7.

RÉSUMÉ: Dans cet article, une première évaluation de l'ensemble des connaissances contenues dans les enregistrements d'essais de charge axiale maintenue à grande échelle sur des pieux en acier hélicoïdaux (HSP) est présentée. Il existe de nombreuses études de cas sur les essais à grande échelle de HSP qui couvrent une variété de configurations (nombre d'hélices, espacement des hélices, profondeur d'installation, etc.), conditions de terrain, procédures d'essai et définitions de défaillance. Cette base de données est en cours d'examen critique par les auteurs et dans cet article, les procédures employées dans l'examen sont décrites et illustrées à travers une sélection d'études de cas. L'examen impliquait d'examiner les données de déplacement temporel et de charge temporelle (lorsqu'elles étaient disponibles), afin de confirmer la fiabilité des étapes de test à partir d'un test donné, puis d'appliquer une condition de défaillance uniforme dans toutes les études. Il est montré que les courtes durées d'étapes de chargement employées dans la plupart des études (essai dit rapide) et n'imposant pas de critère de fluage, en particulier dans les dernières étapes de l'essai, font que la capacité ultime est souvent surestimée. Cette base de données révisée et mise à jour sera utilisée pour évaluer de manière critique les méthodes de calcul de résistance utilisées dans la pratique et développer des procédures de conception basées sur la fiabilité pour les HSP qui sont compatibles avec l'Eurocode 7.

Keywords: Helical piles; field tests; design; safety.

1 INTRODUCTION

Helical steel piles (HSP) in various configurations have been used since the 19th century when Mitchell (1848) proposed their use in providing secure ship mooring and for the foundations of near-shore structures such as lighthouses and piers. For this study, HSP are considered to be a foundation element comprising a central, small diameter shaft of variable length with one or more sections of helix located at intervals along the shaft, from the tip. The helices may have differing diameter but typically are 3 to 5 times the diameter of the shaft and spaced 3 helix diameters apart. This latter ensures a so-called individual helix failure mechanism (Perko, 2009) by minimising interference between the respective failure mechanisms.

Since the 1960s and more-so, the 1980s until the present day, there has been an effort to provide a greater scientific understanding of the mechanisms of load-transfer of HSP, and how e.g. the ultimate resistance might vary from experience and design methods drawn from conventional piles. In reviewing these studies, it became apparent that while testing procedures were broadly similar, i.e. use the so-called "quick test", ASTM (2020): a) often load control was poor and not held within acceptable tolerances of the target value, b) it is not reported if the ASTM recommended consideration of creep was made, to ensure the final load step(s) were stable, and c) a variety of definitions of failure have been employed including maximum attained load or the load associated with a settlement of 10%D, amongst others. It was felt that the former could lead to overstatement of pile resistance, while the latter makes the comparison of results between themselves and in relation to analytical calculation methods, and assessment of their reliability rather difficult. Therefore, it was decided to revisit the body-of-knowledge associated with HSP load testing that is available in the literature. In the following, the methodology adopted in reviewing the HSP database is outlined, along with some examples of its application to selected case studies and how the updating of the database will proceed.

2 METHODOLOGY

In order to uniformize the results of the various HSP load testing studies; first, where possible, the stability of the loading increments and the stability of the settlement versus time were assessed to ensure that each load stage was stable and secondly, a consistent definition for the ultimate resistance of each HSP was applied.

Loading stability was assessed visually for the most part. Figure 1 illustrates poor load control where variations of 20 to 50 kN (3 to 5% of the applied load) occurred. Typically, for the load range of this test, the limit on load variation would be 5 kN (<1 %), ICE (2007). When the load drops off in this manner there is no reliable definition of the load being maintained in a particular load stage, and e.g., the displacement rate will be artificially slowed by the reducing load.

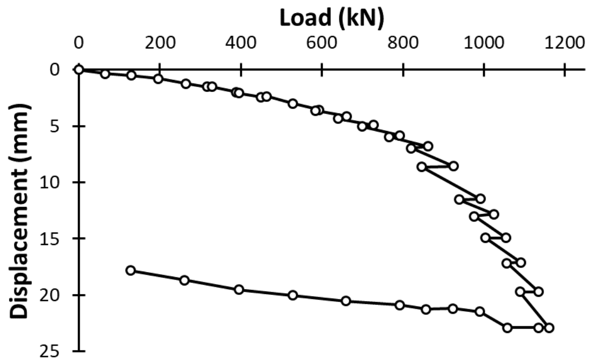

Figure 1. Example of poor load control, from Tappenden (2007).

A simplified version of the approach suggested by England (1992) has been implemented to assess the settlement vs. time, with the time-displacement data fitted with a simgle hyperbolic function to extrapolate and assess whether the recorded settlement was likely to have reached a stable (asymtotic) value at infinite-time. Eqtn. 1 describes this function (shown schematically in Figure 2(a)), where t is the elapsed time during the load stage and s, the increment in displacement in the same period while m and c are the slope and intercept values. The inverse of m, yields the asymptotic value for the displacement as t → ∞.

$$\frac{t}{s} = m.t + c \quad (1)$$

Likewise, following Fleming (1992) but again using a single hyperbolic function, as per Chin (1972), the load-displacement response was extrapolated and used to derive the ultimate resistance. Only data from stable load stages as defined above, was taken forward into this stage. A single function was used on the basis that most of the load resistance derives from the helix(es) and it was also assumed that the elastic shortening on most HSP would be only a few-mm and could be ignored. Eqtn. 2 describes the hyperbolic function used to extrapolate the load-displacement response where N is the applied load and the other parameters were defined for Eqtn. 1 (Figure 2(a)).

$$\frac{s}{N} = m.s + c \quad (2)$$

In this case, the inverse of m, yields the asymptotic value for the load, R_∞ as s → ∞.

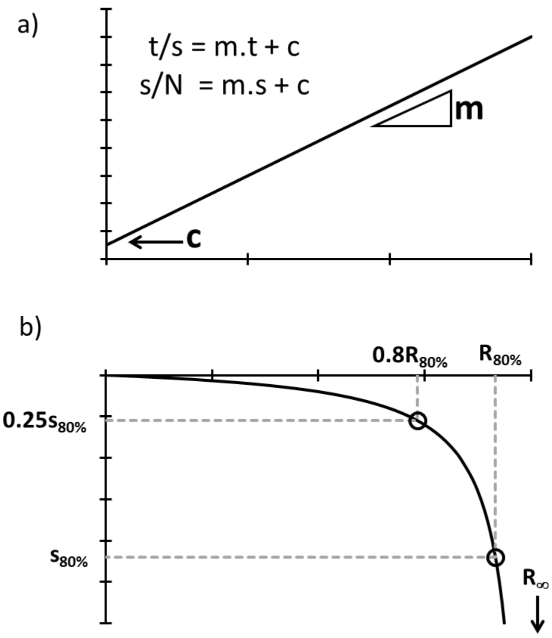

Figure 2. Schematic representation of hyperbolic functions (Equations 1 & 2) and Brinch-Hansen 80% failure criteria.

After some deliberation over the various failure criteria that have been proposed, e.g., as outlined in Fellenius (1980), it was decided that two values would be derived to represent the ultimate resistance, $R_{u,m}$: one based on Brinch-Hansen's 80% criterion (see Fgure 2(b)) which defines the ultimate resistance, $R_{80\%}$ as the load that gives four times the displacement generated by a load at $0.8R_{80\%}$ (Fellenius, 1980) and the asymtotic load obtained from Eqtn. 2. The ratio of $R_{80\%}$ to R_{∞} is about 90±2 %. It is considered that $R_{80\%}$ ensures that a more uniform and comparable state of mobilisation (approching a plunging failure) between case staudies and would be used for the assessment of design methodologies, while R_{∞} will be used in the assessment of analytical calculation models which imply full mobilisation of the pile resistance.

Rather than using the test data directly, Eqtn. 2 was used to derive $R_{80\%}$ and its associated setttlement, $s_{80\%}$ using Eqtns 3 and 4 (see Appendix 1),

$$R_{80\%} = {}^{11}/_{12m} \quad (3)$$

$$s_{80\%} = {}^{11c}/_{m} \quad (4)$$

In some case studies, the test piles were provided with internal sensors, to allow the load-transfer from the pile to the ground to be assessed. Where available, this data has been reassessed and equivalent values for associated resistance parameters (α^* and β^* along the shaft and inter-helix cylinder) and end-bearing capacity factors, N_c^* or N_q^* as appropriate for total and effective stress analysis, were determined. These values are then to be used for comparison with values from analytical solutions. This aspect of the test database will not be discussed here.

3 CRITIQUE OF CASE STUDIES

3.1 Time-extrapolation

The method described above is illustrated here based on the results for tests on HSP in clay reported by Zhang (1999). The compression test shown here was undertaken on a 5.18 m long pile with a 219 mm diam. shaft and 3 no., 356 mm diam. helices, spaced at 1.5 helix diameters. Eleven stages of loading were applied and within each stage, the loads generally varied by less than about ±2 kN (1%).

This is one of the few cases where the author states that creep was considered. However, it is apparent that whatever consideration was made, creep rates were very high from early on when compared to e.g., the 0.25 mm/hr limit referenced by ASTM (2020) or the 0.1 mm/20 min in ISO (2018), for maintained load testing, Figure 3.

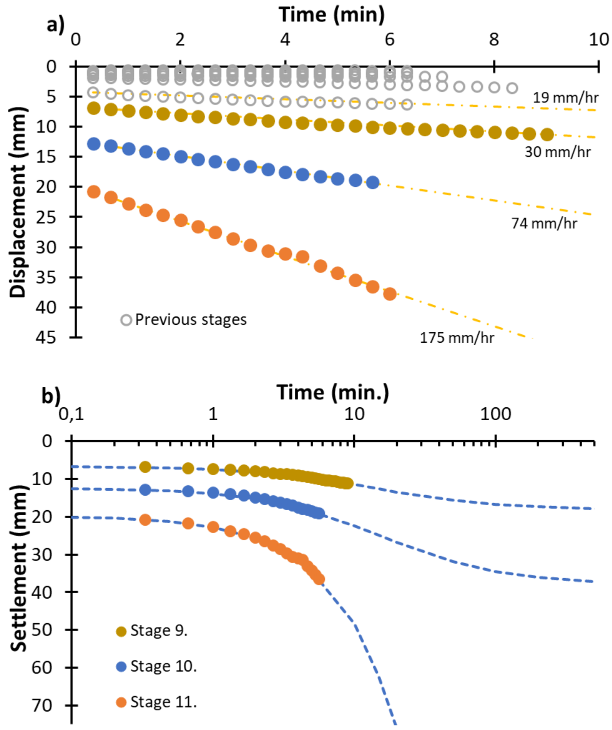

Figure 3. Time extrapolation of load test settlement data.

In Figure 3(a), the settlement rates for the last three stages are examined in more detail. Settlement rates towards the end of each, were in excess of 20 mm/hr. The time-extrapolation of the data from each stage is shown in Figure 3(b) where it can be seen that Stages 9 and 10 are predicted to reach a stable value at ∞-time, while Stage 11 is heading towards a plunging failure. In this example, the stage durations were systematically less than 10 minutes and therefore there is some uncertainty in the extrapolation to ∞-time, especially in the latter stages of the test. It is recommended that loading stages should last at least 30 minutes and/or until the creep rate is less than 0.1 mm/20 min. to increase data reliability.

3.2 Interpretation of ultimate load resistance

In the same example, based on the above, the last stage of the test was deemed to be unstable and therefore should not be considered, i.e., failure occurs at a load between that in Stages 10 and 11 (172 – 177 kN). The failure load reported by Zhang was 180 kN – the load mobilised in Stage 11, as pile settlements reached 10% of the helix diameter (36 mm).

The test stages deemed stable were then treated using the load extrapolation to ∞-displacement, described above. The result of this assesment is shown in Figure 4(a) which illusrates how it is only the last few stages where the effect is significant and how the resulting collapse load can be affected. Figure 4(b) shows the resulting hyperbolic interploation through the treated load-displacement data, along with the failure loads, R_∞ = 177 kN and $R_{80\%}$ = 162 kN. In this example, the difference with respect to the ultimate resistance quoted by Zhang (1999) is less than 5% but with this revision, it is clear that the result is based on stable data.

Figure 5 further illustrates the impact of this reappraisal by comparing the revised results of three tests: *A1 C Long* has already been presented, *A2 C Short* is the same as A1 but with a shorter embedment of 3.1 m, and *A3 C Long* has only two helices with a spacing of 3 helix diameters but is otherwise the same as A1. In all cases, someof the later load stages did not trend to a stable displacement-time response and the revised load-displacement curves led to a reduction in the inferred ultimate resistance, of up to 15% in the case of A2.

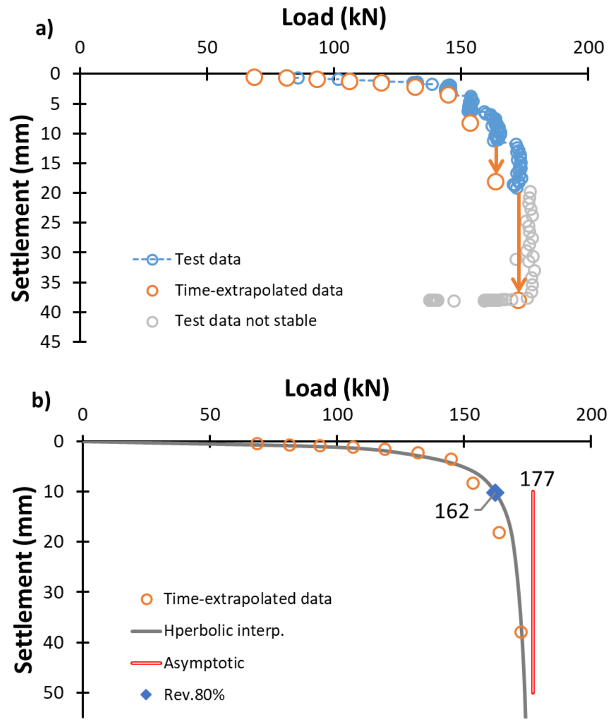

Figure 4. Load-displacement response and failure.

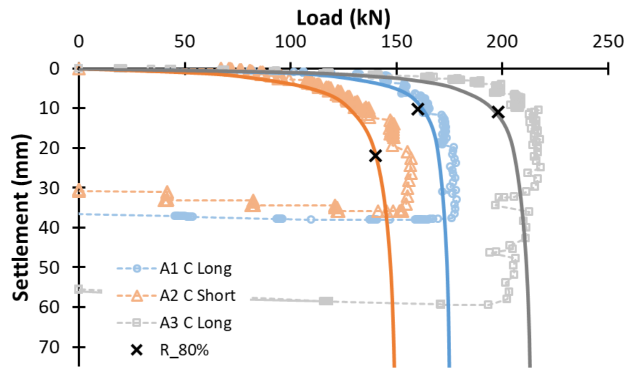

Figure 5. Impact of time & displacement extrapolation on inferred ultimate resistance.

4 FINAL COMMENTS

The purpose of the work presented was to a) develop a sense of the quality and robustness of the field test data relating to HSP that had been published previously and b) reform the data base on the basis of tests that can be demonstrated to be well-controlled and then presented in a uniformized manner to aid further interpretation. This evaluation has also informed the testing specification that will be employed for field testing undertaken as part of the project HELIPORT.

Given the cost of undertaking field load tests on piles (generally), it is imperative that good control of the process is maintained to ensure the data produced are of the best quality and the investment is not wasted. Clear load control (ICE, 2007) and creep (ASTM, 2020) criteria should be specified and checked, and loading stages should be of sufficient length to ensure that it can be verified reliably that the pile settlement will stabilise – from this assessment the load should be held 30 minutes and/or until the creep condition (e.g. 0.1 mm/20 min.) is met.

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APPENDIX 1.

Derivation of Brinch-Hansen 80% failure criteria parameters from hyperbolic function:

$$R_{80\%} = \frac{s_{80\%}}{m.s_{80\%}+c} \qquad [1.1]$$

$$0.8R_{80\%} = \frac{0.25s_{80\%}}{m.0.25s_{80\%}+c} \qquad [1.2]$$

Solving simultaneously,

$$\frac{\cancel{s_{80\%}}}{ms_{80\%}+c} = 1{,}25\left[\frac{0.25\cancel{s_{80\%}}}{m0.25s_{80\%}+c}\right]$$

$$0.25ms_{80\%}+c = 1.25(0.25)m.s_{80\%}+c$$

$$\big(1-1.25(0.25)\big)c = (1.25(0.25)-0.25)ms_{80\%}$$

$$\Rightarrow s_{80\%} = {}^{11c}/_{m} \qquad [1.3]$$

Substituting into [1.1],

$$R_{80\%} = \frac{{}^{11c}/_{m}}{m.\left({}^{11c}/_{m}\right)+c}$$

$$\Rightarrow R_{80\%} = {}^{11}/_{12m} \qquad [1.4]$$