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ABSTRACT

This report considers the development of guidance on rapid load pile testing within the European context that has led to the development of FprEN ISO 22477-10, Geotechnical investigation and testing — Testing of geotechnical structures — Part 10: Testing of piles: rapid load testing. This report summarises current European national guidance on rapid load pile testing and goes on to outline an informative test interpretation method included in FprEN ISO 22477-10 that goes someway to developing design methods under EN 1997-1. The report finishes with considerations for EN 1997-1 evolution and future ETC3 reporting.

1. INTRODUCTION

Guidance on the design of piles based upon the use of rapid load pile testing (RLT) is generally limited outside of Europe and currently lacks codification within CEN or ISO standards. The majority of existing published guidance is limited to general information or execution and testing specification. Currently guidance is lacking on how to interpret measured data captured during rapid testing so that it can be considered a characterisitic measured resistance in EN 1997-1. Published national guidance in both Holland and Germany does though offer some guidance on test interpretation and a way forward in developing design to EN 1997-1 and its evolution. In order to improve European guidance on rapid load testing CEN TC 341 WG7 have recently developed an execution code, FprEN ISO 22477-10, Geotechnical investigation and testing — Testing of geotechnical structures — Part 10: Testing of piles: rapid load testing. The execution code also includes an informative annex outlining a potential method of test analysis but stops short of developing model and characteristic values for RLT. This report identifies current existing European design and execution guidance, considers the national reports, outlines the informative test interpretation guidance given in FprEN ISO 22477-10 and finishes with recommendations for evolution of EN 1997-1 and future reporting of ETC3.

2. EXISTING GUIDANCE AND EXPERIENCE

2.1. National and international guidance

National guidance in the UK is limited to operational and specification type guidance as outlined in SPERW (ICE, 2007). No specific mention is made of how to determine ultimate pile resistance from the test but specific mention is made of how piles subjected to rapid load testing may experience significantly higher loads than during static pile testing and should be designed and reinforced structurally to take these additional loads (Brown & Hyde, 2006). SPERW states that rapid load testing can be considered as either an alternative or complementary method to static load testing providing the results and the interpretation of the results are fully understood. Rapid load testing may also be used for site specific quality and consistency work where a maintained load test is available on an identical pile. Guidance on RLT in the context of other pile testing techniques is also included in the ICE Manual of Geotechnical Engineering (2012).
The most extensive European guidance exists in Dutch guidance in CUR Guideline 230 (Hoelscher et al, 2011) which outlines potential test interpretation and design approaches and also discusses the ethos and development of the design and interpretation methodologies. Two interpretation methods are outlined in detail in this document. The first is a method designed to be applicable in a variety of soil types and is based upon a simplified version of the Unloading Point Method, UPM (Middendorp, 2000). This method requires the use of a soil dependent factor which was developed in CUR Guideline 230 based upon a database of published RLT undertaken in various soils in the USA, Belgium and Holland. CUR Guideline 230 also outlines and discusses the use and interpretation of single or multiple cycle testing for the first time. The second interpretation method outlined (referred to as the Sheffield Method) is designed currently for use in clay soils only and has not been extended to other soil types. This method was initially developed based upon model pile testing and then verified against various clay deposits in the

UK (Brown & Powell, 2013, Brown et al, 2006). Current development allows it to be used in different clay types through correlation of velocity dependant rate effects with simple laboratory consistency measurements (e.g. plastic limit and liquid limit).
In Germany national guidance is covered in EAPfaehle – Recommendations on Piling, (GGS 2013). This covers both execution and test interpretation for design. The interpretation approach outlined is as per that outlined in CUR Guideline 230.
International guidance has been in existence for some time with formal codification in ASTM D7383 and the Japanese Geotechnical Society (JGS). In both of these cases though guidance is limited to execution rather than interpretation and design.

2.2. European experience and national reports

National reporting gives little mention of rapid load testing apart from mention as a possible verification approach in Dutch practice. It is also mentioned in the Belgium national report (referred to as Kinematic testing) as it was undertaken as part of the large screw pile field test study reported in Holeyman et al. (2001) and Holeyman et al. (2003). This lack of inclusion in the national reports may be due to limited experience, omission from reporting templates and current omission from EN 1997-1. It is noted later that the national reporting templates for ETC3 did not include rapid load testing and that RLT now comes under the heading of “non-static piles tests”. Therefore in future it is suggested that RLT is not grouped under the heading of dynamic testing but as a separate entity as recognised by CEN/ISO and that reporting on its use is also identified.

3. DESIGN OF PILES BASED UPON RAPID LOAD PILE TESTING

3.1. Informative guidance on tests interpretation in FprEN ISO 22477-10

As part of the development of FprEN ISO 22477-10 it was identified that as well as giving guidance on execution of RLT it would also be useful to give informative information on the interpretation of RLT especially where RLT is not mentioned in the current EN 1997-1. As FprEN ISO 22477-10 is an execution code it was decided that it could not consider pile design directly but that there was a need to give informative guidance on how to proceed from load and displacement measured during RLT to a characteristic measured resistance ($R_{c,m}$) that could be used as a basis for design. The other reason that the annex was made informative only was that it was felt that only one method of interpretation should be included (due to space considerations) but that as other methods of interpretation do exist that their use should not be precluded. It was also acknowledged that RLT interpetation is still the subject of research and development and that codification should not stifle the development of improved analysis techniques in the future.
The method currently included in the informative annex is based upon the CUR Guideline 230 for the simplified UPM method for single and multiple cycle analysis. This method was used as a basis for the informative annex as it was felt that this method was outlined in both Dutch and German national guidance documents and that it’s development was well documented against a published data base of field testing that can be verified by an end user.

3.2. Unloading Point Method (UPM) for determination of the compressive pile behaviour

3.2.1. General

Rapid load test results can be analysed using the Unloading Point Method (UPM) to derive the measured compressive resistance $R_{c,m}$ and the corresponding load deflection behaviour. The approach can be used for either a single load cycle or multiple load cycles (undertaken on a single pile) as required. Only the method for analysis of a single load cycle is outlined here although multiple cycle analysis is covered in CUR Guideline 230 and FprEN ISO 22477-10.

3.2.2. Analysis of a single load cycle

The process of analysis of a single load cycle is outlined below with Figure 1 to Figure 3 included to clarify the steps of the analysis process. The process is as follows:

a) Obtain the measured signals from the rapid load test
b) Calculation of the inertia corrected mobilised pile resistance at the unloading point:

- Obtain the pile properties required to calculate the mass of the pile, m (pile cross sectional area, pile length, density of the pile material, records of the concrete volume used to form the pile) and the mass of any other components contributing to the inertial resistance of the pile.
- Obtain the variation of force (F), velocity (v), displacement (w) and acceleration (a) with time (t) for a single load cycle.
- Determine the time ($t_{\text{w-max}}$) during the test where the measured pile velocity becomes 0 m/s or a value close to this. Referred to as the unloading point.
- Determine the magnitude of the force measured at $t_{w\text{-}max}$, $F_{c,\ tw\text{-}max.}$
- Determine the magnitude of the acceleration at $t_{w\text{-}max}$, $a_{tw\text{-}max.}$
- Solve equation (1) to determine the inertia corrected pile resistance at $t_{w\text{-}max.}$

$$R_{\text{c, ic, tw-max}} = F_{\text{c, tw-max}} - (\text{m} \times a_{\text{tw-max}}) \tag{1}$$

The parameters in equation (1) are defined as:

$a_{tw\text{-}max}$	is the acceleration measured during the test at $t_{w\text{-}max}$
$F_{c,\ tw\text{-}max}$	is the magnitude of the force measured during the test at $t_{w\text{-}max}$
M	is the mass of the pile and any other components contributing to inertial resistance of the pile
$R_{c,\ ic,\ tw\text{-}max}$	is the inertia corrected pile resistance at $t_{w\text{-}max}$
$t_{w\text{-}max}$	the time some time after the commencement and before the end of the load application phase of the test where the pile velocity effectively becomes 0 m/s or a value close to this.

c) Correction of the inertia corrected pile resistance for the soil dependant empirical parameter

- Determine the soil dependent empirical parameter based upon Table 1 recommendations and calculate the corrected derived static pile resistance, $R_{c,corrected}$ as per equation (2).
- Determine the magnitude of the displacement at $t_{w\text{-}max}$, $w_{tw\text{-}max}$.

$$R_{\text{c,corrected}} = \eta \times (R_{\text{c, ic, tw-max}}) \tag{2}$$

Where:

$R_{c,corrected}$	is the corrected mobilised resistance at $w_{tw\text{-}max}$.
$w_{tw\text{-}max}$	magnitude of the pile displacement at $t_{w\text{-}max}$
η	soil dependant empirical parameter

Where the mobilised pile load deflection behaviour at $t_{w\text{-}max}$ can be shown to correspond to the ultimate resistance of the pile then $R_{c,corrected}$ may be considered equivalent to the measured compressive pile resistance $R_{c,m.}$

The parameters shown in Table 1 should only be adopted where it can be demonstrated that rapid load testing was undertaken on the same type of pile, of similar length and in comparable soil conditions as those that were used to determine the parameters as outlined in CUR Guideline 230.

Table 1 : Selection of soil dependant empirical parameter η

Soil type	**Clay**	**Sand**
Empirical factor, η	0,66	0,94
Standard deviation	0,32	0,15
Coefficient of variation	0,49	0,15
Number of cases	12	22
Number of sites	6	10

The values shown in Table A.1 are based upon data presented in Table C2 for clay soils and Table C3 for sand of CUR Guideline 230.

NOTE 1 Only cases with pile head displacements greater than 5% of the equivalent pile diameter are considered in Table 1.

NOTE 2 The variation of values in Table 1 is significant for clay soils particularly. An alternative suggestion for a selection method for empirical factor for clay based upon measured soil properties can be found in Brown & Powell (2013). The majority of the values presented in Table A.1 are derived from pile tests on driven piles.

NOTE 3 Guidance on analysis in clays and layered soils is also given in Weaver & Rollins (2010).

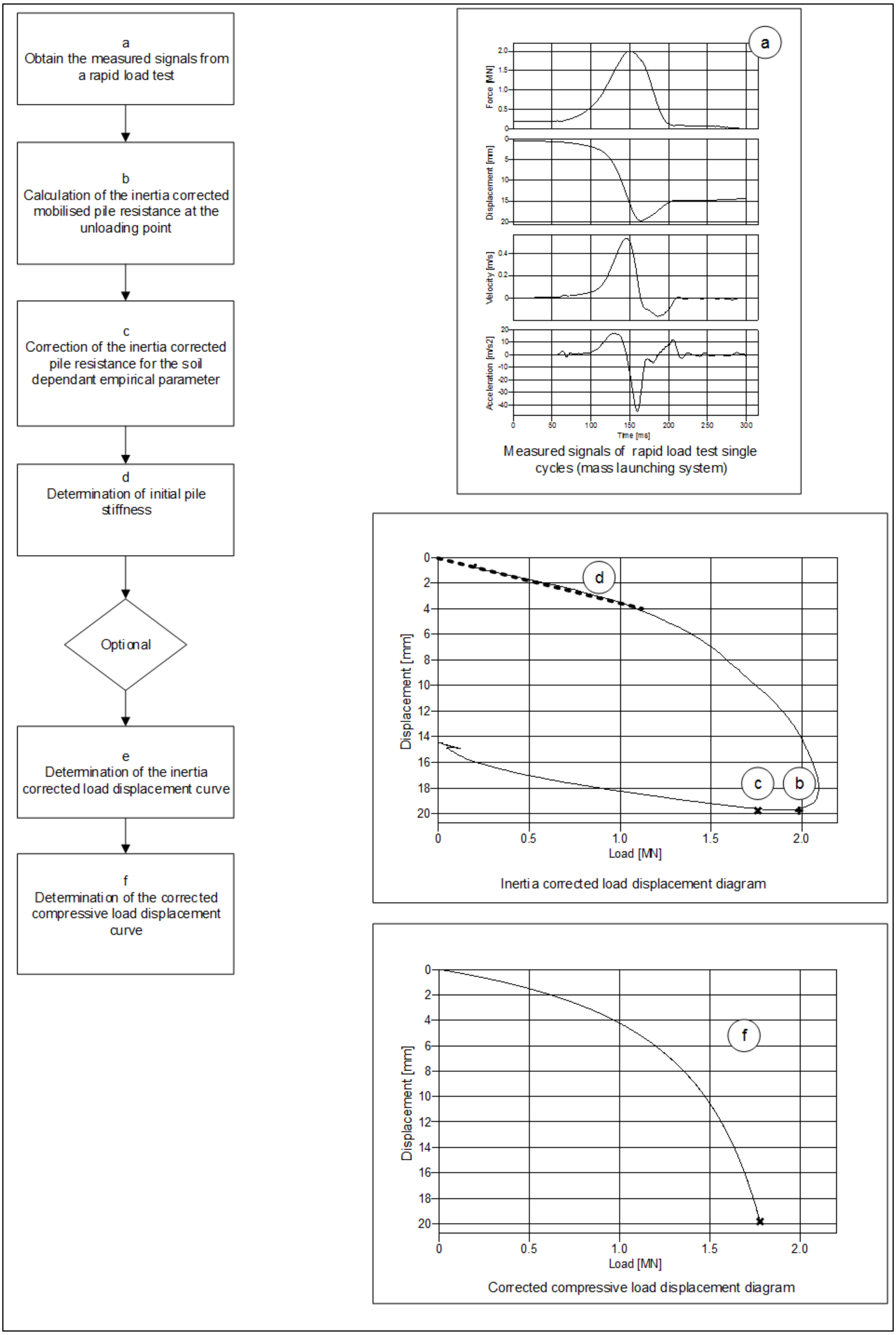

Figure1 : Flow chart showing the analysis process for a single cycle of rapid load testing

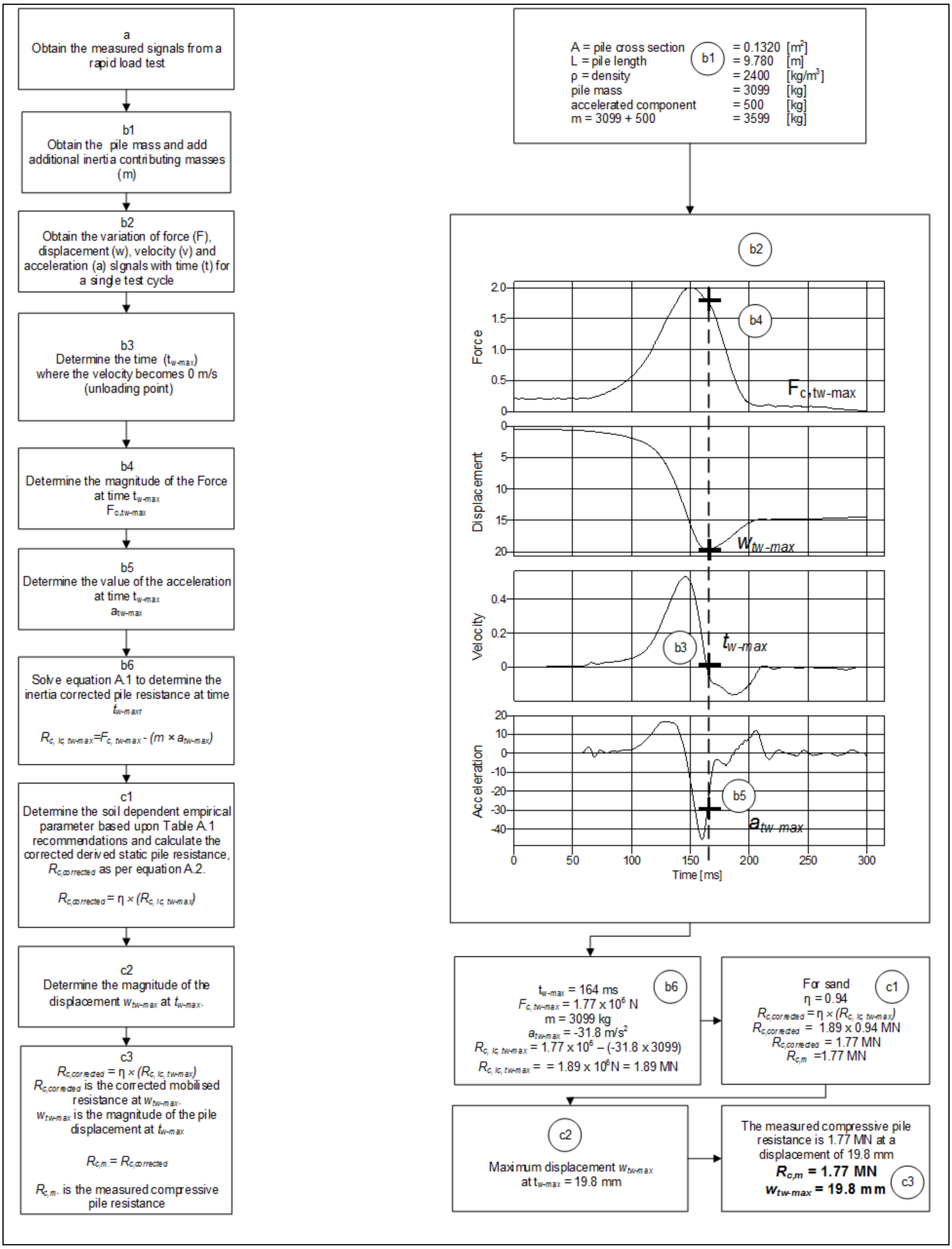

Figure2 : The analysis process for a single cycle using example data and calculation of $R_{c,m}$

d) Determination of initial pile stiffness

If an approximation of the complete corrected load-displacement behaviour during the test is required then further analysis steps are necessary to construct a hyperbolic based approximation of the load displacement behaviour (Figure 3). Firstly it is necessary to determine the initial pile stiffness at low displacement levels.

NOTE The hyperbola is described by $F = w / (p + q \times w)$; p is the inverse value of the initial pile stiffness k_c and q is the inverse value of the hyperbola asymptote. In a hyperbola diagram with coordinates w / F and w, a pure hyperbola will be represented by a straight line. Background information on this technique can be found in Chin (1972). The required steps are as follows:

- Plot the displacement of the pile (w) divided by the inertia corrected pile resistance ($R_{c,\,ic}$) for the complete test versus the pile displacement up to $w_{Fc\text{-}max}$ where $F_{c\text{-}max}$ is the maximum measured force.
- Determine the magnitude of the $w/R_{c,\,ic}$ axis intersection with a best fit linear line to determine the value for the hyperbola parameter p which represents the inverse of the initial pile stiffness, k_c.

e) Determination of the inertia corrected load displacement curve

The procedure for determination of inertia corrected load displacement curve is as follows:

- Determine the initial stiffness parameter as outlined above.
- Calculate the remaining the hyperbola formula parameter q equation (3)

$$q = 1{,}0 / R_{c,\,ic,\,tw\text{-}max} - p / w_{tw\text{-}max} \qquad (3)$$

- Draw the resulting hyperbola load displacement curve using equation (4)

$$R_{c,\,ic} = w / (p + (q \times w)) \qquad (4)$$

f) Determination of the corrected compressive load displacement curve
The procedure for determination of the corrected compressive load displacement curve is as follows:

- Calculate the hyperbola parameter $q_{corrected}$ as per equation (3) with $R_{c,ic,tw\text{-}max}$ replaced by $R_{c,corrected}$;
- Draw the resulting corrected compressed load displacement curve using equation (4) with parameters determined for $R_{c,corrected}$.

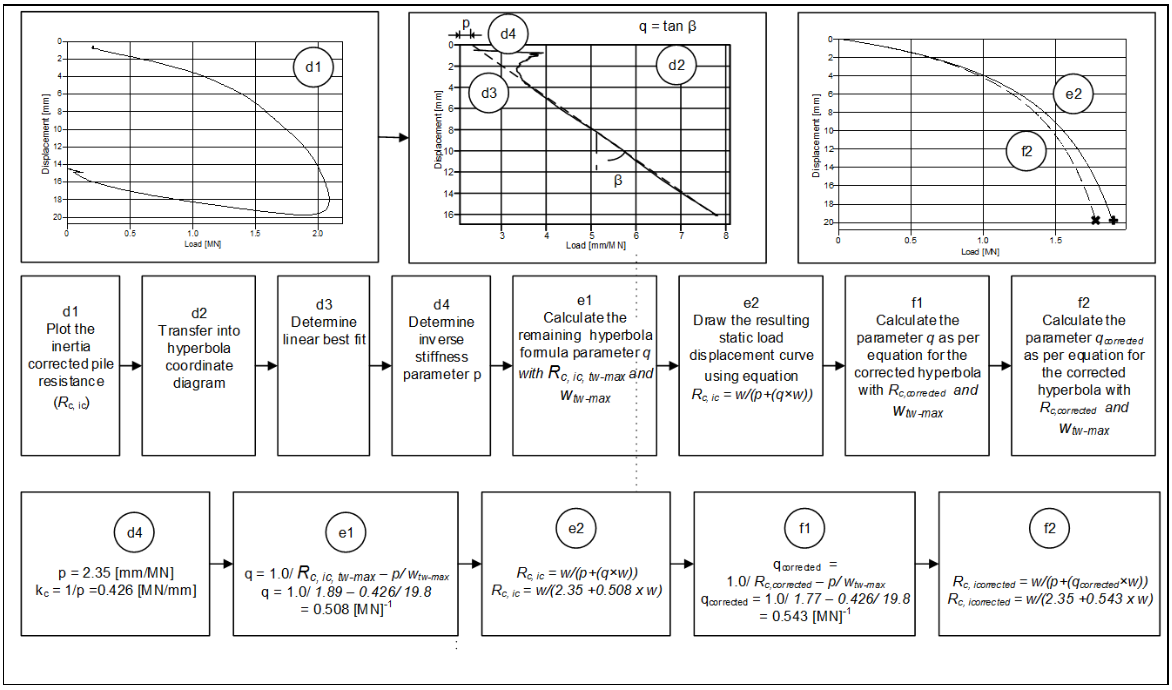

Figure3 : Single cycle load displacement calculation using example data

3.2.3. Correlations for piled foundations

Although FprEN ISO 22477-10 outlines the potential analysis technique above it does not go as far as giving model (if required) and correlation factors for RLT as this is considered “design” and outside of the scope of an execution standard. FprEN ISO 22477-10 states in A.3 “For the verification of Structural (STR) and Geotechnical (GEO) limit states, correlation and model factors should be applied to the $R_{c,m}$ determined from Rapid Load testing to derive the characteristic resistance of axially loaded piles. These should be determined based upon appropriate experience of comparison of Rapid Load testing analysis results with static pile tests for similar pile types and ground conditions. Model factors should be used that reflect the performance of the particular analysis technique used". It is planned to develop such factors based upon and independent data base of piles tests and publish these as an addendum to FprEN ISO 22477-10 with a view to these being incorporated in the evolution of EN 1997-1.

4. CONSIDERATIONS FOR EVOLUTION OF EN 1997-1 & ETC3

4.1. Model and charateristic values for RLT and other pile tests

As mentioned in 3.2.3, model (if required) and characteristic values are required for RLT based design to Eurocode. Therefore clear guidance is required on how these values should be derived for RLT but also for the re-evaluation of the values for other pile testing techniques (previously published in EN 1997-1). One shortcoming of the use of model and characteristic values is that they potentially prescribe pile test analysis techniques and have the potential to stifle the use of newer and improved techniques. This could be avoided by making the use of such factors less prescriptive and giving clear guidance on how these values could be determined for example how many pile tests, comparison to what static equivalent test, how many tests in each different soil type, transparency and publication of data, etc...

4.2. Definition of $R_{c,m}$ and primary measurements

As RLT (and dynamic load tests, DLT) do not measure $R_{c,m}$ directly, and must first undergo some interpretation, then definition of at what stage of the process of interpretation $R_{c,m}$ is defined is required. As EN 1997-1 already includes model and characteristic values for DLT it would be expected that clear definitions of how $R_{c,m}$ should be obtained would exist. Without such guidance it is difficult to maintain consistent analysis and design based upon RLT or DLT. Adding this to an evolved Eurocode 7 would add significant complexity and thus it would seem logical to include this in execution codes for testing methodologies as outlined above in 3.2.2. As there is a requirement for primary measurements (potentially several) and then interpretation there is a need for definition of these meaurements and appropriate symbols within the execution codes.

4.3. The use of piles testing in Europe for verification not design?

Based upon the national reports submitted to ETC3 it would seem that pile load tests are very rarely used (of any type) for stand alone design but are more commonly used as design verification. Thus new guidance on the use for verification rather than just design may be required.

4.4. General considerations for Eurocode evolution main text

Although the presence of execution codes has the potential to reduce test specific text within an evolution of EN 1997-1 there may still be specific requirements for individual test peculiarities to be mentioned. For RLT these may include:

- Notes to the effect that all tests must be analsysed to some extent to determine $R_{c,m}$ and that primary data obtained should not be used for design purposes (See 4.2 above).
- Piles should be designed structurally to withstand higher stresses than they may experience during static loading.
- RLT may not be applied to all pile lengths without first checking that the duration of loading is appropriate for the pile material and pile length being tested. Where the load duration criteria is not met it may be necessary to pre-install appropriate embedded pile instrumentation and specialised analysis will be required.

More generally the use of open format easily readable/transferable data should be encouraged for all pile testing as this leads to greater transparency, opportunities to develop current practice and meet the growing requirements for public accessibility of government funded research.

4.5. Future considerations for ETC3

It is noted that the national reporting templates for ETC3 did not include rapid load testing and that RLT (and DLT) now comes under the heading of "non-static piles tests". Therefore in future it is suggested that RLT is not grouped under the heading of dynamic testing but as a separate entity as recognised by CEN/ISO and that reporting on its use is also identified. Also, it would appear that pile load testing is not frequently used for design purposes but for verification of design approaches. This may form a more useful enquiry heading i.e. pile testing for design and verification of design.

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