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Interpretation criteria for static compression load tests on piles. A multiple case study.

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ABSTRACT: Static compression load tests are commonly used in pile foundation projects to verify the ultimate bearing capacity estimated during design. Numerous interpretation criteria have been proposed over time, some of which are included in current standards. This study reviews these criteria, classifies them by methodological approach, and applies them to four case studies. A comparative analysis identifies the most suitable methods for estimating ultimate capacity. Additionally, a finite element simulation using PLAXIS 2D confirms the consistency of the estimated capacity with the most reliable criteria.

KEYWORDS: Static load tests, compression, piles, interpretation criteria, ultimate load, ultimate capacity.

1 INTRODUCTION

Static load tests verify pile geotechnical capacity under axial and lateral loads by simulating real behaviour and generating load-settlement curves for comparison with design assumptions.

In compression tests, vertical loads are applied incrementally to mobilize shaft and base resistance with continuous monitoring. The resulting curve helps determine bearing capacity, split between shaft friction and base resistance, and can be idealized as a bilinear curve (Figure 1), depending on pile type and soil. Resistance distribution can be estimated based on pile diameter (D). Full shaft resistance is typically mobilized at displacements less than 1% of the pile diameter, while full base resistance usually requires about 10% of the diameter.

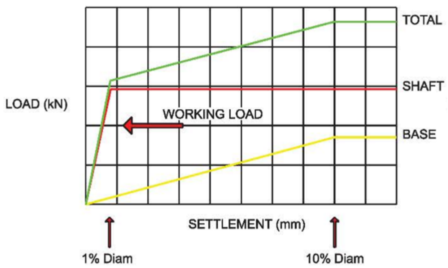

Figure 1. Approximate load-settlement behaviour on piles subjected to compression static load test. After Raison and Egan (2016).

While analytical methods estimate Q_u, static compression load tests offer a more accurate means of verifying the ultimate load, significantly reducing the level of uncertainty associated to traditional calculation methods. However, determining the ultimate load from a load test is not always straightforward, particularly in cases where the pile is not subjected to load magnitudes high enough to reach a failure or plunging state.

Consequently, numerous authors over the years have developed their own interpretations of static compression load tests on piles, aiming to define a specific value for the ultimate load. These interpretations consider a variety of factors and conditions, tailored to the particular aim and context of each study.

This article presents a comprehensive compilation of interpretation criteria and methods for static compression load tests on piles, as proposed by various authors, and offers a critical analysis of their applicability and reliability.

2 INTERPRETATION CRITERIA FOR STATIC LOAD TESTS ON PILES

A state-of-the-art review has been conducted on 17+1 interpretation criteria proposed by various authors, along with interpretation methods included in 7 widely used international standards and guidelines.

2.1 *Terzaghi´s criterion (1942)*

Fellenius (2023) traces this criterion to a misinterpretation of Terzaghi (1942), who stated that determining pile capacity from load tests requires a displacement of at least 10% of the pile diameter at the base.

2.2 *Van der Veen´s criterion (1953)*

This criterion models the load-settlement curve as a hyperbolic function of applied load (Q), ultimate load (Q_u), settlement (δ), and a shape factor (α), expressed by the following equation:

$$Q = Q_u \cdot (1 - e^{-\alpha \cdot \delta}) \quad (1)$$

By applying a value of α = 1 in the above formulation and plotting the settlement (δ) against ln(1 − Q/Qu), the resulting curve exhibits two distinct linear segments: an initial one and a final one that appears once the ultimate load (Qu) is reached.

Figure 2 illustrates an example of application, where the curve that best fits a straight line corresponds to Q_u=3000 KN (highlighted in bold), which matches the desired load.

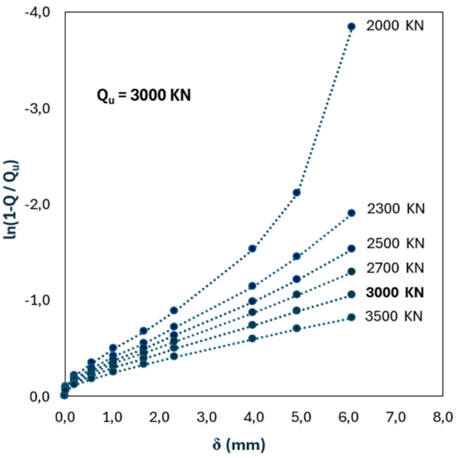

Figure 2. Ultimate load based on Van der Veen´s criterion (1953).

2.3 *Housel´s criterion (1953)*

This method applies equal load increments at one-hour intervals during the compression load test. Displacements from the last 30 minutes of each step are plotted against load on a logarithmic scale. The graph typically shows two linear segments whose intersection defines the *creep load* or ultimate load (Figure 3).

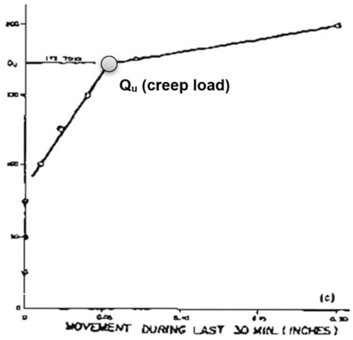

Figure 3. Ultimate load based on Housel´s criterion (1953). Adapted from Fellenius (1975).

2.4 *Brinch-Hansen´s 80% criterion (1963)*

Brinch Hansen's 80% criterion (1963) defines the ultimate load capacity of a pile (Q_u) as the load associated with a displacement (δ_u) equal to four times the displacement corresponding to 80% of that load.

Alternatively, Q_u can be determined analytically by plotting √δ/Q, as expressed in the following equation:

$$Q_u = \frac{1}{2 \cdot \sqrt{C_1 \cdot C_2}} \tag{2}$$

In the √δ/Q - δ graph, C_1 is the slope and C_2 the vertical intercept of the linear segment. Since this method provides an analytical solution, it allows estimating the ultimate load (Q_u) even beyond the maximum test load. Figure 4 shows an example where Equation (2) yields Q_u = 3555 kN.

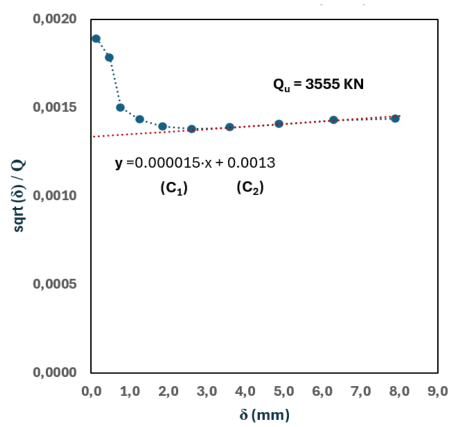

Figure 4. Numerical application of Brinch Hansen's 80% criterion (1963).

2.5 *Brinch-Hansen´s 90% criterion (1963)*

Also in 1963, Brinch-Hansen proposed the 90% criterion later adopted by the Swedish Pile Commission (1970) widely used in Scandinavia. It defines the ultimate load as the load causing twice the settlement produced by 90% of that load.

2.6 *De Beer criterion (1968)*

This method uses a double-logarithmic plot, where two distinct linear segments typically emerge. Their intersection defines the ultimate load (Q_u), as shown in Figure 5.

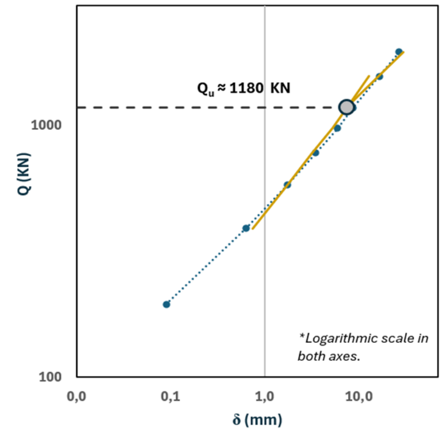

Figure 5. Ultimate load based on De Beer´s criterion (1968).

2.7 *Chin-Kondner´s criterion (1970)*

The criterion is based on fitting the Q-δ curve to a hyperbolic model, defining the ultimate load as the value asymptotically approached when displacement tends toward infinity. Its application involves dividing each recorded displacement (δ) by its corresponding load (Q), resulting in a δ/Q - δ plot. After an initial variation, the resulting function typically follows a linear trend. The inverse of the slope ($1/C_1$) of this linear portion corresponds to the pile capacity or ultimate load (Q_u).

The Figure 6 reflects an example of the method's application, where the inverse of the slope yields a value of 3343 KN.

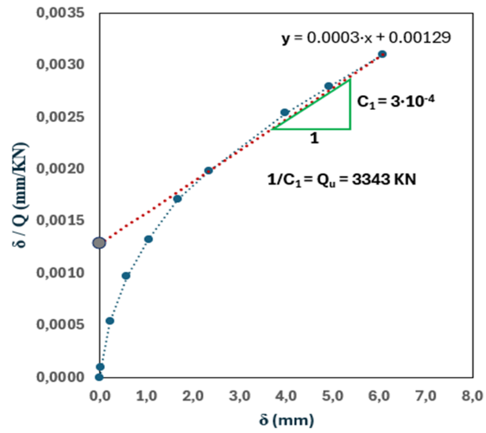

Figure 6. Ultimate load based on Chin-Kondner´s criterion (1970).

2.8 *Fuller & Hoy criterion (1970)*

Fuller and Hoy (1970) proposed that the ultimate load (Q_u) corresponds to the point on the load–settlement curve where the slope exceeds 0.05 inches per ton (0,14 mm/kN), or 0,03 inches per ton (0,08 mm/kN) on the plastic load–settlement curve, which excludes the elastic deformation of the pile. An example of application is shown in Figure 9, where Q_u results 203 tons.

2.9 *Davison´s criterion (1972)*

Davisson (1972) proposed a method based on comparisons between wave equation analyses and quick load tests on small-diameter driven piles. The ultimate load (Q_u) is defined as the intersection of the load–settlement curve with the pile's elastic deformation line (Δ), offset by 3,81 mm plus an additional displacement equal to the pile diameter divided by 120.

$$\text{Offset} = 3{,}81 \cdot D/120 + \Delta \text{ (mm)} \tag{3}$$

The Figure 7 reflects an example, determining a value of Q_u=1875 KN.

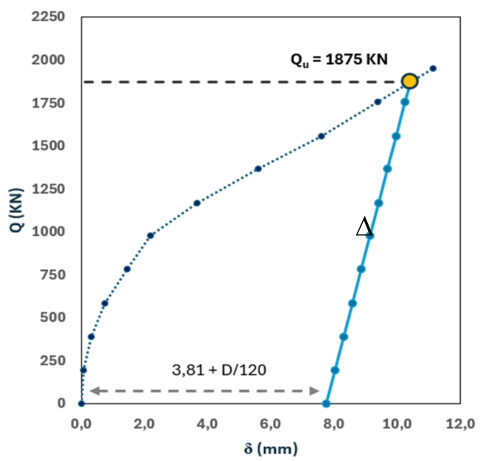

Figure 7. Ultimate load based on Davison´s criterion (1972).

2.10 *Mazurkiewicz´s criterion (1972)*

The criterion allows extrapolation of an ultimate load value (Q) that exceeds the maximum test load applied.

This is achieved graphically by dividing the parabolic portion of the load–settlement curve into equal settlement intervals and drawing auxiliary lines parallel to the settlement axis that intersect and extend beyond the load axis. At each intersection with the load axis, new auxiliary lines are drawn at a 45° angle relative to that axis. These lines intersect the projections of the previously drawn vertical lines, generating new intersection points. Connecting these points forms a new line whose extension intersects the load axis, thereby defining the ultimate load or pile capacity (Q_u) as illustrated in Figure 8.

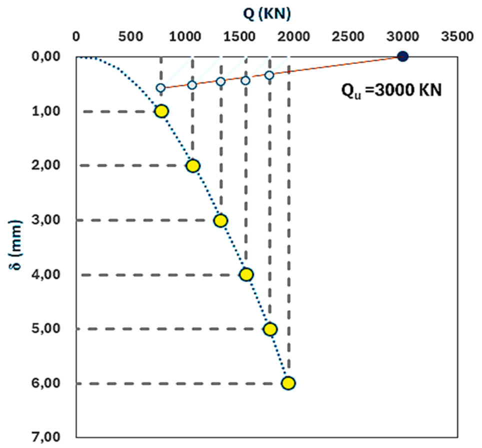

Figure 8. Ultimate load based on Mazurkiewicz´s criterion (1972).

2.11 *Davison´s criterion (1973)*

This version introduced a modification to the offset, making it a function of the pile diameter (D) and a reference diameter (D_R=300 mm).

$$\text{Offset} = 0{,}012 \cdot D_R + 0{,}1 \cdot \left(\frac{D}{D_R}\right) + \Delta \quad (\text{mm}) \qquad (4)$$

The method to determine the ultimate load (Q_u) is identical as illustrated in Figure 7 by changing the offset.

2.12 *Butler & Hoy criterion (1977)*

Butler and Hoy (1977) define the ultimate load (Q_u) as the intersection of two lines on the Q-δ curve: one tangent to the initial linear portion, and another with a slope of 0.14 mm/kN (0.05 in/ton).

As shown in Figure 9, this method yields a pile capacity of 185 tons.

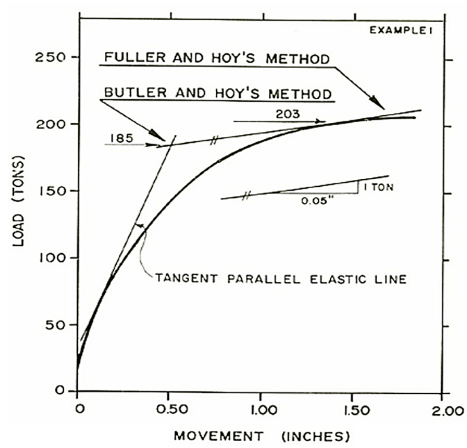

Figure 9. Ultimate load based on Fuller & Hoy (1970) and Butler & Hoy (1977) criteria. Fellenius (1980).

2.13 *Shen´s criterion (1980)*

According to Mishra et al. (2019), Shen's (1980) method estimates the ultimate load (Q_u) by plotting the logarithm of the applied load (Q) versus settlement (δ). The point where the curve becomes linear marks Q_u. Figure 10 illustrates and example, identifying an ultimate load of Q_u= 1738 KN.

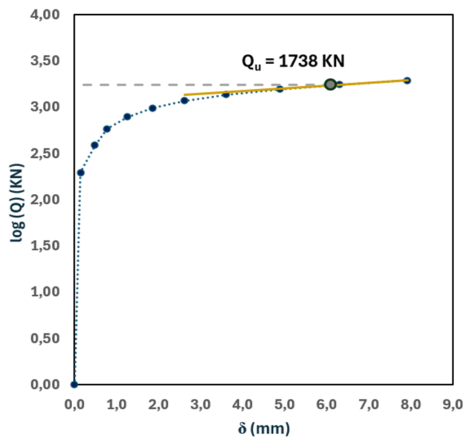

Figure 10. Ultimate load based on Shen´s criterion (1980).

2.14 *O´Rourke & Kulhawy criterion (1985)*

The method defines pile capacity as the load corresponding to a displacement equal to the initial slope of the load–settlement curve, offset by a load value (Q_{L1}) plus 3.81 mm (0.15 in). Figure 11 shows an example of this criterion.

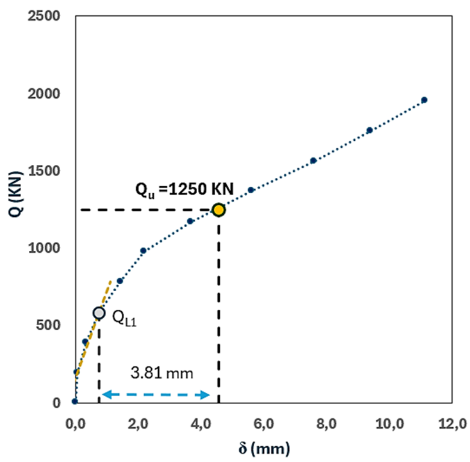

Figure 11. Ultimate load based on O´Rourke & Kulhawy criterion (1985).

2.15 *Hirany & Kulhawy criterion (1988)*

Hirany and Kulhawy (1988) divided the static load test curve into three regions: initial linear, transitional (parabolic), and final linear. The ultimate load (Q_u) is defined at the start of the final linear segment, as shown in Figure 12.

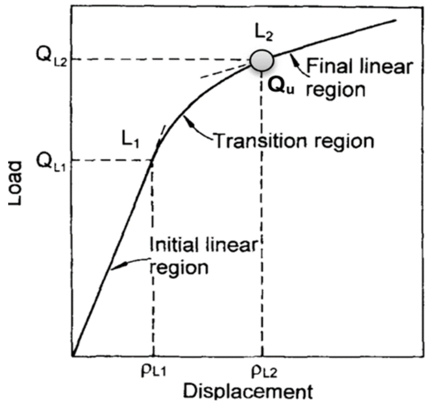

Figure 12. Ultimate load based on Hirany & Kulhawy criterion (1988). Adapted from Hirany & Kulhawy (2002).

2.16 *Decourt´s criterion (1999)*

The method involves dividing each recorded load (Q) from the test by its corresponding displacement (δ), resulting in a Q/δ - Q plot. As shown in Figure 13, the resulting function tends to become linear as it approaches the axis representing the applied test load (Q). By extending this linear segment, its intersection with the load axis defines the ultimate load (Q_u).

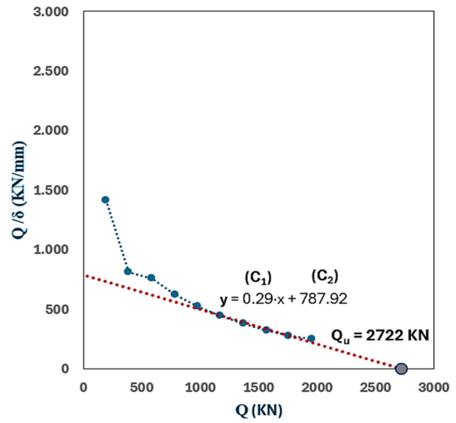

Figure 13. Ultimate load based on Decourt´s criterion (1999).

This criterion assumes a hyperbolic model of the load-settlement curve, which allows the ultimate load (Q_u) to be defined beyond the maximum test load (Q_{max}).

2.17 *Das´s criterion (2010)*

The method determines the ultimate load (Q_u) based on the net load-settlement curve, defined as the difference between the total recorded settlement (s_t) and the elastic settlement of the tested pile. The ultimate load (Q_u) corresponds to the point at which the final segment of the load-settlement curve begins to exhibit linear behaviour. The procedure for determining Q_u is identical to that used in the Hirany & Kulhawy method (see Figure 13).

2.18 *Tangent method (2010)*

The method determines the ultimate load or pile capacity (Q_u) based on the intersection point of the tangents drawn to the initial and final segments of the load-settlement curve obtained from the test, as illustrated in Figure 14.

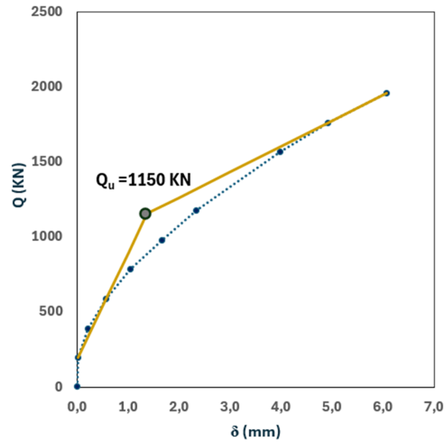

Figure 14. Ultimate load based on tangent method.

2.19 *Standards and guidelines*

The following section presents various interpretation criteria outlined in several existing standards and guidelines.

- *CIRIA (1980):* Ultimate load is the point of continuous settlement without load increase, or settlement equal to 10% of pile diameter.
- *US Army (1991):* Ultimate load (Q_u) is the average of:

  1. Q_1: The load determined using the tangent method.
  2. Q_2: The load associated to a settlement of 6.4 mm.
  3. Q_3: Intersection of load-settlement curve with a 0.025 mm/kN slope line.

- *ASTM (2015):* ASTM recommends continuing or maintaining the applied load during testing until the pile settles by 15% of its diameter or width, especially in cases of plunging.
- *AS 2159 (2009):* The Australian standard AS 2159 (2009) defines the ultimate load as the maximum load sustained at the pile head for 10 minutes. If this can't be confirmed, it is the load causing 5% settlement for precast piles or 10% for cast-in-place piles.
- *NBR 6122 (2010):* The Brazilian standard by ABNT adopts Davisson's (1972) method with a modified offset: the elastic deformation plus a displacement equal to 3.33% (D/30) of the pile diameter. The method must be identical as illustrated in Figure 7 by changing the offset.
- *BS 8004 (2015)*: The British Standard BS 8004:2015 defines the ultimate load as the load causing a settlement equal to 10% of the pile diameter.
- *EN ISO 22477-1 (2019)*: These regulations state that the pile failure criterion must follow EN 1997-1, which defines it (Art. 7.6.1.1) as the load causing a settlement equal to 10% of the pile diameter.

3 CLASSIFICATION OF INTERPRETATION CRITERIA

Based on the theoretical framework presented, the criteria can be grouped as follows:

1. *Methods based on 10% pile diameter settlement*: Terzaghi (1942), CIRIA (1980), AS 22159 (2009), BS 8004 (2015), EN ISO 22477-1 (2019), ASTM (2015).
2. *Offset based methods*: Davisson (1972 & 1973), O´Rourke & Kulhawy (1985), NBR 6122 (2010).
3. *Brinch-Hansen criteria*: 80% & 90% Brinch-Hansen (1963) methods.

4. *Tangent-based methods:* Housel (1953), De Beer (1968), Fuller & Hoy (1970), Butler & Hoy (1977), Shen (1980), Hirany & Kulhawy (1988), Das (2010), Tangent method.
5. *Hyperbolic-parabolic curve models:* Van der Veen (1953), Chin-Kondner (1970), Mazurkiewicz (1972), Decourt (1999).
6. *Mixed method:* US Army (1990).

4 CASE STUDIES

This section presents a practical case study involving four (4) static compression load tests on piles, conducted as part of the design process for a building protect located in Meco (Madrid).

4.1 *Geotechnics*

The Geotechnical Study conducted during the pre-construction phase identified and classified the following soil layers, listed from top to bottom, along with their corresponding geotechnical parameters (Table 1):

Table 1. Geological and geotechnical setting.

Geotech Unit	γ (KN/m³)	ϕ (º)	c´ (Kpa)	E (MPa)
I. Anthropogenic fill	*17,0*	28	0	8
II. Alluvial Clays	*18,5*	30	10	10
III. Alluvial gravels	*20,0*	35	0	40
IV. Tertiary clays	*19,0*	25	30	150

4.2 *Characteristics of the static compression load tests performed.*

All four tested piles are CFA type with a uniform diameter of 450 mm, and lengths ranging from 6.3 m to 7.8 m.

The service load was set at 80 tons for the piles subjected to the load tests, applying safety factors of 2 for shaft resistance and 3 for base resistance. The maximum test load (Q_{max}) was defined as the product of the service load 80 tons and an average safety factor of 2,5, resulting in Q_{max}=200 tons.

Figure 15 presents the load-settlement curves corresponding to each of the tests performed.

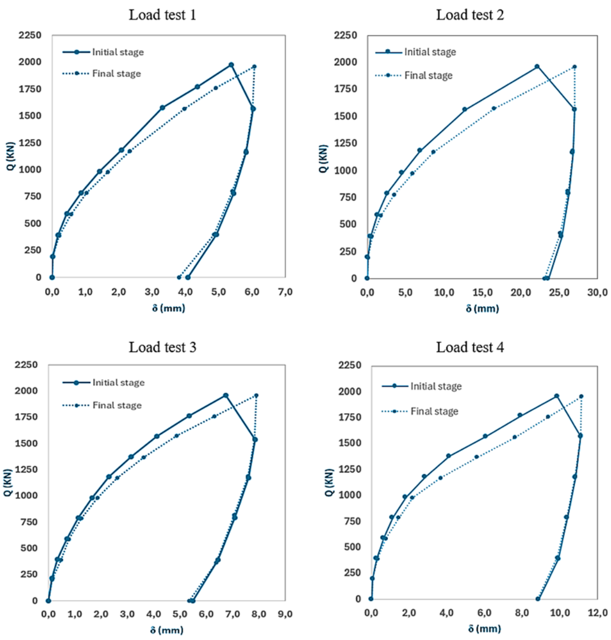

Figure 15. Load–settlement curves recorded during the four static load tests performed.

4.3 *Results for applying the interpretation criteria*

The results obtained from the application of all the interpretation criteria reviewed are presented in Table 2. The criteria considered applicable and yielding a reasonable estimate of the ultimate load (Q_u) are highlighted in bold, while those deemed inapplicable or producing unreliable Q_u values are not emphasized.

Table 2. Summary of ultimate loads (Q_u) in KN obtained from the application of the interpretation criteria.

Criterion	Q_u Load Test 1	Q_u Load Test 2	Q_u Load Test 3	Q_u Load Test 4
Terzaghi (1942)	>1957	>1959	>1957	>1953
Van der Veen (1953)	**3000**	**2800**	**2800**	-
Housel (1953)	-	-	-	-
Brinch-Hansen 80% (1963)	4193	3395	3555	2796
Brinch-Hansen 80% (1963)	>1957	>1959	>1957	>1953
De Beer (1968)	1524	1180	784	785
Chin-Kondner (1970)	**3343**	**3030**	**2722**	**3167**
Fuller & Hoy (1970)	>1957	>1959	>1957	>1953
Davisson (1972)	>1957	1200	2225	1875
Mazurkiewicz (1972)	**3000**	**2800**	**2500**	-
Davisson (1973)	2110	900	1825	1385
Butler & Hoy (1977)	-	-	-	-
Shen (1980)	1505	1573	1738	1288
O´Rourke & Kulhawy (1985)	1575	860	1490	1250
Hirany & Kulhawy (1988)	1740	1573	1720	1171
Decourt (1999)	**3343**	**2868**	**2722**	**3021**
Das (2010)	1567	1573	1758	1525
Tangent method	1150	1210	1198	886
CIRIA (1980)	>1957	>1959	>1957	>1953
US Army (1991)	-	1393	-	-
ASTM (2007)	>1957	>1959	>1957	>1953
AS 2159 (2009)	>1957	>1959	>1957	>1953
NBR 6122 (2010)	>1957	1585	>1957	>1953
BS 2004 (2015)	>1957	>1959	>1957	>1953
EN ISO 22477-1 (2019)	>1957	>1959	>1957	>1953

4.4 *Discussion and analysis of results*

The results obtained from applying the interpretation criteria will be analysed according to the previously defined methodological groups.

4.4.1 *Methods based on 10% pile diameter settlement.*

These criteria require a minimum settlement of 10% of the pile diameter, which was not reached in any of the case studies. Therefore, the method is not applicable to any of them.

4.4.2 *Offset based methods.*

These criteria overlook the shape of the load-settlement curve, which can lead to ultimate load (Q_u) values that do not reflect actual pile failure. In some tests, Q_u could not be determined due to high offset values; in others, it varied across the curve.

4.4.3 *Brinch-Hansen criteria.*

Based on the preceding analysis, it is evident that the 80% and 90% criteria proposed by Brinch-Hansen (1963) rely on a load-displacement hypothesis that may variably approximate actual behaviour. As a result, the ultimate load (Q_u) values fluctuate depending on the characteristics of each test.

4.4.4 *Tangent-based methods.*

In all tests, the estimated ultimate load (Q_u) was lower than the maximum applied load (Q_{max}), due to the flat slope observed in the final segment of the load-settlement curve. As a result, these criteria were deemed inapplicable.

4.4.5 *Hyperbolic/parabolic curve models.*

All four methods classified in this group produced similar and reliable estimates of the ultimate load (Q_u), all exceeding the maximum applied load (Q_{max}). However, the methods proposed by Van der Veen (1953) and Mazurkiewicz (1972) assume a strictly parabolic load–settlement curve, which limits their reliability when the actual curve exhibits a more linear behaviour, as observed in the Load Test 4 results.

Finally, safety factors can be determined that, in some cases, exceed 4 well above the project-defined value of 2,5.

5 ANALYSIS USING A NUMERICAL MODEL

An axisymmetric model was developed in Plaxis 2D software to simulate Load Test 3. The process included generating the load-settlement curve using project parameters, calibrating with test data, and applying a displacement-controlled approach based on Chin-Kondner (1970) theory.

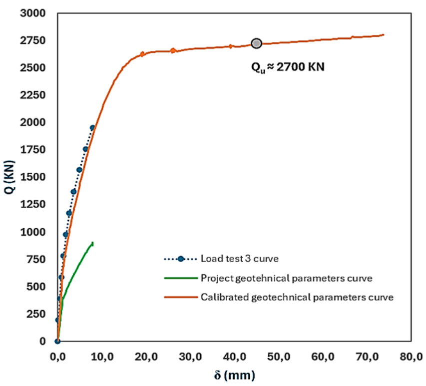

Figure 16. Comparison of the load-settlement curves obtained from numerical model.

Table 3. Calibrated geotechnical parameters in the numerical model and those used in the project (in parentheses).

Geotech Unit	γ (KN/m³)	ϕ (º)	c´ (Kpa)	E (MPa)
III. Alluvial gravels	20,0	35	0	40
IV. Tertiary clays	19,0	25	100 (30)	450 (150)

Based on the calibrated curve (Figure 16), is estimated Q_u≈2700 KN, aligning with results from hyperbolic-based methods as well as Methods based on 10% pile diameter settlement (~45 mm settlement). Matching the curve using the Mohr-Coulomb model required higher cohesion and modulus values for Unit IV Tertiary clays than those originally adopted in the project (see Table 3). These adjusted parameters remain within the ranges recommended by the Madrid City Council (2003).

6 CONCLUSSIONS

According with the study performed, the most appropriate criteria to use to determine the ultimate load (Q_u) are the methods based on Terzaghi´s criterion (1942) and methods based on Hyperbolic/parabolic curve models, Van der Veen (1953), Chin-Kondner (1972), Mazurkiewicz (1972) and Decourt (1999). The remaining methods can be disregarded due to their low reliability or lack of applicability. However, Van der Veen and Mazurkiewicz methods are less reliable when the curve lacks asymptotic shape. In that case, Chin-Kondner and Decourt are the most broadly applicable.

Finally, the analysis indicates that the actual safety factor applied in the Meco (Madrid) project is significantly higher than initially assumed of 2,5.

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