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Predicting driving transferred energy without needing the hammer efficiency: three case studies

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Technical Note

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Effective transferred energy

Abstract

This study presents case studies on the implementation of an innovative method of calculating effective driving energy with no need to account for hammer efficiency. The approach is based on measurements of set and elastic rebound, as well as a site-specific parameter (λ) calibration. The study applied this method to steel piles located in the cities of Santos (SP), Itaguaí (RJ), and Óbidos (PA), with the latter site being built in the Amazon region, near the Amazon River. Following coefficient calibration, the effective driving energy estimation technique exhibited a strong correlation with realistic and accurate energies directly obtained from dynamic loading tests. The method provides a highly accurate means of calculating effectively transferred energy to piles due to hammer blows, without relying on knowledge of the driving system performance. In that way, it can be applied to all the piles at the site (100% of them), including those that are not tested. This optimized and agile approach represents a significant breakthrough in foundation engineering and an enhance of pile foundation quality control.

1. Introduction

In Brazil, as many other countries worldwide, deep foundation control is often carried out using the "dynamic formulae" method. In the mid-20th century, Engineering News-Record documented over 450 dynamic formulae, according to Smith (1960). Over time, hundreds of equations have been developed, with one important distinction being that earlier versions did not account for energy losses due to the hammer stroke. The publication of the well-known Hiley formula (Hiley, 1925) increased the consideration of energy losses in dynamic equations.

Efficiency and effective energy of the blow are important factors in improving dynamic equations and ensuring successful pile driving quality control. As such, it is an important area of research for the advancement of pile driving.

This paper will assess the applicability of the "Querelli's energy method". Querelli (2019) method was developed using a large number of load tests and has been shown to be effective in determining the effective driving energy. One of the benefits of this method is that it eliminates the need for hammer efficiency or instrumentation during the hammer blow. This study evaluates the applicability of the method to reproduce the driving energy in three cases (Itaguaí, Santos, and Óbidos) involving steel-driven piles, using only the measures of pile set and elastic rebound in a rational way.

2. The importance of the energy effectively transferred to the pile

Equations known as dynamic formulae are widely used in the design and quality control of driven foundations to estimate the soil resistance mobilized in response to an impact to a driven pile. Theoretical support for these formulae comes from the concepts of energy conservation, Newtonian shocks, or the elasticity of Hooke's law. Typically, the resistance is estimated using either the set (s), the elastic rebound (K), or both measures.

According to Querelli (2019), there are three primary components of the driving event: the energy (and its losses), the displacement (elastic or permanent), and the mobilized resistance (as a response to the stroke). These components are all correlated in one way or another. The effective energy is one of the base components of the tripod; however, this energy was not always correctly considered for resistance calculation.

One of the earliest formulations is from the first part of the nineteenth century, created by engineer Johann Eytelwein in 1820. Chellis (1961) also noted that this equation is comparable to (or equivalent to) the well-known "Dutch formula". According to Chellis, this equation implicitly assumes a driving system efficiency of 100% (i.e., without losses), and the energy delivered to the pile is regarded as the gravitational potential energy of the blow ($W{\cdot}h$), as shown in Equation 1:

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$$R = \frac{W \bullet h}{s \bullet \left(1 + \frac{W_p}{W}\right)} \quad (1)$$

where R is static resistance of the pile-ground assembly, W is the hammer weight, h is the hammer fall height, s is the set (permanent pile displacement), and W_p is the pile weight.

Two other well-known equations from the 19th century that use the same method to calculate the nominal energy applied are the Engineering News Records equation and Sanders' Formula (Chellis, 1961). Equation 2 was created in 1851 by Major Sanders and compares the nominal energy of the stroke to the work of the ground (product of resistance and permanent displacement). The Engineering News Records formula uses a similar strategy but adds the constant C to account for a part related to the elastic displacement of the pile (Equation 3).

$$R = \left(W \bullet h\right) / s \quad (2)$$

$$R = \left(W \bullet h\right) / \left(s + C\right) \quad (3)$$

Equations 1, 2, and 3, which were published in the 19th century, did not take energy losses into account. However, most of the dynamic formulae stated in later technological contexts started to consider such losses during the 20th century, particularly after the release of the well-known Hiley formula (Hiley, 1925), which is shown in Equation 4.

$$R = \frac{e \bullet W \bullet h}{s + C/2} \cdot \frac{W + \mu^2 \bullet W_p}{W + W_p} \quad (4)$$

where e is the impact efficiency and μ is the coefficient of restitution after the blow.

Equation 5 shows the "energy approach equation" (Paikowsky & Chernauskas, 1992), which also uses effective energy by adding a blow efficiency factor (η). This is another significant formula that was more recently published in the literature.

$$R = K_{sp} \frac{\eta \bullet W \bullet h}{s + \left(D - s\right)/2} \quad (5)$$

where K_{sp} is the total strength reduction coefficient due to dynamic effects.

The main causes of this loss (or dissipation) of energy were listed by Chellis (1961) as follows: effects of winching and hammer-guide-tower friction (in the case of free fall), internal friction of the hammer with the confining case (for hydraulic hammers), energy dissipated in the generation of heat, sound, lateral movements of the pile, eccentric blows, elastic compression of the stump-cap.

The energy delivered to the pile during impact can no longer be considered nominal (weight *vs* height), as strength estimates must be based on a more realistic measure of energy effectively transferred to the pile during the blow. Consequently, the inclusion of energy losses associated with the driving mechanism in equations improves their reliability significantly.

Thilakasiri et al. (2003) investigated the reliability of different formulae and found that the Janbu, Danish, and Hiley equations provided more dependable estimates than the Engineering News Formula. Similarly, Danziger & Ferreira (2000) reported high reliability in the Danish formula estimates made by Sorensen & Hansen (1957) for steel piles.

A study published by Tavenas & Audy (1972) clearly demonstrates how earlier formulae failed to accurately consider energy, resulting in strength estimates with errors on the order of more than 70%. The authors evaluated 478 pile driving records in non-cohesive soil and conducted 45 static load tests, concluding that any pile driving formula using the usual energy estimate will also be erroneous.

It is evident that the proper estimation of this quantity is crucial for accurately estimating the resistance of soil-pile systems. The issue of effectively transferred energy during impact represents a paradigm shift in the field of "dynamic formule". In this regard, the practical methodology developed and published by Querelli (2019) has made a significant contribution to measuring effective energy.

3. Querelli's energy method

Using just the conventional measures of set and elastic rebound, Querelli (2019) proposed a way to estimate the effective (transferred) energy delivered to the pile due to the blow. Unlike usual, the suggested technique does not require instrumenting the pile at the moment of the stroke neither earlier evaluation of the drive system's effectiveness.

The author defined two starting points for the theoretical deduction:

(a) the idealized resistance *vs* pile displacement curve following the application of the blow; and
(b) Hooke's law, as expressed by the Chellis' (1961) formula.

This leads to the application of two simplifying assumptions: the first is that the set is so little compared to the elastic rebound that it can be disregarded (s = 0), and the second is that the soil *quake* exhibits a proportionality connection with the elastic rebound (K), *i.e.*, $C3$ is not constant.

Thus, Querelli created the fundamental equation of the method, which determines the maximum displacement of the pile after the blow (D) (Equation 6). In this equation, the key calibration factor is the λ coefficient. The method deduction was first presented in Querelli (2019), in Portuguese, and later in Querelli & Massad (2019b), in English.

$$D = \lambda \bullet \sqrt{\frac{\eta \bullet W \bullet h \bullet L}{E \bullet A}} \quad (6)$$

When the terms are rearranged to isolate the aimed parameter (effective energy; $E_{ef} = \eta \cdot W \cdot h$), the Equation 7 is achieved as:

$$E_{ef} = \frac{1}{\lambda^2} \bullet \frac{D^2 \bullet E \bullet A}{L} \qquad (7)$$

An important finding regarding the coefficient λ emerged from the author's in-depth analysis of the equation and application method: previous calibrations of λ should always be carried out, as the most suitable value for λ differs from site to site (Querelli, 2019). This formed the basis for the five-step process for applying the methodology.

(a) Choose a sample of piles for testing in the Dynamic Loading Test;

(b) Perform dynamic tests on the piles with increasing energy, simultaneously measuring set and elastic rebound for each blow;

(c) With these two measurements, the geometry (area and length), and the elastic modulus (E) of the pile material, plot the graph of D *vs* $\sqrt{\left[\left(E_{ef} \bullet L\right)/\left(E \bullet A\right)\right]}$ for each of the monitored blows;

(d) A line of best fit passing through the origin [0,0] is plotted for the points. The slope of this line (angular coefficient) represents the parameter λ, calibrated for the specific project;

(e) This (calibrated) λ coefficient, along with the set and elastic rebound measures of blows in unmonitored piles, should be applied to Equation 7 to estimate the effectively transferred energy in each impact of the driving hammer.

This study refers to the approach as "Querelli's energy method" because Querelli (2019) is the original developer of it. The first study assessed fifteen cases in Brazil that used either concrete or steel piles, and the results showed that the λ values ranged from 1.22 to 1.71 for concrete piles and 1.13 to 1.35 for steel piles. To document these findings, Querelli & Massad (2019b) also republished (in English) twelve of these fifteen datasets.

Later, Querelli & Massad (2019a) also presented three new sites in the state of Rio de Janeiro on concrete piles. Their methodology was efficient, obtaining λ values equal to 1.22, 1.28 and 1.39, respectively. There is also a previous case study by Querelli & Massad (2017) in which no mention is made of the referred methodology or even the λ coefficient. However, it is possible to infer, from the presented database, λ values of 1.28 and 1.29 for two neighboring construction sites located in the city of Duque de Caxias (RJ). Souza (2022) also presented two sites verifying the Querelli's method.

4. Case studies

4.1 Geological-geotechnical characterization

The piles are from three independent building sites in the cities of Santos (SP), Itaguaí (RJ) and Óbidos (PA). The location is presented in Figure 1, being important to point that all projects are in Brazil.

The subsoil characteristics of the fields are similar, consisting of coastal formations typical of lowland areas in Santos and Itaguaí or near-river geological formations in Óbidos, which is near the Amazon River. Predominantly,

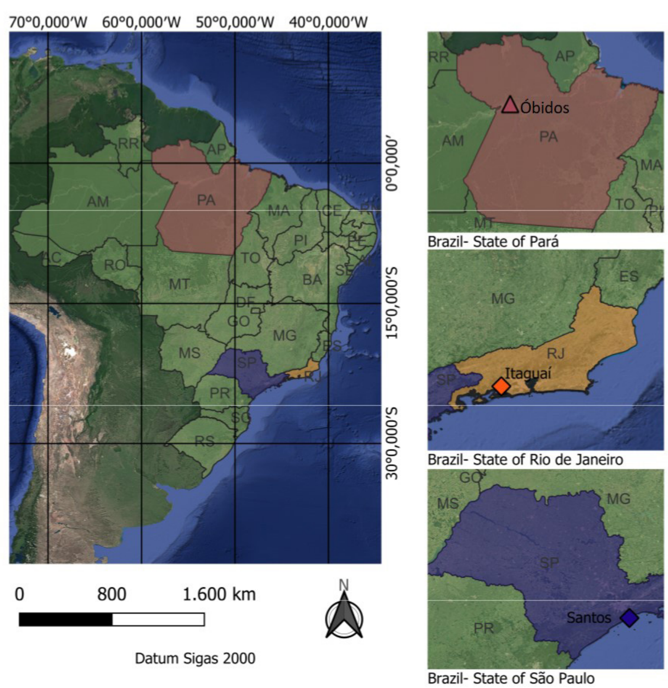

Figure 1. Study area.

the soil is sedimentary, with a layer of compacted backfill followed by very soft dark grey and black organic clay, a layer of medium-sized layers of compacted sand or hard sandy clay with sediments, another layer of soft clay, and finally a layer of very compact residual soil. The water level was found to be quite close to the surface at all sites, and the thicknesses of each layer are summarized in Table 1.

Several authors have researched and distributed information on the unique characteristics of the sediments that make up the soils in lowland and river near areas in the technical literature. Examples of authors that made significant contributions to the study and characterization of soils in the Baixada Santista are Suguio & Martin (1994), who combined the findings of several earlier studies on this topic.

4.2 On-site testing

The dynamic loading tests were conducted using the modality of increasing energy, with a total of 27 piles tested in Santos, 10 in Itaguaí, and 64 in Óbidos. In total, 223 records (blows) were obtained from the dynamic tests. The hammer used in Santos was an 83 kN free-fall type, while in Itaguaí it was a 70 kN hydraulic hammer and in Óbidos a 24 kN free-fall hammer.

The tested piles were steel profiles, including HP 310×110, HP 310×125, and W 360×122, as well as 406 mm-diameter tubed steel piles (9.5 mm thick) cross-sections. Table 2 presents a summary of all tested and evaluated piles.

The analysis methodology adopted the application script presented previously. For each pile, the individual information of each blow applied was used to plot points on graphs of D vs $\sqrt{\left[\left(E_{ef} \bullet L\right) / \left(E \bullet A\right)\right]}$.

Subsequently, the best linear regression (with the highest R^2 value) was plotted through the origin point [0,0]. The angular coefficient of the obtained straight line was then calculated and it is numerically equivalent to the average λ coefficient for each pile.

5. Results and analysis

Figures 2 to 4 show the results in the form of graphs and regressions, with a focus on the λ coefficient, which is the angular coefficient of the linear regression equations.

The site-specific findings are summarized in Table 3, highlighting the importance of the ratio $1/\lambda^2$ as the angular coefficient in Equation 7 for accurately estimating the energy effectively transmitted to the piles.

The λ coefficient obtained was equal to 1.01, 1.17 and 1,11 in Santos, Itaguaí and Óbidos, respectively. The low coefficients of variation observed ranging 7.4% to 13.4%, in association with the high coefficients of determination (R^2)

Table 1. Thickness of the subsoil layers at each evaluated site.

Layer	N_{SPT} (range) average	Soil layer thickness (m)		
		CASE 1: Santos (SP)	CASE 2: Itaguaí (RJ)	CASE 3: Óbidos (PA)
Compacted embankment	7-14	2.5-4.5	2-3.5	-
Very soft clay (organic)	0-1	16-20.5	12-14	9-16
Sand / Sandy Clay	12-20	9-12	4-7	-
Soft Clay	1-4	6-10	3-4.5	4-7
Compact to very compact sand (residual)	19-40	15-18.5	9-13	8-13

Table 2. Summary of data.

Case/ Municipality	Number of tested piles	Number of records of the dynamic test	Pile length range (m)	Tested Section
Case 1 - Santos (SP)	27	126	47.4 to 59.5	126 W360×122
Case 2 - Itaguaí (RJ)	10	33	36.0 to 39.5	8 HP310×110 and 25 HP310×125
Case 3 - Óbidos (PA)	64	64	20.0 to 30.0	6 TUBE 406 mm diam., 9.5 mm thick

Table 3. Summary of results.

Case	Location	Λ (average)	Standard deviation	Coefficient of variation (%)	R^2	$1/\lambda^2$ (average)
Case 1	Santos (SP)	1.01	0.075	7.4	0.95	0.98
Case 2	Itaguaí (RJ)	1.17	0.115	9.8	0.86	0.73
Case 3	Óbidos (PA)	1.11	0.149	13.4	0.99	0.81

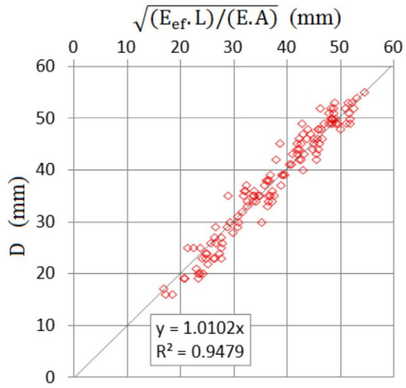

Figure 2. Case 1: Santos (SP).

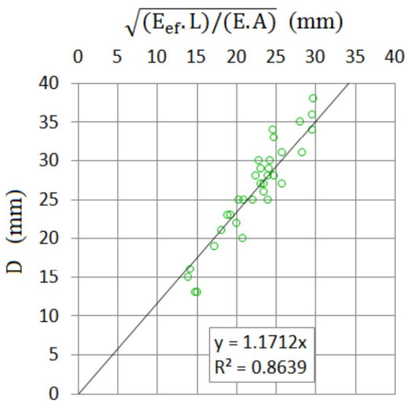

Figure 3. Case 2: Itaguaí (RJ).

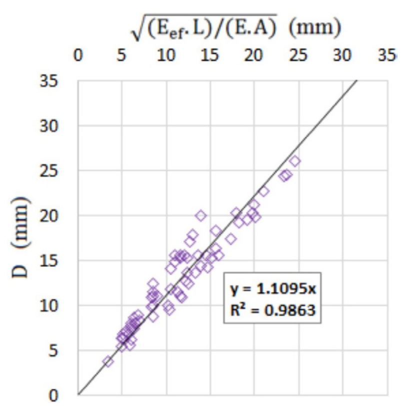

Figure 4. Case 3: Óbidos (PR).

of the calibrations, demonstrate the degree of effectiveness of the average adjustment of the method.

6. Conclusion

The results confirm the effectiveness of Querelli's energy method as it was possible to obtain average λ values with high determination coefficients (R^2 equal to 0.95, 0.86, and 0.99) and low coefficient of variation of λ (< 13.5%).

The average λ for the Santos site (1.01) is even lower than the lowest value found by Querelli (2019) and Querelli & Massad (2019b) for steel piles (1.17).

The average value of 0.98 obtained for the ratio $1/\lambda^2$ in Case 1 (Santos) is almost 35% higher than that obtained for Case 2 (Itaguaí), which is equal to 0.73. The Óbidos site falls in the mid-range of the others. This reinforces Querelli's (2019) finding that the method should be applied through previous calibrations ("site-to-site") of the λ ratio through dynamic tests to contemplate local particularities, making its use more effective. It is a "site-specific" parameter.

The article contributes to the validation of the method proposed by Querelli (2019), which is a paradigm shift in foundation engineering because it allows for the estimation of the effective energy of pile driving without requiring the efficiency of the hammer or instantaneous instrumentation (at the moment of the blow).

Declaration of interest

We authors have no conflicts of interest to disclose.

Authors' contributions

André Querelli: conceptualization, methodology, data curation, formal analysis, writing – original draft. Tiago de Jesus Souza: data curation, validation, writing – reviewing and editing.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

List of symbols

e	Impact efficiency
h	Hammer fall height
s	set; permanent pile displacement
A	Cross-section area
C	Elastic deformation coefficient. Equal to 2.54 cm for free fall hammers and 0.254 cm for steam hammers
$C3$	Soil Quake; elasticity of soil below pile toe
D	Maximum displacement of the pile after the blow (set + elastic rebound)
E	Pile material's Young Modulus
E_{ef}	Energy effectively transferred to the pile (equal to $\eta.W.h$)
K_{sp}	Total strength reduction coefficient due to dynamic effects
K	Pile's elastic rebound

L	Pile length
N_{SPT}	Number of blows in the SPT test for penetration of the last 30cm of the standard sampler in the soil
R	Static resistance of the pile-ground assembly
W	Hammer weight
W_p	Pile weight
μ	coefficient of restitution after the blow
η	Efficiency of the driving system
λ	Lambda; coefficient of the energy estimation method

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