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Insights on drop mass systems to predict pile compressive resistance from dynamic load test energy measurements

Perspectives sur les systèmes de masse tombante pour prédire la résistance à la compression des pieux à partir des mesures d'énergie des essais de chargement dynamique

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ABSTRACT: We are currently immersed in the era of big data, where large volumes of data is generated and stored daily. However, the true challenge lies in transforming this data into meaningful and actionable information. To extract insights from these vast datasets, there is a growing dependence on machine learning techniques, which essentially build upon the foundation of traditional statistical methods. These techniques enable the creation of models that enhance our understanding of diverse subjects and facilitate informed decision-making. This study focuses on the establishment and exploration of a database derived from dynamic load tests on piles (DLT). In DLT on piles, impact hammers are employed, characterized by their potential energy or kinetic energy just before impact. Testing on high-capacity drilled deep foundations presents several challenges, including the need for sufficient energy to mobilize compressive static resistance of the pile. The investigation delves into understanding the correlation among various DLT test variables and uncovering potential relationships using supervised models, such as linear and non-linear regressions. The findings from this exploration have unveiled crucial insights, such as the influence of diameter on resistance and the existence of a non-linear relationship between resistance and the maximum energy transferred to the pile.

RÉSUMÉ: Nous sommes actuellement plongés dans l'ère du big data, où un volume immense de données est généré et stocké quotidiennement. Cependant, le véritable défi réside dans la transformation de ces données en informations significatives et exploitables. Pour extraire des insights de ces vastes ensembles de données, il existe une dépendance croissante aux techniques d'apprentissage automatique, qui s'appuient essentiellement sur les méthodes statistiques traditionnelles. Ces techniques permettent la création de modèles qui améliorent notre compréhension de sujets divers et facilitent la prise de décision éclairée. Cette étude se concentre sur l'établissement et l'exploration d'une base de données dérivée de essais de chargement dynamique de pieux (DLT). Dans le DLT sur les pieux, des marteaux d'impact sont utilisés, caractérisés par leur énergie potentielle ou leur énergie cinétique juste avant l'impact. Les essais sur des fondations profondes forées à haute capacité présentent plusieurs défis, notamment la nécessité d'une énergie suffisante pour mobiliser la résistance statique en compression du pieu. L'enquête vise à comprendre la corrélation entre diverses variables de test DLT et à découvrir des relations potentielles en utilisant des modèles supervisés, tels que des régressions linéaires et non linéaires. Les résultats de cette exploration ont révélé des informations cruciales, telles que l'influence du diamètre sur la résistance et l'existence d'une relation non linéaire entre la résistance et l'énergie maximale transférée au pieu.

Keywords: Dynamic load testing; exploratory data analysis; supervised models; pile foundation.

1 INTRODUCTION

Dynamic load testing systems use a mass to apply load to the head of the pile. This can be achieved either through a pile driving hammer, known as an impact driving system, or by dropping a mass, referred to as a drop mass system. Dynamic load testing can be conducted during the pile installation of precast concrete piles or steel piles (displacement piles) when driving with a hammer. Drop mass systems are employed to test cast-in-situ piles (bored piles, continuous flight auger, or other cast-in-situ piles) or testing associated with re-driving. These drop mass systems are characterized by their mass and maximum stroke (drop height), or the respective potential energy (mass × acceleration × stroke) or kinetic energy immediately just before impact.

Testing high capacity drilled deep foundations poses several challenges, one of which is determining the required energy level to mobilize the compressive static resistance of the pile. Hussein et al. (1996) conducted a wave equation analytical study for the selection of a hammer for DLT of cast-in-place shafts. The studied shafts have ranges of diameters from 750mm to 1500mm and lengths from 10 to 30 diameters. Analysis results suggest as a general guideline that the hammer weight should be about 1.5% of the pile resistance.

According to EN ISO 22477-4:2018, the mass of the drop mass should be chosen to be greater than 2% of the design compressive static resistance of the pile (where the mass of the drop mass is expressed as a weight). In very hard soils, piles resting on hard bedrock, or where a pile is installed with a rock socket, drop mass weights of 1 % of the required design compressive static resistance can be sufficient to mobilize pile resistance.

Ideally, the applied energy or the stroke of the drop mass should be adjusted to achieve full mobilization of the pile skin friction and tip resistance. This study focuses on the establishment and exploration of a database derived from dynamic load tests on cast-in-place foundation piles of the Tagus River Lezíria Bridge River.

2 CASE STUDY

The Tagus River Lezíria Bridge comprises the north viaduct, the main bridge and the south viaduct with a total length of about 12 km. The viaducts are supported by piles with a diameter of 1500mm, and their lengths vary between 25 and 55 meters.

The construction methodology defined to install the piles is the following (Caputo, 2009):

i. Placement of a guide-steel tube with 6.00m of length.
ii. Driving a temporary casing with the use of vibrator down to the design depth.
iii. Internal cleaning of the casing up to the design depth with a hydraulic rig.
iv. Placement of the steel reinforcement cage.
v. Cleaning of the pile tip by "air-lift".
vi. Pouring of the pile concrete simultaneously with the removal of the steel casing.

To validate the construction methodology and the pile design, a series of static and dynamic load tests were conducted (Santos, 2005).

Dynamic load tests were performed on 9 trial piles (6ϕ800mm and 3ϕ1500 mm) using specific equipment called SIPEX — Impact System for Trial Piles.

This system utilizes the free fall of two 100kN weights with a maximum drop height of 3m, capable of acting together or separately. The setup includes a guide tube and an attached steel cap block placed over the pile. The cap block ensures the centred and vertically applied impact and serves as protection against potential damage to the pile head (Figure 1). While this equipment is designed for testing ϕ1500 mm piles, it can also accommodate lower diameter piles using a reducer.

Multi-blow dynamic testing technique was employed, with applied energy varying between 40 and 600 kJ (or kNm) (Paraíso and Santos, 2020).

Figure 1. SIPEX: Drop mass system 100+100 kN.

The load tests were carried out in 3 locations along the route of the viaducts, and a supplementary ground investigation campaign was defined, consisting of boreholes accompanied by SPT tests and SCPT tests. There are alluvial deposits (soft silty clay, sands) overlying gravels, boulders and the Miocene bedrock (Figure 2).

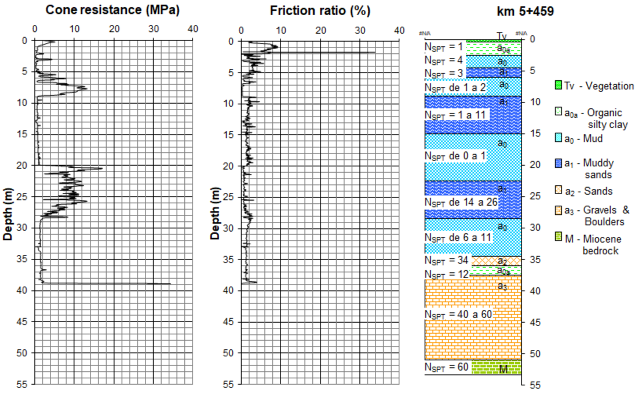

Figure 2. Typical Geological and Geotechnical Profile.

3 METHODOLOGY AND RESULTS

In the current investigation, we have at our disposal four variables derived from the DLT test: the diameter of the pile (D), the maximum potential energy of the hammer or rated energy (EP), the maximum energy transferred from the hammer to the pile (EMX), the mobilized resistance (R), and the ratio between the mobilized resistance and the service load $\left(\frac{R}{Qs}\right)$. To gain a deeper understanding of our data and the interplay among these variables, we initiated an exploratory data analysis (EDA). This type of analysis enables us to discern the strengths of relationships between variables and to further elucidate these connections. The data underwent processing utilizing the Python open-source language, leveraging prominent libraries including Pandas, Scipy, NumPy, Seaborn, and Matplotlib.

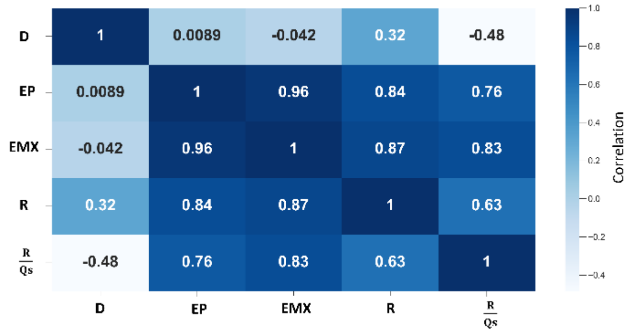

Figure 3. Correlation matrix for input variables.

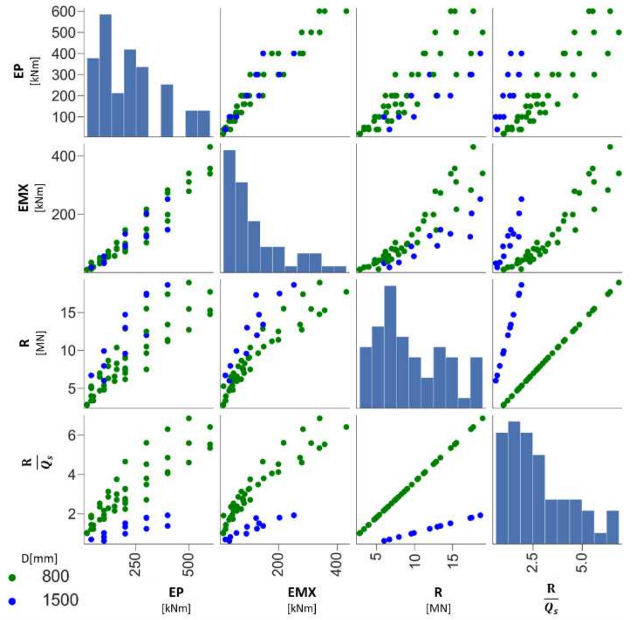

Figure 4. Scatterplot matrix depicting the relationships among the investigated variables. The green color represents the piles with 800 mm diameter and the blue the ones with 1500 mm.

Figure 3 showcases the correlation matrix for the aforementioned variables, while Figure 4 illustrates scatter plots for variable pairs. In this plot, piles with a diameter of 1500 mm are depicted in red, and those with an 800 mm diameter are represented in blue, complemented by variable histograms. A careful examination of these visualizations reveals that the diameter (D) demonstrates linear independence from rated energy (EP) but shows a weak correlation with the mobilized resistance (R). As anticipated, a larger diameter would correspondingly increase resistance. Additionally, it is apparent that there exists a non-linear relationship between mobilized resistance (R) and maximum energy transferred from the hammer to the pile (EMX), with a correlation coefficient of 0.87. The influence of pile diameter is also evident, separating the data into two groups, easily discernible by colour in the scatter plot.

Efficiency of the hammer is commonly assessed by calculating the ratio between the rated energy (EP) and the maximum energy transferred from the hammer to the pile (EMX). The maximum hammer height of drop is 3m leading to a 600 kNm rated energy, displayed in Figure 5 as EP, we can see that the survey was carried out for several heights (multi-blow testing technique), since the weight of the hammer was kept constant and equal to 200 kN. As depicted in Figure 5, it is evident that EMX is approximately 0.7 times EP, indicating a 30% energy loss.

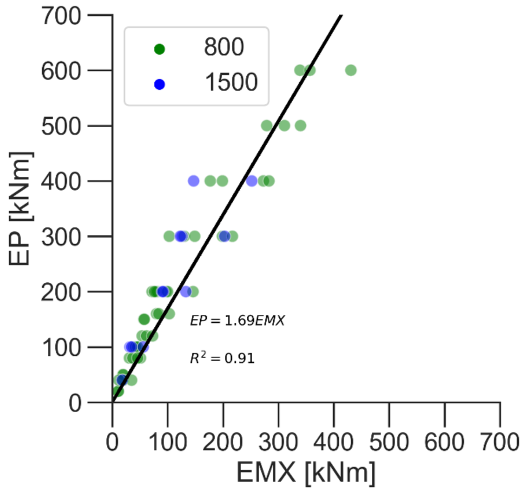

Figure 5. Relationship between the rated energy (EP) and the maximum energy transferred from the hammer to the pile (EMX), for both diameters 800mm (green) and 1500 mm (blue).

In this study, we determined the equivalent η coefficient to be 0.024m, as depicted in Figure 6 (η=EP/R). This value aligns with existing literature; for instance, Paraíso and Costa (2006) reported a value of 0.033m, while Paikowsky (2004) presented a value of 0.025m. The dataset in our study displays lower dispersion, and the regression analysis yields a coefficient of determination (R^2) of 0.89, indicating a strong fit to the observed data.

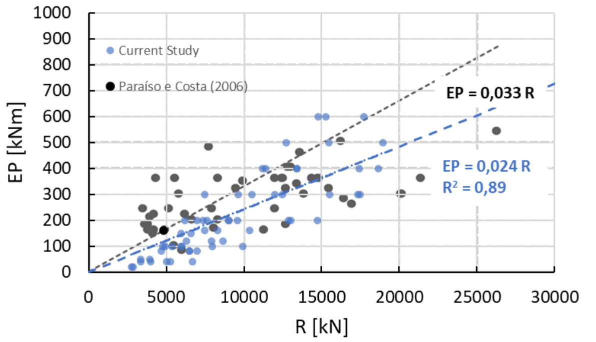

Figure 6. Comparison between the dataset of the current study (in blue) and the one presented in Paraíso e Costa (2006) (in black).

It is well-known that not all energy can be transferred from the hammer to the pile. If this were possible, the coefficient η would represent the displacement associated with the plastic deformation occurring at the lateral interface of the soil-pile and at the tip (Paraíso & Santos, 2020).

As indicated by EN ISO 22477-4:2018, Rausche et al. (2008) and Hussein et al. (1996), recommends that the weight of the hammer should be 1% - 2% of the desired resistance. Figure 7 elucidates this reasoning, where the ratio between the maximum energy transferred from the hammer to the pile (EMX) and the rated energy (EP) is plotted against the ratio between the hammer weight (W) and the resistance (R).

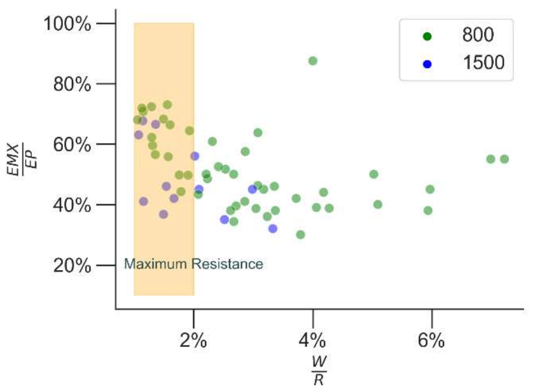

Figure 7. Relationship between the ratio of maximum energy transferred from the hammer to the pile (EMX) to rated energy (EP) and the ratio of hammer weight (W) to resistance (R).

It is evident that for the 800 mm diameter, the loss of energy is minimized when the weight/resistance ratio falls between 1% - 2% (shaded area in Figure 7), more precisely between 1% – 1.3%, in this study, for the blows which mobilized the maximum resistance. However, for the 1500 mm diameter, three points deviate from the trend, and within this interval, they still exhibit a lower energy ratio, approximately 40%. The efficiency of the hammer range from 30% to 87.5 %, with a mean of 50.9%.

If we look closer to the distribution of EMX for both diameters, depicted in Figure 8, we observe that both exhibit similar means. However, the 1500 mm diameter piles display higher dispersion due to the limited number of samples, which could justify this misalignment with the trend in Figure 7.

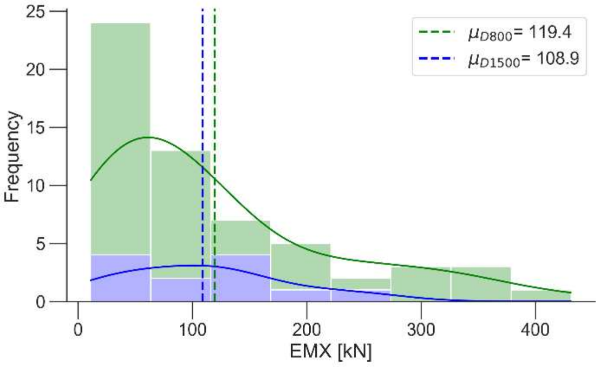

Figure 8. Distribution of the maximum energy transferred from the hammer to the pile (EMX) for both diameters. The green color represents the 800 mm diameter while the blue represents the 1500mm. The dashed lines are the mean of each distribution.

While the presented results are intriguing, the ultimate aim is to offer practical insights beneficial for designers. A key interest lies in determining the hammer parameters required to attain a specific resistance. To address this, we conducted a non-linear fitting between EMX and R, as depicted in Figure 9. Various functions underwent testing, and the one presented yielded the lowest Root Mean Square Error (RMSE).

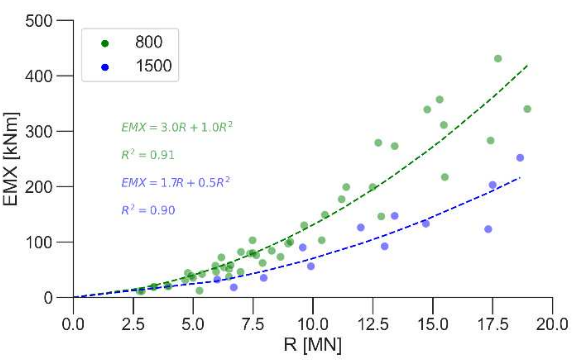

Figure 9. Non-linear relationship between the maximum energy transferred from the hammer to the pile (EMX) and the mobilized resistance (R). The green color represents piles with a 800 mm diameter while the blue represents those with a 1500mm diameter.

Notably, the equation for the 800 mm diameter is approximately double that of the equation for the 1500 mm diameter, revealing the influence of the diameter at the equation. It's essential to highlight that we constrained the regression to pass through the origin, underlining our expectation of zero energy applied for zero resistance. This graphical representation underscores that the requisite energy for achieving a given resistance is consistently lower for the larger diameter, thereby justifying an increased cost in pile designs with a corresponding reduction in associated equipment, or where the applied energy should be limited due to displacement issues.

4 CONCLUSIONS

In this comprehensive investigation, we examined variables derived from the Dynamic Load Test (DLT) such as the maximum potential energy of the hammer or rated energy (EP), the maximum energy transferred from the hammer to the pile (EMX), the mobilized resistance (R) and delved into their interrelationships. Practical implications to predict pile compressive resistance from dynamic load tests energy measurements are underscored and materialized by means of regressions equations. The results obtained not only align with current literature but also pave the way for valuable insights. Specifically, the formulated equations for predicting pile compressive resistance demonstrate excellent agreement with the dataset, boasting a coefficient of determination (R^2) around 0.9 (Figure 6 and Figure 9). This high level of correlation underscores the robustness and reliability of the equations in capturing the dynamics of the system.

As we strive for a more comprehensive understanding, future investigations should extend beyond the scope of this study. Exploring relationships with other variables tied to in situ characteristics, such as soil parameters, the lateral resistance, and tip resistance separately, holds the potential to enhance the accuracy and applicability of the derived equations. This broader inquiry would not only augment our confidence in employing these equations but also contribute to a more nuanced comprehension of the dynamic interactions at play during pile driving operations.

This study stands as a significant contribution to the field, providing practical tools for engineers and designers involved in pile-related projects.

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