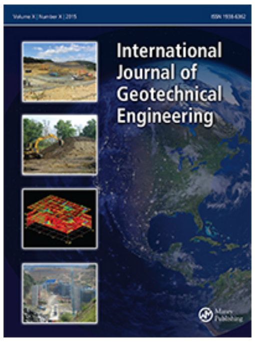

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BRIEF REPORT

Prediction of in-situ dry unit weight considering chamber boundary effects on lateritic soils using Panda® penetrometer

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ABSTRACT

Lateritic soils are the most common materials in tropical areas and widely used in pavement engineering. In fact, in these areas, pavement compaction control is generally performed through the measurements of the in-situ unit weight of the soils. However, these methods are time-consuming and expensive. So, in many countries, methodology based on the use of the dynamic penetrometer has become widespread for rapid and less costly control of pavement quality. This methodology is efficient but requires calibration between the cone resistance and the dry unit weight. Due to the specific nature of lateritic soils, to their assumed wide variability and probably to other reasons, no calibration has actually been performed in-situ for these soils. The calibrations performed until now, has been carried out using chambers in the laboratory. This process provides some bias for the prediction of in-situ dry unit weight, due to the chamber boundary effects which affect cone resistance. This paper proposes a methodology that consists of testing the soils in-situ and in the laboratory, studying cone resistance according to compaction parameters in order to estimate the boundary effects and to propose a model to take them into account when predicting in-situ dry unit weight.

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KEYWORDS
Lateritic soils; compaction control; boundary effect; dynamic penetrometer; pavements

1. Introduction

Lateritic soils are an abundant source of materials used for pavement construction in tropical countries (Ampadu et al. 2016; Autret 1983; Bagarre 1990; Bohi 2008; Fall 1993; Millogo 2008; Ndaye 2013; Terzaghi and Robertson 1958) and as a base, subbase or subgrade for roads, embankments, dams and airfields. But, due to the tropical climate conditions, these soils have specific characteristics (Autret 1983; de Carvalho et al. 2015; Terzaghi and Robertson 1958; Wooltorton 1948) and need further analysis before mastering the process to use them properly.

In fact, the quality control of pavement compaction is ensured during construction with the use of in-situ devices such as: sand cone method or nuclear density metre (AFNOR NF P 94-061-2 1996; ASTM D 1556-90, 1990) for the measurement of the soils unit weight. Knowing the water content and the unit weight of in-situ soils, the compaction quality is appreciated comparing in-situ dry unit weight to the dry unit weight of the soils measured in the laboratory. These methods offer advantages for direct measurement of the soil's unit weight for compaction control. But they are also time-consuming and expensive, and laboratory testing involve sampling disturbance (Ampadu et al. 2016; Chaigneau 2001; Ghafghazi 2011; Pournaghiazar 2011). Therefore, in many, mainly Anglo-Saxon, countries, cone penetration tests have been developed as a rapid, less costly and continuous method of soundings with good repeatability (Gabr, Coonse, and Lambe 2001; Pournaghiazar 2011; Scala 1956).

On the other hand, the used of the cone penetrometer for compaction control, requires calibration between cone resistance and dry unit weight from tests in the laboratory and in-situ. Much research has been channelled on this subject, mainly on the interpretation of the cone penetration and calibration tests (Chaigneau 2001; Lunne, Robertson, and Powell 1997; Parkin and Lunne 1982). Calibration tests are usually carried out in a chamber and, because of the chamber boundary effects, in-situ dry unit weight is overestimated. This issue led to the proposal of large calibration chamber and theoretical or experimental models in order to take into account the chamber boundary effect on the calibration results of cohesionless and cohesive soils, principally sand and clay (Ampadu et al. 2016; Bellotti 1984; Chaigneau 2001; Schnaid and Houlsby 1991). These models link cone resistance (q_d in MPa) to the dry unit weight (γ_d in kN/m^3) of the soils, as proposed by Chaigneau (2001) (Equation (1)), where γ_d and q_d are dry unit weight and cone resistance respectively.

$$\gamma_d = a_1 \times \ln(q_d) + b_1 \tag{1}$$

But no reliable models are available for predicting in-situ dry unit weight following laboratory calibration tests (Pournaghiazar 2011). Moreover, no similar research has been dedicated to lateritic soils. Existing investigations by Ampadu et al. (2016) are another interpretation of the penetration tests, linking the compaction level (γ_d/γ_{dmax}) to the dynamic cone penetration index (DPI in mm/blow) (Equation (2)) with evaluation of an in-mould effect from in-mould laboratory tests, where γ_{dmax} and DPI are the maximum dry unit weight and the dynamic cone penetration index respectively, a_i and b_i coefficients depending on several factors such as the nature of the soil, the dry unit weight and the moisture content.

$$\log\left(\gamma_d / \gamma_{d_{\max}}\right) = a_2 + b_2 \times \log(DPI) \tag{2}$$

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This research, based on a large study of the basic geotechnical parameters and the variability of lateritic soils in Burkina Faso, mainly studies the calibration of cone resistance and the dry unit weight of lateritic soils using the Panda® dynamic penetrometer. The objective is to propose a methodology for predicting in-situ dry unit weight from penetrometer tests in a calibration chamber or any other chamber, given its dimensions. Two aspects have, therefore been considered. The first consisted of studying the relationship between cone resistance and dry unit weight in the laboratory (in a calibration chamber) under various water conditions and dry unit weights. The second consisted of the tests in the laboratory and in-situ for consideration of the chamber boundary to predict the in-situ results.

2. Materials and methods

2.1. Materials

2.1.1. Soils

Based on the geotechnical parameters of 661 samples distributed across the surface area of Burkina Faso, the analysis and the classification of these lateritic soils through three international classification standards (see Table 1) provide the following results (Table 1). The lateritic soils are mainly classified as B6 or B4 according to the French GTR classification system (SETRA-IFSTTAR 2000) and A2-6 according to the AASHTO classification system (AASHTO 1945). Other studies on the classification of lateritic soils in Burkina Faso, have highlighted the fact that lateritic soils used for pavement design mostly belong to the same geotechnical class (Fall 1993).

These analyses show a very low variability of lateritic soils in the area. The soils are distributed across one to two groups according to international classification standards.

Finally, two (02) representative soils were collected at two (02) different sites (Pabré and Gonssé, located approximately 30 km north and 50 km east of Ouagadougou, the capital of Burkina Faso). One of the two selected samples underwent laboratory tests and the other underwent in-situ tests. The preliminary tests were interested in the basic geotechnical parameters of these soils, mainly in the distribution of particle size, the Atterberg limits, the optimum moisture content (OMC) and the maximum dry unit weight of modified Proctor. Some characteristics are shown in Table 2. It can be seen that the geotechnical parameters of the two (02) soils are similar and can be classified as B6 under the French GTR classification system (SETRA-IFSTTAR 2000), A2-6 under the AASHTO classification system (AASHTO 1945) and GC under the Unified Soil Classification System USCS (Corps of Engineers 1960). This result is in accordance with the literature review.

2.1.2. The dynamic cone penetrometer

There are many penetration tests (SPT and CPT) and penetrometers. But the penetrometer used in this study was a light dynamic cone penetrometer (DCP), named 'PANDA' developed by Gourvès (1991). Compared with the other technologies, its differences lie in its less cumbersome composition, its lightness and simplicity, and its ability to acquire in-depth compaction control. It weighs twenty kilograms (20 kg) and it is composed of a string of rods fitted with a cone, an anvil, a green box (acquisition unit), a dialog terminal (microcomputer) and a hammer (Figure 1). The test consists of using the hammer to drive the string of rods (14 mm diameter) with a 2 cm^2 cone into the soil (Benz Navarrete 2009; Chaigneau 2001). The hammering energy and the penetration depth of the cone are recorded automatically by the computer after each blow. Cone resistance is calculated using Dutch's formula, reported by many authors (Benz Navarrete 2009; Escobar Valencia 2015; Gourvès 1991; Zhou 1997). Cone resistance per blow according to penetration depth provides a curve (penetrogram) as shown in Figure 1(b), whose, average value is considered as the cone resistance of the tested soils.

Table 2. Geotechnical characteristics of lateritic soils.

	Up to 80 µm (%)	PI (%)	D_{max} (mm)	$w_{MP\text{-}OMC}$ (%)	$\gamma d_{MP\text{-}MAX}$ (kN/m^3)
Soils tested in laboratory	15 5	15	25	9	22.6
Soils tested in-situ	15.9	15.3	31.5	9	22.2

PI: plasticity index; D_{max}: maximum diameter of grains, $w_{MP\text{-}OMC}$ & $\gamma d_{MP\text{-}MAX}$: optimum moisture content & maximum dry unit weight of modified Proctor.

2.2. Methods

2.2.1. Calibration

In order to calibrate dynamic cone resistance with the dry unit weight, the lateritic soil was compacted in a chamber measuring 38 cm in diameter and 83 cm in height (Figure 2) under different water conditions and different levels of unit weight. The chamber used for this study was that suggested by Chaigneau (2001). Compaction was performed in two layers using a static compaction machine (3R). Sensors placed on the machine, were used to record the stresses and the strains of samples. The loading speed was around 5 kN/s. After compaction of the two layers, the samples were subjected to penetration tests using the Panda® penetrometer and average cone resistances was computed across the entire range of the tests. The tests were repeated three times with three different moisture contents (6.5%, 9% and 11%, corresponding to dry, medium and wet water conditions respectively) and five different dry unit weights, varying from bulk to the maximum dry unit weight of modified Proctor. Hence, 3x3x5 samples were prepared in a reference chamber for penetration tests with the dynamic penetrometer and measurement of the dry unit weight. However, the result obtained was the average of the three repeated tests. Table 3 provides the exact values of the five dry unit weights.

Table 1. Variability and classification of lateritic soils in Burkina Faso.

	GTR (France) [IFSTTAR, 2000]				AASHTO (USA) [HRB, 1945]					Brazilian method [Rodriguez, 2010]		
Groups	B2	B4	B5	B6	A1-a	A1-b	A2-4	A2-6	A2-7	SLA	SLP	SLF
Percentages	0.45	33.13	0.15	66.26	1.66	1.36	13.31	62.63	21.03	45.23	54.31	0.45

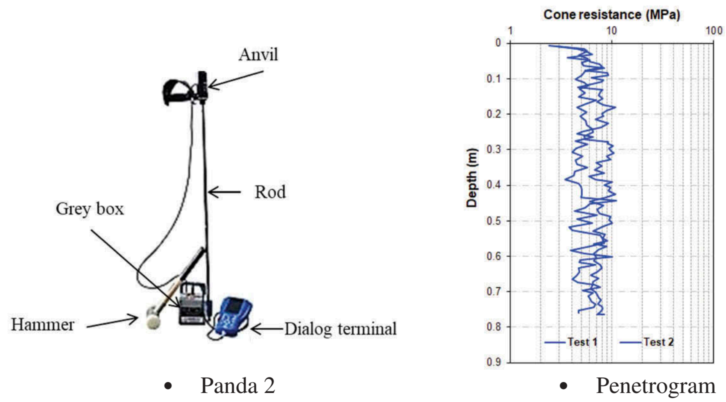

Figure 1. The Panda® dynamic penetrometer (a) and an example of a penetrogram (b).

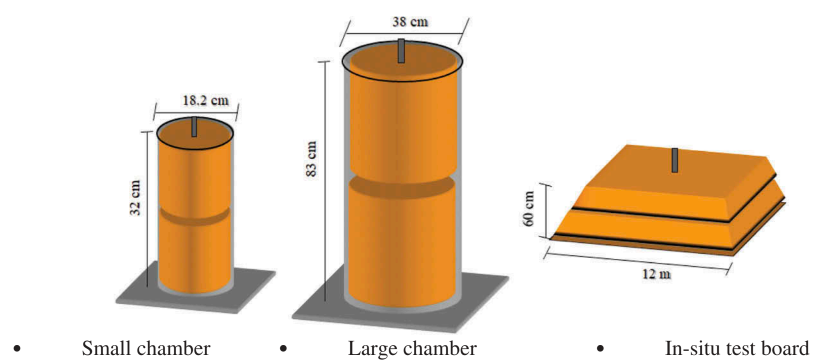

Figure 2. Dimensions of the test's conditions.

2.2.2. Chamber boundary effect

In order to take boundary effects into account, the tests were repeated under three conditions: in a small chamber, in a large chamber (calibration chamber) and in-situ. The first two tests were performed in the laboratory and the final one in-situ. The dimensions of these conditions and the soil are shown in Figure 2. The test process was as described in the previous paragraph. Conversely, with the in-situ test, it was difficult to target the unit weight of lateritic soils with the compactors. Therefore, the in-situ materials were subjected to three levels of compaction with a vibrating roller compactor in order to achieve just three different unit weight levels, plus the unit weight level of the soil in expanded state (bulk unit weight) and with three moisture contents. Thus, a 120 m test board, in two layers, was created, each layer being divided into three different moisture contents (dry, medium and wet) and each moisture content into four different dry unit weights. Each unit weight was measured using two different methods for comparison purposes (a gamma-densimeter and the sand cone method). In all, 2 × 45 penetration tests in laboratory and 2x3x3x4 penetration tests in-situ, and also the measurement of 2 × 45 dry unit weights in laboratory and 2x2x3x3x4 dry unit weights in-situ were performed. However, during the penetration tests, it was observed that cone resistance is very sensitive to a slightest increase in unit weight. In the case of significant dry unit weight (tending towards the maximum), cone resistance also became significant and hammering too resistant. So, it was impossible to reach the last level unit weight of some samples as planned in the laboratory.

Table 3. Values of the five dry unit weights.

	Dry unit weights in kN/m^3				
Soil	12.6 ± 0.2	15.1 ± 0.0	18.0 ± 0.4	20.5 ± 0.2	23.0

3. Results and discussions

3.1. Calibration curves

The compaction and penetration tests were performed in the small chamber, the large chamber and in-situ. By analysing the test results, it was able to reproduce a calibration curve showing cone resistance according to the moisture content (dry, medium and wet) and dry unit weight. Figure 3 shows the calibration curves under the three conditions. The cone resistance is noted q_d and expressed in MPa. The points on the curves are experimental and correspond to a measured level of cone resistance for a given dry unit weight and moisture content.

Under the different conditions, cone resistance increases according to moisture content and dry unit weight. This relationship between cone resistance and the compaction parameters is particularly strong and evolves according to a logarithmic law as shown in Equation (3), where a, b and c are coefficients, under normal conditions, on the nature of the soil. This model provides us with additional information, particularly on the influence of the moisture content that should be taken into account.

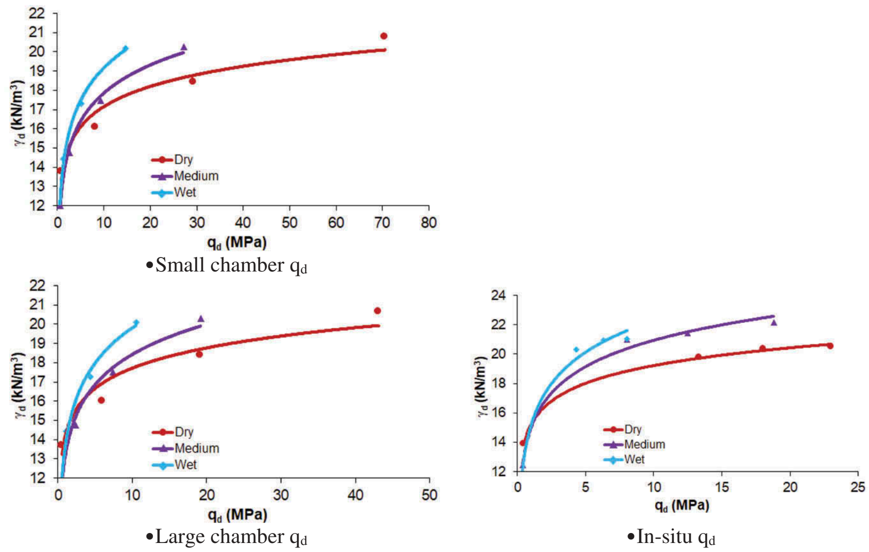

Figure 3. Calibration curves of lateritic soils.

Conversely, in the models mentioned above, cone resistance or dynamic cone penetration index (DPI) depends only on dry unit weights. This is more or less to be expected because these models have been established through classical tests based on a single moisture content: optimum moisture content. The idea in this study is first, to estimate the dry unit weight from dynamic cone resistance for compaction control of lateritic soils, whatever their moisture content. The values of the coefficients a, b and c are provided in Table 4. It may be seen that the coefficients are different depending on the conditions (small chamber, large chamber and in-situ) in which the tests are performed. Which differences could be the result of the boundary effect?

$$\gamma_d = a \times \ln(q_d) + b \times \left(\frac{1}{w}\right) + c \qquad (3)$$

3.2. Chamber boundary effects

First of all, the boundary effect was analysed using an approach that compared the results of the different test conditions from the point of view of cone resistance. To achieve that, some operations were required. First, the model of estimated dry unit weights (obtained from calibration curve) was expressed as percentages in reference to the dry unit weight of modified Proctor at optimum moisture content (OMC). In which form the compaction level is generally assessed. Then, three specific compaction levels (precisely: 90%$\gamma_{d\ MP}$, 95%$\gamma_{d\ MP}$ and 100%$\gamma_{d\ MP}$) were considered and the corresponding cone resistance were determined under the diverse conditions (small chamber, large chamber and in-situ). That is in comparison with the compaction level for subgrade, subbase and base soils of roads, which are in reality: 90%$\gamma_{d\ MP}$, 95%$\gamma_{d\ MP}$ and 100%$\gamma_{d\ MP}$ respectively. Finally, the large chamber was considered as a reference chamber and the different cone resistances divided by the cone resistance of the large chamber. The results are shown in Table 5. q_d is dynamic cone resistance and the indexes s, l and i are used for small, large and in-situ.

Table 4. Coefficients in the small chamber, the large chamber and in-situ.

	Coefficients		
Type	*a*	*b*	*c*
Small chamber	2.0	−23	15.80
Large chamber	2.2	−24	16.40
In-situ	2.7	−23	17.88

The ratios obtained are variable. This variability depends on the moisture content, the compaction level and the boundary conditions (in the chamber and in-situ). It is lower considering moisture content and dry unit weight, and greater, considering the boundary conditions. Indeed, in the small chamber, the average ratio is about 1.45 while it is 0.27 in the in-situ test. These results highlight the existence of the boundary effect, depending on the size of the chamber or the space. The larger the chamber, the less the dynamic cone resistance and vice versa. In Table 6 the chamber or space size (k) is characterized by the following ratio: chamber diameter $\phi_{chamber}$/cone diameter $\phi_{cone,}$ and the cone resistance ratio can be summarized according to the size of the chamber or the space.

Knowing the dynamic cone resistance ratio in each calibration chamber, it is easy to estimate the in-situ cone resistance. With regard to the large calibration chamber, the in-situ cone resistance, considered to be the actual value, represents one-third (1/3) of the cone resistance in the large chamber, as indicated in Equation (4), where qd_i is the in-situ cone resistance and qd_l the cone resistance in the large chamber. These results are in accordance with the findings by Ampadu et al. (2016). This approach, although in agreement with that proposed by Ampadu et al. (2016), is too simple and cannot be used for reliable consideration of the chamber boundary effects that depend on the chamber size and the unit weight, as noted by Schnaid and Houlsby (1991).

$$q_{d_i} = 0.27 \times q_{d_l} \qquad (4)$$

However, secondly, by considering the results from the aspect of dry unit weight, a distinction is noted between estimated dry unit weights (obtained through model [3], knowing the

Table 5. Cone resistance ratios by reference chamber.

	q_{ds}/q_{dl}			q_{dl}/q_{dl}			q_{di}/q_{dl}		
	Dry	Medium	Wet	Dry	Medium	Wet	Dry	Medium	Wet
90%γ_dOPM	1.49	1.41	1.34	1.00	1.00	1.00	0.25	0.29	0.34
95%γ_dOPM	1.50	1.46	1.38	1.00	1.00	1.00	0.23	0.28	0.31
100%γ_dOPM	1.50	1.52	1.43	1.00	1.00	1.00	0.20	0.26	0.29

Table 6. Cone resistance ratio by reference chamber.

Type	Small chamber	Large (reference) chamber	In-situ
k $_{(chamber/cone)}$	11	15	75
q_d/q_{dl}	1.45 ± 0.06	1	0.27 ± 0.04

dynamic cone resistance) and actual dry unit weights (or measured dry unit weights) obtained experimentally under the various conditions (small chamber, large chamber and in-situ). A graphical representation of the estimated and actual dry unit weights, shows a slight difference according to the chamber (the small chamber, the large chamber or in-situ) where the soils are compacted and tested (Figure 4). A possible explanation of this difference is the boundary effect of the calibration chambers.

Dry unit weight may be predicted by formalizing a calibration model that can reproduce actual unit weight under the different conditions (in the laboratory or in-situ). Considering the large chamber and optimum parameters of modified Proctor as the reference conditions, the boundary effect can be estimated through a multiplying coefficient α of the estimated dry unit weight. This coefficient depends on the chamber diameter and can be expressed as shown in Equation (5). The experimental model of evolution of this coefficient is represented in the first graph (Figure 5) and composed of three points. Each point represents the ratio between the dry unit weights in the different situations (in the small chamber, the large chamber considered the reference chamber and in-situ) and the dry unit weights in the reference chamber. It may be seen that the curve starts with a first point on a nonzero ordinate and tends to an asymptotic value, corresponding to the in-situ unit weight divided by the unit weight in the reference chamber. This value numerically reaches 120 cm in diameter and remains nearly constant up to 1200 cm (spacing of in-situ tests), finally leading to a model comparable with an ideal model that includes two parts: an increasing part and a constant part whose equation in this specific case is provided through Equation (5). $\phi$is the diameter of the chamber.

$$\alpha = 0.92 + 0,24 \times \left(1 - e^{-\phi/95}\right) \tag{5}$$

By considering the results of the study, a general model can be proposed for assessing the dry unit weight, given

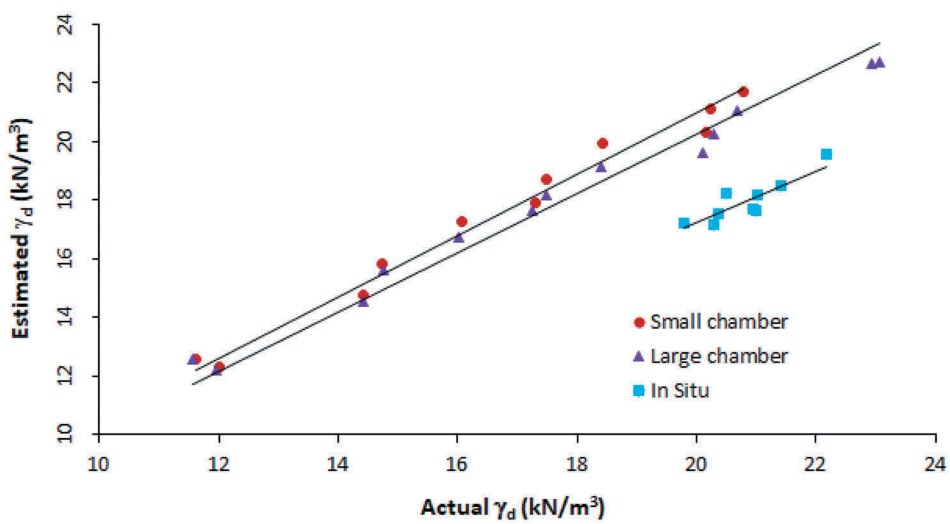

Figure 4. Comparison of estimated and actual dry unit weight with boundary effects.

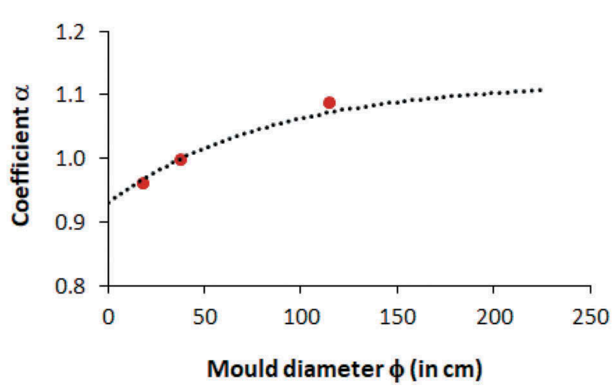

Figure 5. Model of the coefficient α estimation and depending on the chamber size.

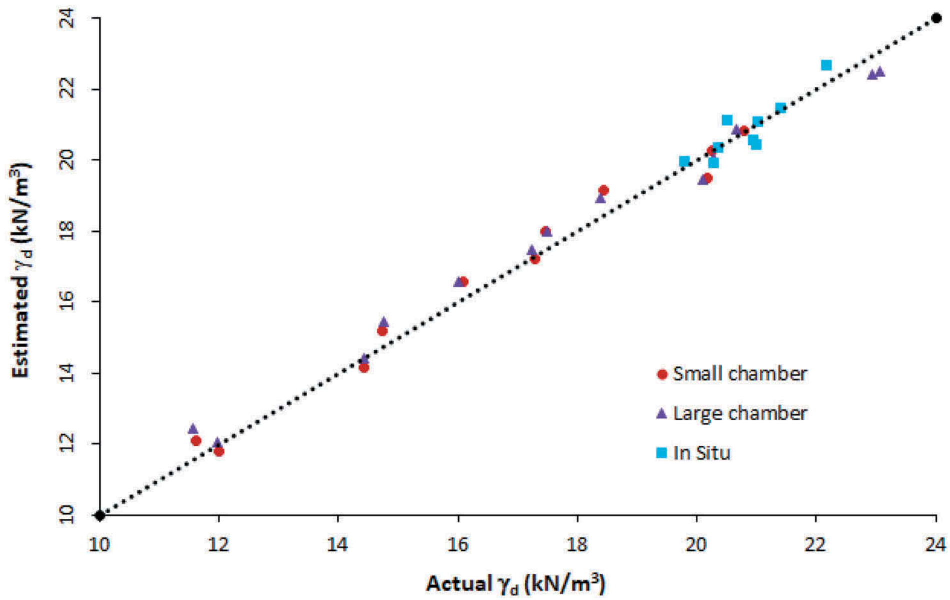

Figure 6. Comparison of estimated and actual unit weight without in-chamber effect.

the cone resistance and moisture content, whatever the chamber diameter, taking into account the chamber boundary effect through the model presented in Equation (6). A consideration of the model and its representation produces the graph of the Figure 6 graph, in which estimated and the actual dry unit weights are close.

$$\gamma_d = \left[0.92 + 0,24 \times \left(1 - e^{-\phi/95}\right)\right] \times \left[a \times \ln(q_d) + b \times \left(\frac{1}{w}\right) + c\right] \quad (6)$$

This study presents many advantages in predicting the in-situ dry unit weight from laboratory tests, taking into account diverse factors such as the nature of the soil, its moisture content and the boundary effects of the compaction chamber. Generally, the calibration proceeds by static compaction into two or more thin layers of soil and by protecting the chamber wall with a lubricated, thin and flexible plastic membrane to avoid lateral friction and to obtain more homogeneous unit weight inside the calibration chamber. Under such conditions, penetration tests may be reproduced on many soils tested around the world, particularly in temperate areas, such as clay, sand, gravel, etc. These observations are also true for the specific lateritic soils found in tropical climates and studied in this paper. However, the models proposed for assessing the boundary effects and for predicting the dry unit weight are specific for these tested soils. They could, nevertheless, be extended to other soils and, in this case, further studies would be necessary.

4. Conclusion and recommendations

It has been shown that lateritic soils are common materials for tropical regions and are used for pavement engineering. The problem is that there is no supervision road-building on lateritic soils. In addition, the technology used for pavement compaction control has limitation in terms of in-depth and fast control and, therefore, becomes time-consuming. On the other hand, the use of the dynamic cone penetrometer as a simple and rapid means of assuring pavement quality in some countries is successful and can be also an alternative in other countries, since it enables soil compaction quality to be verified and ensured. However, calibration is required when it is used on lateritic soils, under a variety of conditions (a range of moisture content, dry units weights and spaces with different dimensions), to link the penetrometer's cone resistance to the dry unit weights (measured using direct methods: sand cone or nuclear density metre methods) and for predicting the in-situ dry unit weight from laboratory tests. The results of lateritic soil calibration using the Panda® penetrometer show that dynamic cone resistance is closely correlated to the soil's dry unit weight and its moisture content. However, the results from the various places (small chamber, large chamber and in-situ test board) are different. Which difference arises from the chamber boundary effect mentioned by many authors and this must be taken into account for a better prediction of the in-situ dry unit weights. Careful consideration of this effect reveals that it depends on the chamber or the space size (or dimensions). Two approaches were proposed in order to predict the in-situ results. The first, overly simple approach, took into account the in-situ cone resistance prediction, resulting in an in-situ and laboratory cone resistance ratio of one-third (1/3). This result is comparable to that obtained by Ampadu et al. (2016) with the DCP. The second, more reliable approach, took into account the in-situ dry unit weight prediction. This yielded a model in order to take into account the chamber boundary effect and to estimate the in-situ dry unit weights whatever the chamber dimensions.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Symbols and abbreviations

α	Coefficient of the chamber Boundary effects
AASHTO	American Association of State Highway and Transportation Officials
a, b and c	Coefficients depending on the nature of soils
AFNOR	Association Française de Normalisation
ASTM	American Society for Testing and Materials
CEBTP	Centre Expérimental de recherches et d'études du Bâtiment et des Travaux Publics
CPT	Cone Penetration Test
DCP	Dynamic Cone Penetrometer
D_{max}	Maximum diameter of soils
DPI	Dynamic Penetration Index
	Diameter
γ_d	Dry unit weight of soils
$\gamma_{d\ MP\text{-}MAX}$	Maximum dry unit weight of Modified Proctor
GTR	Guide de Terrassement Routier
HRB	High Research Board
IFSTTAR	Institut Français des Sciences et Technologies des Transports, de l'Aménagement et des Réseaux
k	Coefficient derived from the ratio between the mold and the cone diameters
MAX	Maximum
MP	Modified Proctor
NF P	Normes Françaises
OMC	Optimum Moisture Content
PANDA	Penetromètre Alpha-Numerique Dynamique Assisté
PI	Plasticity Index
qd	Cone resistance
$q_{d\ l}$	Cone resistance in large calibration chamber
$q_{d\ i}$	Cone resistance in-Situ
$q_{d\ s}$	Cone resistance in small calibration chamber
SETRA	Service d'Etudes Technique, des Routes et Autoroutes
SPT	Standard Penetration Test
W	Moisture content
$W_{MP\text{-}OMC}$	Optimum moisture content of Modified Proctor

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