A field investigation of confinement effect on dynamic cone penetration index of a lateritic soil

Une étude de terrain sur l'effet de confinement sur l'indice de pénétration du cône dynamiqu e d'un sol latéritique

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ABSTRACT: The use of the dynamic cone penetrometer (DCP) for compaction verification requires the in situ development of a calibration equation between the level of compaction achieved and the dynamic cone penetration index (DPI). In order to be able to transfer in-mould laboratory generated calibration for in-situ application, the effect of horizontal confinement imposed by the rigid mould has to be accounted for. Due to the differences between field compaction by vibratory compactors and laboratory impact compacted samples, this study seeks to determine the effect of horizontal confinement on DPI and on the calibration equation parameters during in-situ compaction. Confinement elements consisting of metal moulds of diameters varying from 100mm to 530mm were included in an experimental test bed. The moulds were filled and covered with a lateritic soil at the optimum water content and subjected to different number of passes of a compaction plant, followed by the in-situ DCP test in the confinement elements followed by determining the in-situ density by sand replacement test. The unconfined DCP test was used as the control test. The study evaluates the effect of different confinement element diameters on the DPI values and on the calibration equation parameters.

RÉSUMÉ: L'utilisation du pénétromètre à cône dynamique (DCP) pour la vérification du compactage nécessite le développe ment in situ d'une équation d'étalonnage entre le niveau de compactage obtenu et l'indice de pénétration du cône dynamiqu e. Afin de pouvoir transférer le calibrage généré en laboratoire dans le moule pour une application in situ, il faut tenir co mpte de l'effet du confinement horizontal imposé par le moule rigide. En raison des différences entre le compactage sur sit e des compacteurs vibrants et les échantillons compactés par impact de laboratoire, cette étude cherche à déterminer l'effet du confinement horizontal sur l'indice de pénétration du cône dynamique et sur les paramètres de l'équation d'étalonnage lo rs du compactage in-situ. Des éléments de confinement constitués de moules métalliques de diamètres variant entre 100 m m et 530 mm ont été inclus dans un banc d'essai expérimental. Les moules ont été remplies et recouvertes d'un sol latériti que à la teneur optimale en eau et soumises à un nombre différent de passes d'un compacteur, suivies du test DCP in sit u dans les éléments de confinement, aussi suivies de la détermination de la densité in situ par la méthode du sable. Le te st DCP non confiné a été utilisé comme test témoin. L'étude évalue l'effet de différents diamètres d'élément de confinemen t sur les valeurs de l'indice de pénétration du cône dynamique et sur les paramètres de l'équation d'étalonnage.

KEYWORDS: Dynamic Cone Penetrometer, field compaction, confinement element, level of compaction

1 INTRODUCTION

1 .1 *Study Background*

The Dynamic Cone Penetrometer has several applications including in-situ determination of CBR and stiffness of pavement layers (Kleyn, 1975; Livneh, 1987; Chen et al., 1999). However recently it has been proposed as a simple compaction verification tool (Chaigneau et al., 2000, Gabr et al., 2001; Ampadu and Arthur, 2006; Ampadu and Fiadjoe 2015) especially on small projects including low volume roads in remote areas where full scale conventional methods including the sand replacement method (ASTM D 1556-90) and the nuclear gauge method (ASTM D2922-96) are considered uneconomical or impractical. The use of the DCP for compaction verification requires the establishment, in the field, of a calibration equation between the level of compaction achieved at the optimum moisture content (w_{opt}) and the rate of penetration per blow known as the Dynamic Penetration Index (DPI). However, field calibration is tedious and time consuming. Therefore various investigations have been undertaken to allow the generation of the calibration equation from laboratory in-mould tests. However in the use of laboratory in-mould tests, one major hurdle that needs to be overcome is the effect of horizontal confinement of the walls of the mould on the DPI values. The effect of horizontal confinement is defined in terms of the diameter of the confining mould. Nguyen and Mohajerani, (2012, 2015) accounted for the effect of the horizontal confinement by reducing the size of the DCP equipment. Ampadu et al (2017), on the other hand, directly evaluated the effect of horizontal confinement on the DPI values of the standard DCP equipment on laboratory-compacted lateritic soil.

These studies were conducted on laboratory compacted soil samples. However, the mode of energy application and the boundary conditions during laboratory compaction are quite different from those that pertain during field compaction. Whereas both the soil and the compaction energy in in-mould laboratory compaction are confined, under field compaction they are unconfined. As a result, even at the same dry density, the soil structure produced by field compaction is quite different from that produced by laboratory compaction (Lambe 1958). Compaction-induced structure has been shown to strongly influence the behaviour of compacted soils (Holtz et al 2011), Vipulanandan (2013). The question therefore is whether the effect of confinement on the DPI during field compaction is the same as during laboratory in-mould compaction and whether the relationships derived between confined and unconfined DPI values from laboratory compaction can be transferred to field compaction.

1 .2 *Study Scope and Objectives*

This study therefore seeks to investigate the effect of the diameter of confinement elements on the DPI determined under field compaction conditions and the influence of the level of compaction, for the case of a lateritic subgrade material at the optimum water content. It also seeks to compare the DPI values measured in laboratory in-mould DCP tests with that measured in unconfined DCP tests in-situ. DCP tests were conducted in the field in confinement elements of different diameters ranging from 100mm to 530mm and also under unconfined conditions at compaction levels of 84%, 89%, 94% and 100% of the standard Proctor maximum dry density. The results of this study are presented and discussed.

2 MATERIALS AND METHODS

2 .1 *Materials*

The confinement elements used for this study consisted of six steel tubes, ranging in diameter from 100mm to 530mm with a thickness of 8mm. The key characteristics of the tubes are shown in Table 1. The compaction plant was a 90kg vibratory plate compactor 550mm long and 505mm wide. The DCP equipment used is a standard equipment meeting the specifications of ASTM D6951-03. The key characteristics are described in Ampadu et al. 2017.

Table 1 Key Characteristics of confinement elements

Diameter (mm)	100	159	214	240	385	530
Height (mm)	200	195	185	190	250	250

2 .2 *Methods*

2.2.1 *Laboratory Tests*

The soil for testing was delivered in a dump truck and samples were air-dried for four days and bagged for all the laboratory tests. From this source, samples were taken and prepared for routine laboratory tests for characterization. The grading and Atterberg limits were determined in accordance with BS1377 Part 2:1990. The compaction characteristics by the standard Proctor specifications (ASTM D698-00) were also determined. Then using the optimum water content samples were prepared in the standard Proctor mould (100mm) using 10, 15, 23 and 28 blows of the 2.5kg rammer corresponding to 0.4, 0.6 0.92 and 1.12 of the standard Proctor specific energy (Ec) respectively. For each compacted sample, the in-mould DCP test was performed.

2.2.2 *Field Tests*

The concept for the procedure for the fieldwork was adapted from the laying of geocell confinement systems. The top-soil at the test site was removed and leveled. Then soil was taken from the heap and mixed thoroughly with water and brought to the optimum water content. The six confinement elements were then arranged upright on the prepared subgrade as shown in Figure 1. Then by means of a twine dawn from steel pegs, the positions of the centres of the confinement elements were marked. Using a shovel, the mixed soil was spread evenly in and around the confinement elements to a loose lift of about 285mm and 350mm for the shallow and deep section respectively. The loose surface was then leveled with a rake and three passes of the plate compactor were applied evenly over the surface. The DCP equipment was performed at the centre of each confinement element and also at the unconfined test location recording the penetration for each blow of the hammer. The sand replacement test was also performed, in accordance with ASTM D1556-90, at the two locations identified as shown in Figure 1 to determine the in-situ density. The compacted material was excavated and replaced and the whole process was repeated increasing the number of passes of the roller to six, then 9 and finally to 12.

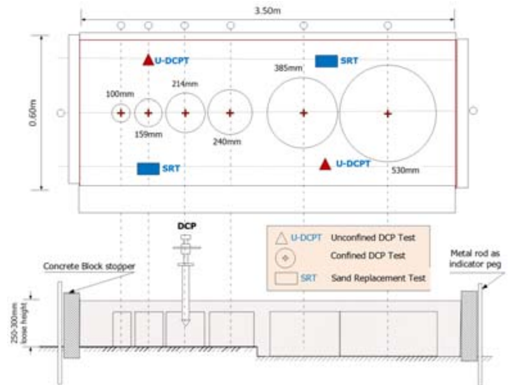

Figure 1. Layout of test site

3. DISCUSSION OF TEST RESULTS

3 .1 *Test Sample Properties*

The sample used for this study was a reddish-brown lateritic sandy gravel with a liquid limit of 26, a Plasticity Index of 11 and a fines (i.e. the portions passing sieve No 200) and gravel contents of 33.8% and 31.8% respectively. Figure 2 shows the grading characteristics of the sample. The compaction characteristics are shown in Figure 3 and show a maximum dry density (MDD) value of 2044kg/m^3 at an optimum water content of 11.8%.

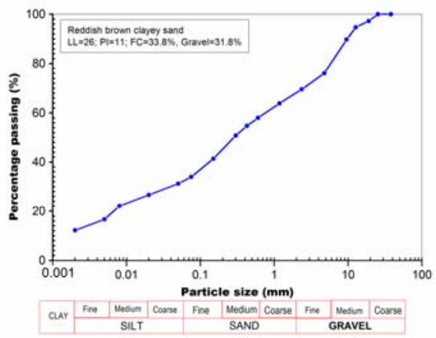

Figure 2 Grading Curve

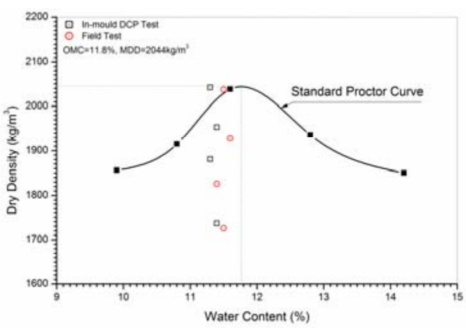

Figure 3 Compaction curve showing test points

3 .2 *In-Mould Laboratory DCP Test Results*

The results of the in-mould DCP test are summarized in Table 2. The DPI values measured ranged from 26.8mm/blow for 1.12Ec to 44mm/blow for 0.4E_c. These measured DPI values were corrected for the effect of water content using the equation proposed by Ampadu and Fiadjoe (2015) to obtain DPI_{opt}.

Table 2 Summary of in-mould laboratory DCP test results

Test ID	Water Content (%)	Dry Density (kg/m^3)	Level of Compaction (%)	Measured DPI	$w-w_{opt}$ (%)	DPI_{opt}
P-10	11.4	1736	85.0	44.0	-0.40	49.6
P-15	11.3	1881	92.0	35.5	-0.50	41.2
P-23	11.4	1953	95.6	31.4	-0.40	35.4
P-28	11.3	2042	99.9	26.8	-0.50	31.1

$DPI_{opt}=DPIx10^{-0.13(w-wopt)}$ (Ampadu and Fiadjoe, 2015)

3 .3 *Field Test Results*

The in-situ levels of compaction increased from 84.4% to 99.7% as the number of passes of the compactor increased from 3 to 12 passes respectively. The compacted thicknesses for the shallow and deep sections respectively were about 215mm and 290mm for 3 passes and 210mm and 285mm for 12 passes. Since the sand replacement test covers only the top 150mm of the compacted layer the dry density can be reasonably correlated to the DCP test results only within the same depth. Therefore in the analysis of the in-situ DCP test results, as much as possible, the linear regression took into account only penetrations that fell close to the top 150mm. The plot of the cumulative number of blows against the penetration for typical number of passes of the compactor is illustrated with nine passes in Figure 4. As expected it can be seen that the bottom part of the layer has lower levels of compaction as shown with an increase in DPI for the results of the 100mm, 240mm and the 385mm confinement elements.

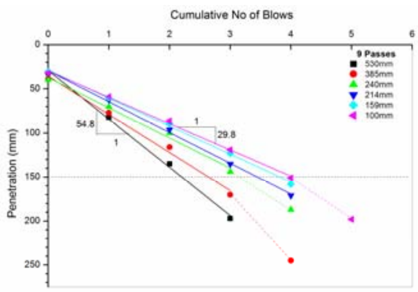

Figure 4 Cumulative Blows-Penetration plot for 9 passes

A summary of the results of the field tests is shown in Tables 3 and 4. The DPI values at the optimum water content obtained from the in situ DCP tests in the confinement elements, have been corrected for the water content deviations. The corrections increased the measured DPI values by between 6% and 13% of the measured values for $w-w_{opt}$ values of -0.2 to -0.4%.

Table 3 Summary of Field DCP test Results

No. of Passes	Water content (%)	$w-w_{opt}$ (%)	Dry Density kg/m^3	Compaction level (%)	Unconfined DPI mm/blow
3	11.5	-0.3	1725.8	84.4	170.7
6	11.4	-0.4	1825.9	89.3	102.3
9	11.6	-0.2	1928.7	94.4	58.9
12	11.5	-0.3	2037.3	99.7	35.6

$DPI_{opt}=DPIx10^{-0.13(w-wopt)}$

Table 4 Summary of Field DCP test Results

No. of Passes	DPI_{opt} (mm/blow) Confinement Element Diameter (mm)					
	100	159	214	240	385	530
3	53.6	56.9	72.2	91.9	101.7	169.6
6	48.4	51.6	57.1	54.1	59.2	103.7
9	31.6	33.7	36.1	36.3	40.9	54.7
12	21.5	24.7	26.8	29.5	34.5	38.5

$DPI_{opt}=DPIx10^{-0.13(w-wopt)}$

3.3.1 *Effect of Diameter of Confinement Elements*

The ratio of the confinement element diameter to DCP cone diameter (R_D) for this study varied between 5 and 26.5 for 100mm and 530mm diameter confinement elements. The DPI_{opt} values achieved in the different confinement elements have been plotted against R_D in Figure 5. The unconfined DPI values are also indicated. The results show some scatter in the data that could have arisen from inevitable non-uniformity in the material in terms of either the grading, water content or level of compaction. However, a Boltzmann curve can be fitted to the data to give average values by smoothing over the scattering in the results (Ampadu et al 2017).

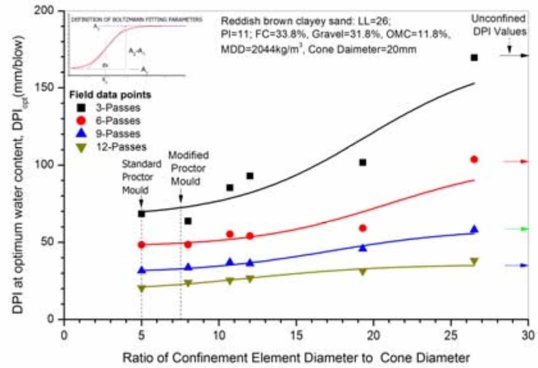

Figure 5 Variation of DPI with R_D

The trend shows that as the R_D-value increases, the DPI values also increase at an initially increasing rate that begins to slow down beyond the centre of the curve. Finally at R_D of around 26.5, the DPI value in the confinement element is similar to the unconfined DPI values. This result shows that at R_D values greater than about 26.5, the effect of confinement is insignificant which agrees with the results of laboratory compaction (Ampadu et al. 2017, Mohammadi et al. 2008) and also broadly with those on (Static) Cone Penetration Tests (CPT) in calibration chamber tests (Ghionna 1984).

The DCP test may be modeled with a deep foundation failure mechanism involving the development of slip planes whose size and orientation depend on the soil strength. Since the presence of confinement element hinders the full development of the slip planes, increasing diameter of confinement element will lead to increasingly full development of slip planes, until beyond a critical value, R_D ceases to have any influence.

3.3.2 *Effect of Level of Compaction*

The effect of relative compaction was examined using the averaged DPI_{opt} values obtained from the Boltzmann fit to the data and the level of compaction in Figure 6. A linear regression to each set of data showed a very high degree of fit with coefficient of correlation values ranging between 0.965 to 1.000, confirming the validity of Equation 1 for lateritic soils (Ampadu and Arthur 2006, Ampadu et al 2017).

$$\mathrm{Log}\left(\frac{\rho_d}{(\rho_d)_{max}}\right)=\kappa\text{-}\lambda\mathrm{Log}\left(DPI_{opt}\right) \qquad \text{Equation 1}$$

The intercepts and gradients (κ and λ) from the fitting equations have also been plotted against R_D in Figure 7. The results show that both κ and λ increase only slightly with increasing R_D, and then reduce to the unconfined values of 2.163 and 0.106 which were lower than the values (2.182 and 0.138) in the smallest diameter (100mm) of confinement element.

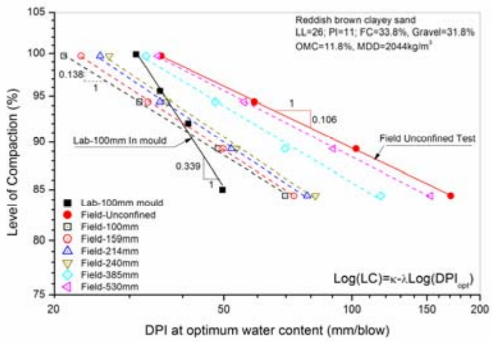

Figure 6 Level of Compaction-DPI relationship

It can also be seen that the values of the calibration parameters (κ and λ) from the in-mould test in the 100mm diameter mould (2.507 and 0.339) are much higher that the values (2.182 and 0.138) from the 100mm confinement element under field compaction. The ratios of the κ and λ values are summarized in Table 6 and it can be seen that the drop with R_D is relatively small compared the drop from laboratory to field values. This suggests that the mode of compaction energy application has a far larger influence on κ and λ values than the diameter of the confining element. The implication of this is that field compaction data is required to derive the transfer relationships for field application of in-mould laboratory generated calibration equation.

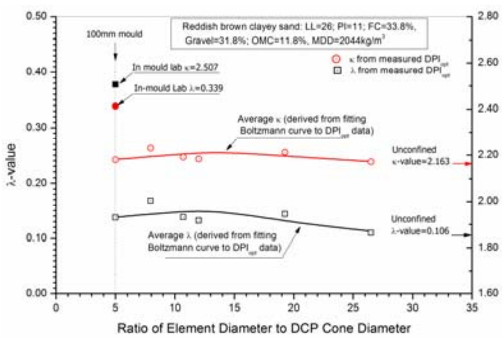

Figure 7 Variation of Calibration Parameters with R_D

Table 5 Summary of Calibration parameters

Parameters	In-mould 100-mm Lab Test	Field Test in 100-mm confinement element	Unconfined Test
κ	2.507	2.182	2.163
λ	0.339	0.138	0.106
$\kappa_{field}/\kappa_{lab}$	1.000	0.870	0.863
$\lambda_{field}/\lambda_{lab}$	1.000	0.407	0.312

4 CONCLUSION

From the results of DCP tests in confinement elements on a study site and in-mould DCP test on laboratory compacted samples of lateritic soil, it has been shown that field compaction data is required to derive the transfer relationships for field application of in-mould laboratory generated calibration equation. Specifically, the study has shown that:

1. The effect of confinement during vibratory compaction in the field depends on the level of compaction.
2. Vibratory compaction in the field has a far larger influence on the values of the calibration parameters, κ and λ than the diameter of the confining element.

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