In situ characterization of an old railway platform with DCP

Caractérisation in situ d'une ancienne plate-forme de chemin de fer avec PCD

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ABSTRACT
The elastic stiffness measured *in situ* is considered a good indicator of the performance of railway platforms. The deformation modulus obtained from the Plate Load Test (PLT) is commonly considered representative of that stiffness. Nevertheless, the PLT is a very expensive and time consuming test. Moreover, it is very difficult to perform when the purpose is to characterize ancient platforms of railway lines that must be maintained active during the renewal works. The Dynamic Cone Penetrometer (DCP) is a much cheaper and simpler test, traditionally used to control the compaction of soils and granular materials. The paper reports the experience of the combined use of PLT and DCP tests for characterizing the platform of the main railway line in Portugal (built in the XIXth century), which has recently been upgraded to high speed passenger trains and freight trains with higher maximum axle load. Correlations between the average resistance to penetration of the DCP and the deformation modulus from PLT are presented for coarse-grained and fine-grained soils. A criterion is proposed for the depth over which the DCP results should be averaged for correlation with the modulus from the PLT.

RÉSUMÉ
La raideur élastique mesurée *in situ* est considérée un bon indicateur de la performance des plateformes ferroviaires. Les valeurs du module sous chargement statique à la plaque sont, généralement, ceux qui sont établis à titre de référence. Néanmoins, l'essai à la plaque est lent et coûteux et il est difficile à réaliser pour la caractérisation d'anciennes plateformes de voies de chemin de fer en opération. Le Pénétromètre à Cône Dynamique est une méthode beaucoup moins chère et plus simple qui a été utilisée pour contrôler le compactage des sols et des matériaux granulaires. Cet article présente l'expérience de l'utilisation combinée de l'essai à la plaque et du Pénétromètre à Cône Dynamique au cours de l'évaluation d'une ancienne voie de chemin de fer en opération au Portugal (construite au XIXème siècle) qui à été modernisée. Il a été possible d'établir une assez bonne corrélation entre la résistance à la pénétration du Pénétromètre à Cône Dynamique et le module de déformation à la plaque. Différentes corrélations ont été établies pour les sols à gros grains et à grains fins. Il est proposé un critère sur la profondeur au cours de laquelle la valeur moyenne des résultats du Pénétromètre doivent être calculés pour être en corrélation avec le module de l'essai à la plaque.

Keywords : Dynamic Cone Penetrometer, Plate Load Test, Railway Subgrade, Deformation Modulus

1 INTRODUCTION

The design and the quality control during construction of the subgrade and foundation layers (capping layer, sub-base or sub-ballast) of transportation infrastructures should be based not only on the physical properties but also on the mechanical parameters of the materials and compacted layers. This is the basis of the so-called mechanistic approach. This approach is more rational but requires broader input data, such as soil stiffness and information related to permanent deformation behaviour.

The resilient modulus of soils and granular materials obtained in the lab, under state controlled conditions of the specimens, by means of cyclic triaxial tests is a mechanical paramount parameter (Gomes Correia 2001). However, a proper evaluation of that modulus is very demanding, as a result of the complexity of the testing device and of the dependency of the results on the state conditions and on the stress path. Moreover, when it is necessary to characterize ancient substructures, which were typically constructed with a large variability of materials, reliable lab results are severely limited by the serious difficulty of reproducing in the lab such heterogeneity and of collecting *in situ* undisturbed samples.

Some studies showed that the *in situ* measured elastic stiffness is a reasonable indicator of the infrastructure foundation performance. Although there are a number of devices capable of measuring the *in situ* stiffness (Brown 1999; Quibel 1999; Fortunato et al. 2007), the values obtained from the Plate Load Test (PLT) are those commonly taken as reference. Nevertheless, the PLT is expensive, time consuming, requires heavy equipment and in some cases it is very difficult to perform, particularly when the track to be characterized is part of a line in operation.

The Dynamic Cone Penetrometer (DCP) is a simple and fast method that has been widely used to control the compaction of soils and granular materials (Gabr et al. 2001). Moreover, correlations between the results of DCP and the ground stiffness are available.

This paper reports results of the use of DCP for the characterization of an ancient (XIXth century) railway track in service. Some correlations are presented between DCP and PLT test results.

2 SOME CORRELATIONS BETWEEN STIFFNESS AND DYNAMIC CONE PENETROMETER RESULTS

The use of static and dynamic penetrometer for a qualitative ground assessment and for evaluating physical and mechanical soil parameters, through appropriate correlations, is a traditional practice. The DCP has been increasingly used in many countries when dealing with soil (subgrade), granular material, and lightly stabilized soils for road and railway platforms.

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The DCP consists of a steel rod with a steel cone at one end which is driven into the ground to be characterized by means of a sliding hammer. The advantages of the method are: a) the device is cheap, light and simple to operate; b) the test can be made in different types of soils; c) it is possible to correlate its results with the ones provided by other methods and tests. Nevertheless, some authors have pointed out the limitations of assessing deformation parameters from a penetration test such as the DCP. In fact, this test induces large deformations in a volume of soil around the cone, creating localized zones of failure (Chua 1988). A further difficulty is that, very often, the results reveal a large scatter, depending on the maximum grain size and on the quantity and type of fines.

A number of studies have been conducted to investigate the use of the DCP and the factors affecting its results, which are normally represented by the so-called DCP index, DCPI, expressed in mm/blow (Rahim & George 2002). Then, the lower the DCPI the stiffer the material is, and vice versa. Throughout the last three decades, a large amount of data has been compiled relating that index to the California Bearing Ratio, CBR, particularly through an equation of the type:

$$\log CBR = a - b \cdot (\log DCPI)^{c} \qquad (1)$$

where a, b and c are constants.

In these cases, the resilient modulus, E, can be estimated using the equation:

$$E(MPa) = 10\,CBR \qquad (2)$$

Although the appropriateness of this equation is quite controversial (Ping et al. 2001), it is widely used in practice.

Based on a study dealing with natural deposits and with compacted fills constructed with a broad range of soils commonly employed in pavement foundation, Livneh et al. (1995) proposed for the coefficients a, b and c the values 2.14, 0.69 e 1.5, respectively. Some other authors proposed a simplified version of equation (1) with the constant a ranging from 2.44 to 2.60, the constant b ranging from -1.07 to -1.16 and the constant $c = 0$ (Amini 2003).

Other studies attempted to directly correlate DCPI with the resilient modulus from cyclic triaxial tests or deformation modulus from *in situ* load tests, according to the following equations (De Beer 1991; Konrad & Lachance, 2000; Chen et al. 1999):

$$\log(E) = a - b \cdot \log(DCPI) \qquad (3)$$

or:

$$E(MPa) = c \cdot (DCPI)^{d} \qquad (4)$$

where a, b, c and d are constants.

Given the fact that the DCP test is destructive in nature, it might not be realistic to expect a one-to-one relation between E and DCPI. Therefore, some authors suggest to include basic soil state properties as independent variables in the regression models, for example, dry unit weight, water content, liquid limit, plasticity index, percentage passing the #200 sieve and uniformity coefficient (George & Uddin 2000). For granular materials, coefficient of uniformity and maximum grain size are reported to be the primary factors. An increase in the percentage of the fines generally decreases DCPI, for the same target density. Conversely, an increase of density for a similar gradation or individual material type decreases DCPI.

Rahim and George (2002) investigated the feasibility of using the automated DCP to correlate DCPI with the resilient modulus measured both in the lab in a cyclic triaxial test and *in situ* using non destructive load tests. In this study the soil parameters referred above were used to improve the robustness of the regression models. The results suggested two relationships, for fine-grained and for coarse-grained soils (AASHTO 1995):

$$E = a_0 \cdot (DCPI)^{a_1} \left[\gamma_{dr}^{a_2} + \left(\frac{w_L}{w_c} \right)^{a_3} \right] \qquad \text{fine-grained soil} \qquad (5)$$

$$E = b_0 \cdot \left(\frac{DCPI}{\log C_u} \right)^{b_1} \left[\gamma_{dr}^{b_2} + w_{cr}^{b_3} \right] \qquad \text{coarse-grained soil} \qquad (6)$$

where

E – laboratory resilient modulus, calculated at 37 kPa deviatoric stress and 14 kPa confining pressure;
C_u – uniformity coefficient;
γ_{dr} – actual unit weight /standard Proctor maximum unit weight;
w_c – water content (%);
w_{cr} – actual water content /optimum water content;
w_L – liquid limit;
a_i, b_i – constants.

For a coefficient of determination (R^2) about 0.7, the constants a_i and b_i have the following values: $a_0 = 27.86$; $a_1 = -0.114$; $a_2 = 7.82$; $a_3 = 1.925$; $b_0 = 90.68$; $b_1 = -0.305$; $b_2 = -0.935$; $b_3 = 0.674$.

It should be emphasized that all these constants must be strongly related with test conditions.

3 DYNAMIC CONE PENETROMETER AND PLATE LOAD TEST PERFORMED AT AN ANCIENT RAILWAY

Some railway lines in Portugal are being upgraded to high speed passenger trains and freight trains with higher maximum axle load. Performance requirements of the renewed railway tracks included the specification of minimum values for the deformation modulus at the top of the capping layer and at the top of the new sub-ballast layer (UIC 1994). The design of these layers was based on a careful evaluation of the geotechnical properties of the ancient subgrade, because the decision to remove, to maintain or to improve the existing subgrade was of utmost relevance with regard to the cost and the construction time, as well as the perturbation on line operation during the upgrading works.

During the renewal of the most important railway track, built in the XIX[th] century, connecting Lisbon and Porto, an extensive field survey was performed on the track subgrade, in order to collect data about the thickness and the stiffness of the existing layers and the characteristics of the soils, namely the grain-size distribution, plasticity, water content, as well as the degree of compaction.

The ancient subgrade revealed pronounced heterogeneity regarding the constitutive materials and their conditions (water content and degree of compaction).

In order to assess the deformation modulus of the subgrade, a number of plate load tests were done (Figure 1).

Figure 1. Plate Load Test during survey of railway subgrade

However, it was difficult to perform systematically these tests due to the intense traffic of the line and its total length (about 330 km). Therefore, other non-destructive and semi-destructive *in situ* mechanical methods have been used with similar purpose (Fortunato 2005). Bearing in mind the advantages discussed above, the DCP was intensively used.

DCP tests were performed at the same places as PLT tests aiming to establish a correlation between DCPI and the deformation modulus in the second loading cycle of a Plate Load Test, EV_2 (AFNOR 2000).

In order to take into account the heterogeneity of the subgrade and, in some cases, the presence of particles with large diameter, two DCP tests were done at each site, with 30-50 cm spacing. The results for each site were taken as the average values of the resistance to penetration (Figure 2).

Figure 2. DCP during field survey of the old railway platform

Figure 3 presents the type of soils tested *in situ* (AASHTO 1995). It should be noted that the number of samples of fine-grained soils is about 30% of the total of the tested soils.

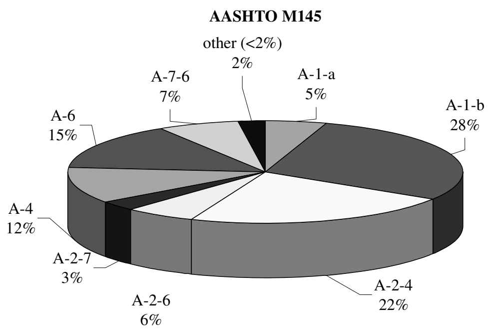

Figure 3. Schematic representation of the types of soils tested

The characteristics of the used DCP device are the following: i) hammer weight, 10 kgf; standard drop height, 0.50 m; tip area 10 cm^2; weight of the shaft, 3.79 kgf; angle of cone tip, 90º. The resistance to penetration is measured in terms of the number of blows needed to penetrate 100 mm. From this value the DCPI, in mm per blow, is calculated.

The analysis of the results of 80 tests performed (two at each of the 40 different sites) showed that this value typically decreases in depth. Some graphs are presented in Figure 4 in order to illustrate the pattern of the behaviour. In coarse-grained soils, particularly, it was observed that DCPI values obtained at small depths were significantly higher than those obtained at greater depths. Since the material and the degree of compaction were very similar in depth, it can be concluded that such pattern is due to the increase of the effective confining pressure (Jayawickrama et al. 2000).

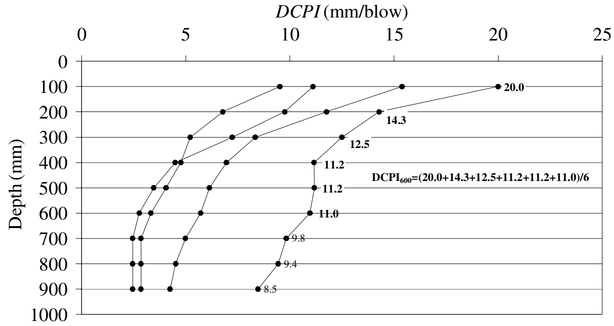

Figure 4. DCPI values obtained for different depths

Due to this evidence, in order to correlate DCPI with EV_2, it is necessary to find a representative value of the subgrade DCPI at each test site. With that purpose, it was calculated for all the sites the average values, $DCPI_n$, between the ground surface and a certain depth n, multiple of 100 mm, down to a depth of 900 mm (Figure 4 shows an example of calculation of $DCPI_{600}$ for one curve).

The correlations between the different values of $DCPI_n$ and EV_2 were analysed, and the respective coefficient of determination was calculated for all the sites. The best correlation (R^2=0.56) was obtained for $DCPI_{600}$. This can be related to the fact that the plate diameter was 600 mm.

With the purpose of improving this correlation, further analyses were carried out, by considering separately the results concerning coarse-grained and fine-grained soils (AASHTO 1995). Figure 5 presents the R^2 variation with depth. The maximum values of the coefficients of determination obtained in this way significantly increased up to 0.76 and 0.78, respectively. These values can be considered quite reasonable for this kind of correlation.

The R^2 variation with depth was more important for the coarse-grained soils, particularly when shallower zones are considered for computing DCPI. For fine-grained soils, R^2 values are lower when depth over 700 mm are considered.

Taking into account these results, in order to correlate DCPI with EV_2, it is suggested that the representative value of the subgrade DCPI at each test site be calculated as an average value between the ground surface and a depth equal to the plate diameter of the PLT.

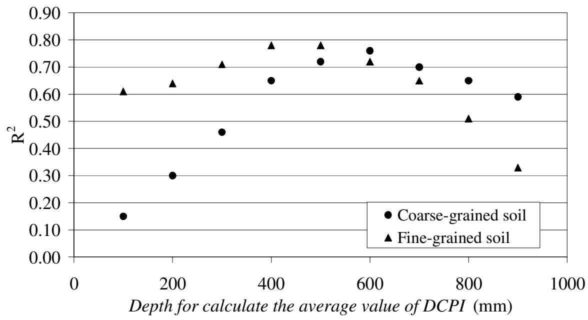

Figure 5. Coefficient of determination (R^2) obtained for different depths

Figures 6 and 7 present the best correlations between DCPI and EV_2, for coarse-grained soils and fine-grained soils, respectively. The values of EV_2 are in the range between 20 and 80 MPa for fine-grained soils and between 50 and 130 MPa for coarse-grained soils.

The best correlations obtained between DCPI and EV_2, are:

$$EV_2 = 199.17\left(DCPI_{600}\right)^{-0.42} \qquad \text{coarse-grained soil} \qquad (7)$$

$$EV_2 = 310.22\left(DCPI_{400}\right)^{-0.80} \qquad \text{fine-grained soil} \qquad (8)$$

These correlations are very useful, especially in situations similar to those described above. However, an additional effort is necessary to obtain more results in order to improve the robustness of the relations.

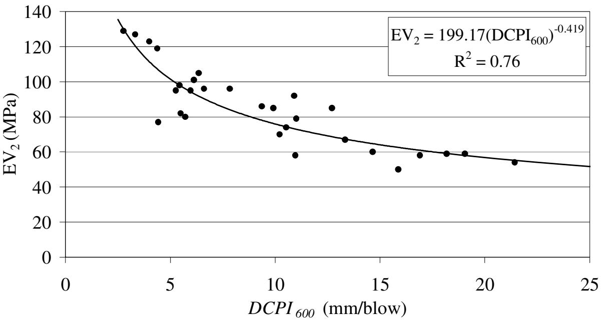

Figure 6. Relation between $DCPI_{600}$ and EV_2 for coarse-grained soils

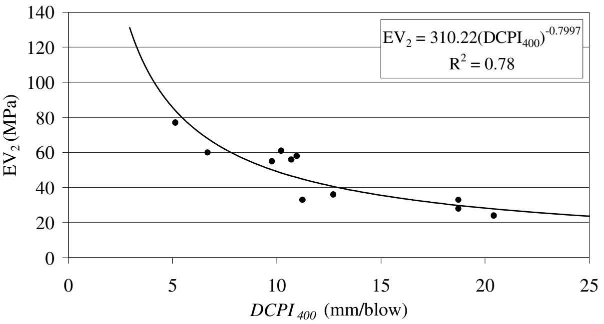

Figure 7. Relation between $DCPI_{400}$ and EV_2 for fine-grained soils

4 CONCLUSIONS

When the design studies for the renewal of ancient railway tracks are undertaken, it is of utmost importance to characterize the stiffness of the existing platform in order to design the new capping and sub-ballast layers. The deformation modulus from the PLT is a reference parameter in this context. However, it is not possible to support the design options just on this type of test, particularly when the railway line is being operated. Then, the use of expeditious tests, such as the DCP, is attractive.

During the renewal of the most important railway track in Portugal, it was possible to establish fairly good correlations between the average resistance to penetration of the DCP and the subgrade deformation modulus from Plate Load Tests. The correlations are more robust when coarse-grained and fine-grained soils are separately considered.

In order to correlate DCPI with EV_2, it is suggested that the representative value of the subgrade DCPI at each test site be calculated as an average value between the ground surface and a depth equal to the plate diameter of the PLT.

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REFERENCES

AASHTO American Association of State Highway and Transportation Officials M 145. 1995. Classification of soils and soil-aggregate mixtures for highway construction purposes. Standard Specifications for Transportation Material and Methods of Sampling and Testing.

AFNOR Association Française de Normalisation. 2000. NF P 94-117-1 – Soils: investigation and testing. Formation level bearing capacity. Part 1: plate test static deformation module (EV_2).

Amini, F. 2003. Potential applications of dynamic and static cone penetrometers in MDOT Pavement Design and Construction, Report FHWA/MS-DOT-RD-03-162, Jackson State University, Jackson, Mississippi.

Brown, A. 1999. In-situ assessment of unbound granular materials for performance based specifications. Proc. of Int. Workshop on Modelling and Advanced Testing for Unbound Granular Materials. Lisbon, pp. 135-140.

Chen, J.; Mustaque, H. & LaTorella, T. 1999. Use of falling weight deflectometer and dynamic cone penetrometer in pavement evaluation, TRR 1655, Transportation Research Board, National Research Council, Washington, D.C., pp. 145-151.

Chua, K. 1988. Determination of CBR and elastic modulus of soils using a portable pavement dynamic cone penetrometer. Penetration Testing 1988, ISOPT-1. Rotterdam: Balkema, pp. 407-414.

De Beer, M. 1991 Use of the Dynamic Cone Penetrometer (DCP) in the Design of Road Structures, Tenth African Regional Conference on Soil Mechanics and Foundation Engineering, Maseru, Lesotho, September 1991. Geotechnics in the African Environment, Blight, et al (eds.). Rotterdam: Balkema, Vol. 1, pp. 167-183.

Fortunato, E. 2005. Renewal of Railway Platforms. Studies about Bearing Capacity. Ph.D. thesis, Faculty of Engineering, University of Porto, Portugal (in Portuguese).

Fortunato, E.; Bilé Serra, J. & Marcelino, J. 2007. Application of spectral analysis of surface waves (SASW) in the characterisation of railway platforms. Int. Conference on Advanced Characterization of Pavement and Soil Engineering Materials. Athens.

Gabr, M., Coonse, J. & Lambe, P. 2001. A potential model for compaction evaluation of Piedmont soils using dynamic cone penetrometer (DCP), Geotechnical Testing Journal, GTJODJ, Vol. 24, No. 3, September, pp. 308-313

George, K. & Uddin, W. 2000. Subgrade Characterization for Highway Pavement Design. FHWA/MS-DOT-RD-00-131, Final Report. The University of Mississippi.

Gomes Correia, A. 2001. Soil mechanics in routine and advanced pavement and rail track rational design. Geotechnics for Road, Rail Tracks and Earth Structures. Rotterdam: Balkema, pp. 165-187.

Jayawickrama, P.; Amarasiri, A. ; Regino P. 2000. Use of dynamic cone penetrometer to control compaction of granular fill. TRR 1736, Transportation Research Board, National Research Council, Washington, USA, pp. 71-80.

Konrad, J-M.; Lachance, D. 2000. Mechanical properties of unbound aggregates from DCP and plate load tests. Proc. of the 5th Int. Symposium on Unbound Aggregates in Road. Nottingham, pp. 225-229.

Livneh, M.; Ishai, I. & Livneh, N. 1995. Effect of vertical confinement on dynamic cone penetrometer strength values in pavement and subgrade evaluations. TRR 1473, Transportation Research Board, National Research Council, Washington, pp. 1-8.

Ping, W.; Yang, Z.; Liu, C.; Dietrich, B. 2001. Measuring resilient modulus of granular materials in flexible pavements. TRR 1778, Transportation Research Board, National Research Council, Washington, D.C., pp. 81-90.

Quibel, A. 1999. New *in situ* devices to evaluate bearing capacity and compaction of unbound granular materials. Proc. of Int. Workshop on Modelling and Advanced Testing for Unbound Granular Materials. Lisbon, pp. 141-151.

Rahim, A. M. & George, K. P. 2002. Automated dynamic cone penetrometer for subgrade resilient modulus characterization, TRR 1806, Transportation Research Board, National Research Council, Washington, D.C., pp. 70-77.

UIC Union Int. des Chemins de Fer. 1994. Ouvrages en terre et couches d'assise ferroviaires. Code UIC 719R, 2ème édition.