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Development of a New Dynamic Lightweight Penetrometer for the Determination of Mechanical Properties of Fine-Grained Soils

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Abstract: Dynamic cone penetrometer is mainly used as an in situ device and laboratory application, in a mould, has rarely been reported due to the confining effect. In this study, a dynamic lightweight cone penetrometer that can be used in a CBR (California bearing ratio) mould in the laboratory as well as in the field, with similar results, was developed. The results show that the influence of the mould confinement can be eliminated when the hammer mass is 2.25 kg. A strong correlation was found between CBR values and the new dynamic lightweight penetrometer index, for six fine-grained soil samples, with different moisture contents, used in this study.

Key words: Dynamic cone penetrometer, fine-grained soils, light penetrometer, pavement materials, CBR.

1. Introduction

DCP (dynamic cone penetrometer) has been used for many years as an in situ device to assess and monitor the characteristics of pavement materials (Scale [1]). The standard DCP described in the Australian Standard, AS 1289.6.3.2 [2], consists of a 16 mm steel rod, to which a steel cone with a 20 mm base diameter and 60° cone tip is attached. The DCP is driven into the soil by a 9 kg hammer with a falling height of 510 mm. In testing, the DCP is held vertically to the surface of the soil to be tested and two operators are required. One person is to hold the device, lift the hammer to the stop and drop the hammer freely onto the anvil to drive the DCP into the soil and another one is to record the readings. The accumulative number of blows and penetration depth is recorded during the operation. The slope of the curve defining the relationship between the penetration depth and number of blows is described as the DCPI (dynamic cone penetration index) in mm/blow.

Generally speaking, the DCP is an inexpensive, portable and easy to operate instrument. However, performing the DCP experiment can be labour intensive due to the heavy hammer. Parker and Hammons [3] proposed an idea for an automated dynamic cone penetrometer. Basically, the set up consists of a vertical frame with wheels for lifting and dropping the hammer. The results are collected automatically by a data logger. In a similar attempt, Webster et al. [4] at the US Army Corps of Engineers proposed the dual mass dynamic cone penetrometer, a modified version of the DCP with 8 kg hammer [5]. In the dual mass dynamic cone penetration device, the hammer weight decreased to 4.6 kg. This mass for the hammer reduces the DCPI by half of that of the original DCP with a mass of 8 kg. With the same objective, Fumio et al. [6] also developed an automated data collection system for portable DCP with a hammer mass of 3 kg. However, this use was limited to field surveys and no information was mentioned about the laboratory application.

It is true that the DCP was mainly designed for field conditions. The application of DCP in the laboratory has rarely been reported, and it may be due to the effect

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of the lateral confinement. When performing the DCP in laboratory conditions inside a compaction mould or a CBR mould, the confining effect becomes very significant and the results will not be comparable with those obtained in the field. The objective of this investigation was to study the effect of the confinement of a CBR mould on the DCP test results and develop a light DCP that can be used in the laboratory, in the CBR mould, as well as in the field for the determination of CBR, and other soil parameters, for fine-grained subgrade soils.

2. Materials and Methods

2.1 Physical Properties of Experimental Soils

The experimental fine-grained soils were collected from different suburbs in Melbourne, Victoria. The physical properties of the soils were determined according to the Australian Standards. A summary of the soils properties measured is presented in Table 1.

2.2 Laboratory Test Procedure

The testing program consisted of two stages. The first stage was the development of the new lightweight DCP that can be used in the laboratory and in the field. The second stage was the investigation of the

relationship of CBR and the DLP (new lightweight DCP index).

In the first stage, two sets of DCP tests were performed on compacted S1 (soil 1) in M1 (mould 1) and M2 (mould 2), as shown in Fig. 1. The soil was compacted, in both moulds, with OMC (optimum moisture Content) (19.5%) and the same density was produced in order to achieve comparable data.

The main purpose for using the large mould was to simulate the field conditions by eliminating the confining effect of the wall of the mould on penetration results. The fundamental background to simulate the field condition comes from the conclusion of Abu Farsakh et al. [7] and Mohammadi et al. [8]. In their investigation of the effect of the mould sidewalls on the DCP test results, they proposed that the minimum distance between the cone tip and the edge of the testing mould should be 250 mm in order to completely eliminate the mould size effect.

Technically speaking, the hammer mass has a significant impact on the value of DCP index. Therefore, a wide range of hammers, including 2.5, 3.5, 4.6, 6.0, 8.0 and 9.0 kg was selected and used in the current work. The range of hammers was selected based on the literature review and after some trial

Table 1 Physical properties and compaction results of soil samples used in this study.

Sample No.	Sample location	USCS symbol	OMC (%)	MDD (t/m ³)	LL (%)	PL (%)	PI (%)
S-1	Deer park bypass, deer park	CL	19.5	1.49	25.3	18.2	7.1
S-2	Featherbrooke estate, point cook	CL	26.8	1.41	39.1	24.1	15.0
S-3	Waverley park estate, Mulgrave	CL	20.1	1.57	31.8	22.1	9.7
S-4	Garnet street, Ferntree gully	CH	22.9	1.67	56.0	23.4	22.6
S-5	Kingsley avenue, point cook	CL	19.6	1.52	25.4	13.7	11.7
S-6	Processed quarry by-product	SC	17.0	1.81	31.0	21.0	10.0



Fig. 1 DCP test in the CBR mould (M1) and in the 700 mm × 700 mm × 700 mm mould (M2).

experiments. For example, the selection of 9 and 8 kg hammers are from the AS 1289.6.3.2 [2] and ASTM D6951 [5], respectively. Moreover, the 4.6 kg hammer is from Webster et al. [4] at the US Army Corps of Engineers. In this stage, all penetration tests were conducted with the Australian dynamic cone penetrometer with different hammer masses (AS 1289.6.3.2 [2], steel cone-30 degrees angle, 20 mm diameter rod, 510 mm drop height).

In the second stage, CBR tests and penetration tests using the newly developed lightweight DCP have been carried out on all compacted soil samples in a CBR mould. For the CBR and penetrometer tests, different moisture content was used as shown in Table 3. The compaction effort was kept constant throughout testing. Each specimen was tested only once at each varying moisture content due to time constraints. A total of 24 CBR tests and 24 lightweight DCP test was performed.

3. Results and Discussions

The results of the DCP tests in mould M1 and M2 are summarised in Table 2 and illustrated in Fig. 2 [9].

The results show that DCPI values are significantly higher for the larger hammer masses and the difference in DCPI values from the small and large moulds increases with the increase in the hammer mass. The differences clearly show the confining effect of the CBR mould (M1) on the DCP test results with different hammer masses.

Furthermore, the difference in value of DCPI reduces to an insignificant value for a hammer mass of less than 2.5 kg, for the experimental soil, and a number of tests carried out in this study. It means that the results of a DCP test in a CBR mould in the laboratory will be almost similar to the results from a DCP test in the field using the same hammer for the

Table 2 DCPI for mould M1 and mould M2.

Hammer mass (kg)	DCPI in mould M1 (mm/blow)	DCPI in mould M2 (mm/blow)	The difference of DCPI, in Mould 1 and Mould 2 (mm/blow)
9.0	14.3	25.5	11.2
8.0	10.6	17.3	6.7
6.0	6.9	11.7	4.8
4.6	5.2	8.6	3.4
3.5	3.7	4.7	1.0
2.5	2.3	2.4	0.1

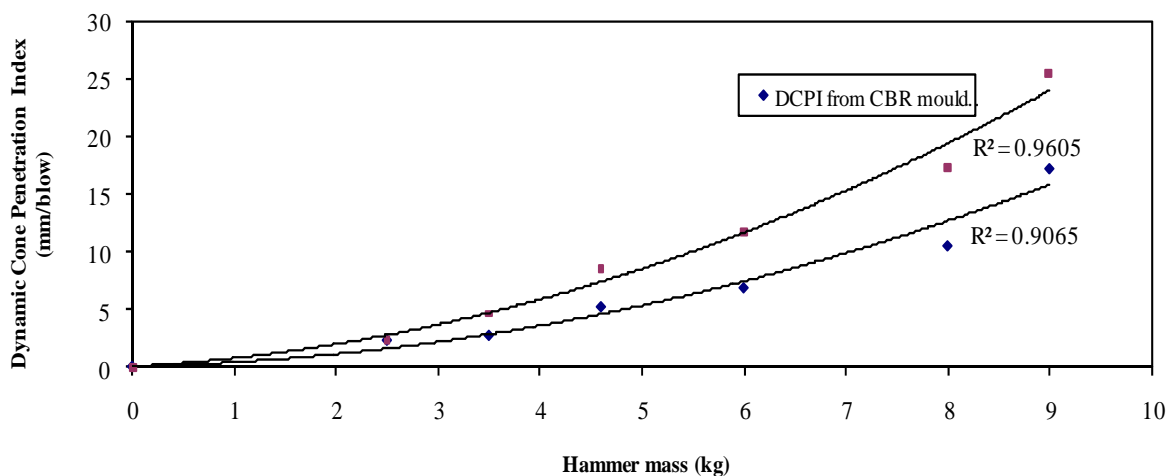


Fig. 2 DCPI vs. hammer mass for mould M1 and M2 for soil S-1 used in this study.

same soil conditions. Based on these findings, the optimised mass for the hammer of the new lightweight DCP can be selected as 2.25 kg, which eliminates the influence of the confining pressure from the sidewall in a CBR mould.

In the second stage, DCP and CBR experiments were performed with different soil samples at different moisture contents. The summary of dynamic light penetrometer (DLP) and CBR results are presented in the Table 3.

Based on the literature review, the most widely accepted model for representing the correlation between CBR and the field DCP index is in the format of a log-log relationship. In this study, a variety of correlations such as linear, power and exponential were examined and the log-log regression relationship gave the highest value for the coefficient of determination (R^2).

$$\text{Log[CBR]} = 1.647 - 1.06 \times \text{Log[DLP]} \quad R^2 = 0.87 \quad (1)$$

where, CBR = California bearing ratio (%)

DLP = new lightweight dynamic cone penetration index (mm/blow)

Fig. 3 shows this relationship for all experimental soil samples used in this study.

Fig. 3 and equation 1 show that there is a strong correlation between DLP and CBR for the soils used in this study at different moisture contents. The major advantage of using the new lightweight penetrometer is that the relationship shown in Fig. 3 can be used in the laboratory as well as in the field for the evaluation of CBR of a soil with similar results. All the correlations reported in the literature can only be used with the standard DCP in the field.

Table 3 DLP and CBR values for soil sample S-1, S-2, S-3, S-4, S-5 and S-6.

Sample No.	Moisture Content (%)	DLP (mm/blow)	CBR (%)	Comments
S-1	19.5	2	20	OMC
S-1	23.0	3	7	Wet of OMC
S-1	17.0	2	19	Dry of OMC
S-1	29.0	10	5	Soaked condition
S-2	26.8	3	14	OMC
S-2	30.0	6	5	Wet of OMC
S-2	24.0	5	8	Dry of OMC
S-2	37.0	11	2	Soaked condition
S-3	20.1	2	26	OMC
S-3	23.0	5	5	Wet of OMC
S-3	17.0	2	21	Dry of OMC
S-3	27.0	11	3	Soaked condition
S-4	20.4	1	35	OMC
S-4	23.0	6	12	Wet of OMC
S-4	18.0	2	31	Dry of OMC
S-4	27.0	8	4	Soaked condition
S-5	17.5	2	27	OMC
S-5	20.0	3	25	Wet of OMC
S-5	15.0	3	24	Dry of OMC
S-5	24.0	26	2	Soaked condition
S-6	17.0	2	27	OMC
S-6	19.0	10	3	Wet of OMC
S-6	14.5	5	11	Dry of OMC
S-6	19.5	12	3	Soaked condition

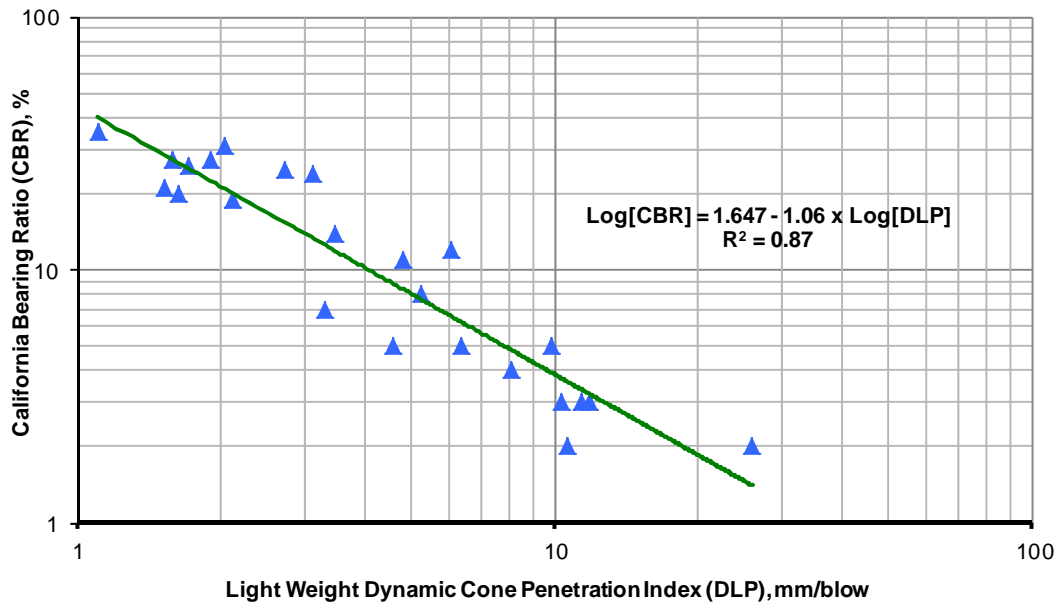


Fig. 3 Log[CBR] versus Log[DLP] for soil sample S-1, S-2, S-3, S-4, S-5 and S-6.

4. Conclusions

The objectives of this study were to develop a lightweight DCP that can be used in a CBR mould in the laboratory as well as in the field, with similar results for the same fine-grained subgrade soil, and to investigate the relationship of CBR and the new dynamic lightweight penetrometer index. The experimental program consisted of two stages. In the first stage, two sets of DCP tests were performed on a compacted soil, one in a standard CBR mould and the other in a large cubic mould (700 mm × 700 mm × 700 mm). The soil was compacted at the same moisture content and the same density in the small and large moulds to achieve comparable results for DCP testing. A wide range of hammer masses, including 2.5, 3.5, 4.6, 6.0, 8.0 and 9.0 kg was used in the study, with the Australian standard dynamic cone penetrometer. In the second stage, the CBR and new lightweight DCP tests were carried out for six soil samples at different moisture contents.

The results show that DCPI values are significantly higher for the larger hammer masses and the difference in DCPI values from the small and large moulds increases with the increase in the hammer mass. The differences clearly demonstrate the confining effect of

the CBR mould on the DCP test results. Therefore, a new lightweight penetrometer with 2.25 kg hammer that can be used in a CBR mould in the laboratory as well as in the field with similar results for the same soil is proposed. A strong correlation ($R^2 = 0.87$) has been found and established between CBR and the new lightweight DCP index. More experimental works will be conducted to confirm the findings in this study and further authentication.

Notation

- CBR: California bearing ratio (%)
- DCP: dynamic cone penetrometer
- DCPI: dynamic cone penetrometer index (mm/blow)
- DLP: new lightweight dynamic cone penetration index (mm/blow)
- HM: hammer mass (kg)
- LL: liquid Limit (%)
- M1: CBR mould
- M2: large mould 700 mm × 700 mm × 700 mm
- MDD: maximum dry density (t/m^3)
- OMC: optimum moisture Content (%)
- PI: plasticity index (%)
- PL: plastic limit (%)
- USCS: Unified Soil Classification System

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