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Applying the Dynamic Cone Penetrometer (DCP) Design Method to Low Volume Roads

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Abstract. The Dynamic Cone Penetrometer (DCP) is a simple, cheap and effective apparatus for assessing the bearing capacity of in situ materials for the design of new roads or the upgrading of unsealed or existing sealed roads. Although a number of methods have been described for the use of the DCP for the design of low volume roads, no comprehensive method has been published. This paper summarizes the investigation, analysis and design techniques for application of this very useful and cost-effective design method taking into account traffic and environmental conditions. Use of the method is illustrated by actual design examples.

Keywords. Dynamic Cone Penetrometer, road, pavement, design

Introduction

The Dynamic Cone Penetrometer (DCP) [1] has been in use since the 1950s for various applications in pavement investigation [2]. During the 1980s, Kleyn and Van Zyl [3] described a method for upgrading unsealed roads to light sealed road standard based on in situ testing using the DCP. Although this is a simple, cheap and effective method for assessing the bearing capacity of in situ materials for the design of new roads or the upgrading of unsealed or existing sealed roads, a fundamental understanding of the in situ conditions is essential. A number of methods of use have been described and applied for the use of the DCP for the design of low volume roads, but no comprehensive method has been published. This paper summarizes the fundamentals, investigation, analysis and design techniques for application of this very useful and cost-effective design method taking into account the prevailing material, traffic and environmental conditions. Use of the method is illustrated by two actual design examples.

1. Background

The DCP is a highly cost effective technique for acquiring large quantities of data on sub-surface material strength and thickness quickly and essentially in a non-destructive process. However, the strength information acquired is related directly to the in situ moisture and density conditions at the time of the investigation. Although the dry density of the in situ materials is relatively constant over time, the wet density of the materials beneath unsealed roads varies almost continuously with time and this is manifested in the in situ strength estimated from the DCP data. As the in situ strength is directly and inversely proportional to the density and the moisture content, respectively (i.e. the in situ strength increases with increasing density and decreases with increasing moisture content), it is essential, although difficult, that these relationships are considered during the pavement design process. The designer should preferably be on site during the DCP investigation.

1.1. *Moisture content*

Estimation of the moisture content at the time of testing can be difficult. Although it is recommended that samples are taken for gravimetric moisture determination, this is usually only practicable for the upper and possibly the second 150 mm layer without excavating large holes. Kleyn and Van Zyl [3] described the classification of the overall moisture regime at the time of DCP testing in terms of the expected moisture levels that will prevail during the service of the road. This can be effective as a general classification and the percentile of the determined strengths selected for the analysis will be based on this (see example).

This should be considered in the light of the potential equilibrium moisture content of the completed road [4] bearing in mind that the outer edges of the road will be subjected to seasonal fluctuations in moisture content.

A method for estimating the material G-class [5] based on the DCP penetration rates and the estimated moisture content was developed in 1985 [6] and improved in 1992 (Table 1) [7]. The use of this method requires a visual estimate of the field moisture content at the time of DCP testing but also has the limitation of assuming that the subgrade moisture content is uniform and is a direct function of the climate. Excavation of holes into the wearing course and underlying layers and extraction of samples for laboratory moisture determination would be highly beneficial.

Table 1. Estimate of material G-class from DCP results

Material classification	Soaked CBR	Approximate field DCP-CBR: gravel roads					
		Subgrade		Wearing course			
		Wet climate	Dry climate	Very dry state	Dry state	Moderate state	Damp state
G4	80	-	-	260	205	151	96
G5	45	-	-	188	148	109	69
G6	25	56	66	146	115	85	54
G7	15	52	62	137	108	79	50
G8	10	39	46	101	80	59	37
G9	7	38	44	-	-	-	-
G10	3	35	41	-	-	-	-

Use of Table 1 without actual moisture content determinations requires an estimate of the moisture content in terms of the optimum moisture content (OMC) for the materials. This can usually be obtained by experienced engineers based on squeezing a sample of the material in one hand and assessing the “cohesion”. At OMC (damp) the material can be squeezed into a “sausage” that remains intact. In the very dry state (less than about 25% of OMC), the material is dusty and loose and has absolutely no cohesion. In the dry state (about 50% of OMC), the material will have no cohesion when squeezed into a sausage whereas in the moist state (about 75% of OMC), the material may just be squeezed into a sausage but will be friable and break easily. The expected subgrade equilibrium moisture contents for wet and dry climates are about 95 and 90% of OMC respectively.

1.2. *In situ density*

The in situ density obviously affects the DCP penetration rate considerably. This is a difficult parameter to estimate during the DCP survey, but on an existing unsealed road, it can be assumed that there has been some traffic compaction over time, probably to at least that normally specified for a subgrade or even subbase under a sealed road. It is thus possible to relate the densities to the expected final pavement structure. If the road is to be widened, however, it is usually necessary to carry out testing adjacent to the road to assess the strength of the uncompacted in situ material. This, of course, can also be done to assess the effect of traffic compaction on the material density by comparing DCP penetration rates of obviously un-trafficked material adjacent to the existing road with trafficked material under the road.

2. Design process

2.1. *Traffic determination*

As in any pavement design, the cumulative traffic over the design life of the road should be estimated. This estimate is much more difficult for low volume roads (less than about 300 000 equivalent standard axles (E80s) as the heavy vehicles during short periods of intensive traffic (eg, during agricultural harvesting seasons or temporary delivery seasons for mining produce) are often difficult to estimate accurately. Short periods of heavy traffic also have a disproportionate influence on the overall traffic of low volume roads. As the traffic estimate will directly influence the pavement design, this should be done as carefully as possible, taking into account such issues as the potential for overloading.

2.2. *Required pavement structure*

The required pavement structure will usually be determined from available catalogues [8] [9] [10], or for very low traffic roads (less than about 50 000 E80s) from past experience or comparison with other similar roads. This should provide an indication of the number and strengths of the different layers as well as the individual layer thicknesses at the expected worst moisture condition in the road. In the two cases shown in the examples, the proposed structural design included 100 mm G4 base, 125 mm G6 subbase and 150 mm G9 support. From this, the necessary layer strength diagram (LSD) can be constructed. This relates the individual layer strengths to the CBR for that layer as shown in Fig. 1. The plots are for the standard soaked CBR design as well as the required LSDs for different DCP test moisture conditions based on Table 1.

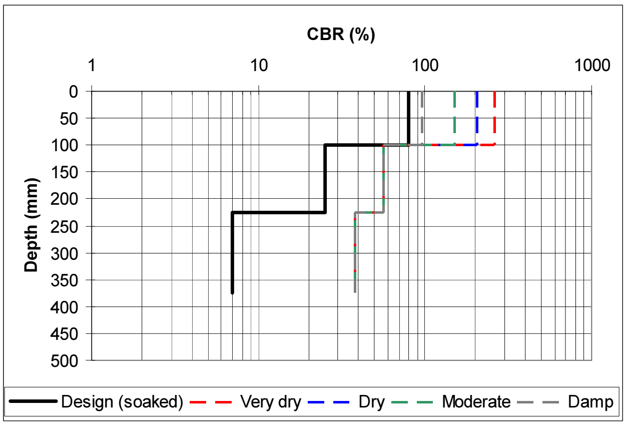

Figure 1. Layer strength diagram for road with 30 000 to 100 000 E80 design traffic and different moisture conditions.

2.3. *DCP survey*

2.3.1. Depth, interval and number of DCP tests

The DCP survey will be carried out to a depth of at least 450 mm but preferably to at least 600 mm, the so-called material depth of the pavement [8]. It is recommended that DCP testing is carried out at 200 m intervals with additional testing in any obviously problematic areas (e.g., wet, cracked). In relatively uniform areas, testing at up to 500 m intervals could be accepted. In general a minimum of about 10 tests per uniform section should be carried out.

2.3.2. Moisture conditions

The moisture conditions at the time of the DCP survey need to be carefully estimated as discussed in Section 1.1. As the moisture content at the time of testing determines the in situ strength at that time, this needs to be carefully assessed and preferably supported by laboratory determinations of the moisture content. This will relate to which of the curves in Figure 1 will be used for the design.

2.3.3. Uniform sections

The road should then be divided into uniform sections based on the DCP results. Various techniques are available for this, but it has been found that the cumulative sum technique [11] is simple and appropriate. This involves determining the average DCP CBR for all of the results (for each 150 mm layer tested), subtracting the individual results from the average and then summing these. A plot of the results will show inflection points where each section changes (see example).

Once the uniform sections have been identified, each of these will need a specific pavement design or treatment.

2.4. *Pavement design*

The pavement design process needs to fit the pavement structure (Fig.1) to the in situ conditions on each uniform section determined from the DCP survey as shown in Section 3 (Figure 2). Where the in situ strength is less than the design strength, improvement of the material needs to be carried out. The method should try and fit the pavement design to the available structure as far as possible, without importing additional material.

2.5. *Specific treatments*

To minimize costs, use of the in situ material in all of the layers should be considered. However, mechanical treatment of the in situ materials such as ripping and re-compaction may not always be sufficient for the proposed pavement design and some other form of treatment or stabilization may be necessary. This could range from removal and replacement, heavy compaction or mechanical or chemical stabilization. Indications of the need for treatment will be obtained from the DCP results when particularly poor material properties in the upper layers are identified.

3. Examples

Examples of the use of the DCP design technique for the upgrading to sealed standard of two existing gravel roads are discussed. Different approaches were used for each.

The first road was through a mountainous area in the Western Cape. The second example was for the upgrading of a local access road in the Eastern Cape Province.

The same basic design was proposed for both pavements, which were Category D roads in areas with Weinert N-values of about 8 and 1.8 respectively with a 10 year design life. The estimated traffic was less than 100 000 standard E80 axles for both roads. From TRH 4 [8] this would require a structure of 100mm G4 base over 125 mm G6 subbase. A 150 mm G9 support layer would be required under this. The thickness of the subbase was increased to 150 mm in both cases.

3.1. *Western Cape example*

DCP data from the mountainous pass were all plotted using a computerized DCP code and the mean penetrations for the layers between 0 and 150 mm (proposed subbase), 150 and 300 mm (proposed upper selected) and 300 to 450 mm (proposed in situ subgrade) along the centre-line were determined. It should be noted that only 3 of the 10 penetrations were able to reach more than 450 mm, 4 reached more than 300 mm and 8 reached deeper than 150 mm before reaching refusal. The results obtained are summarized in Table 2 and shown graphically in Figure 2.

Although the road is in a dry area and the testing was carried out at the end of the wet season, the 25th percentile value for the CBR was utilized. This decision was based on the frequent presence of springs adjacent to roads in such mountainous areas. The following conclusions were drawn from the data.

Table 2. Summary of DCP results and statistics

Kilometer point	Depth and DCP-CBR (%) at depth			
	0 – 150 mm	**150 – 300 mm**	**300 – 450 mm**	**Depth of refusal (mm)**
13.4	65	200	200	120
14.66	113	202	200	250
17.16	88	200	200	150
18.16	98	200	200	180
20.89	200	200	200	60
21.89	184	200	200	150
22.89	65	103	64	800
23.39	94	106	45	800
23.89	113	115	200	300
24.7	84	132	190	500
Mean	110	166	170	331
25th percentile	85	119	193	150
75th percentile	113	200	200	450

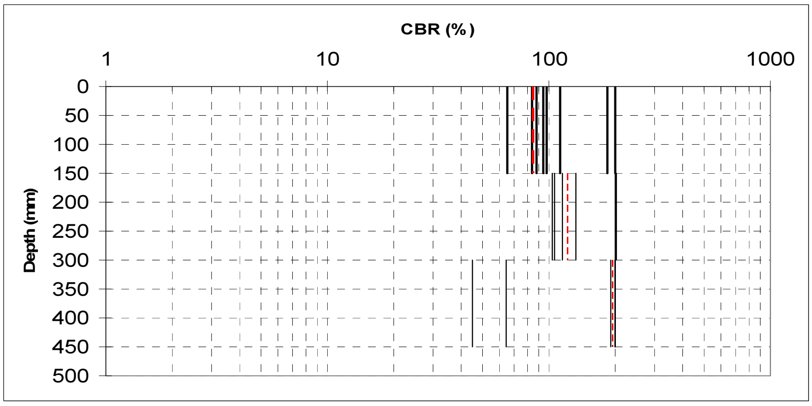

Figure 2. Plot of DCP data (25th percentiles dashed red lines).

300 – 450 mm depth

No problems exist at this depth where a G9 material would be required (minimum soaked CBR of 7%). The minimum average in situ CBR was 45% with a 25th percentile of 193 for the entire road, and generally the material was impenetrable.

150 – 300 mm depth

The proposed upper selected layer requires a G9 (soaked CBR of 7%). The mean CBR was 166 and the 25th percentile 113, indicating adequate materials. The in situ material should, however, be disturbed as little as possible during construction. The cumulative sum analysis (Figure 3) showed two distinct sections (from the start to km 22.0 where refusal was reached, and from there to the end), but both had strengths well in excess of those required (Table 2).

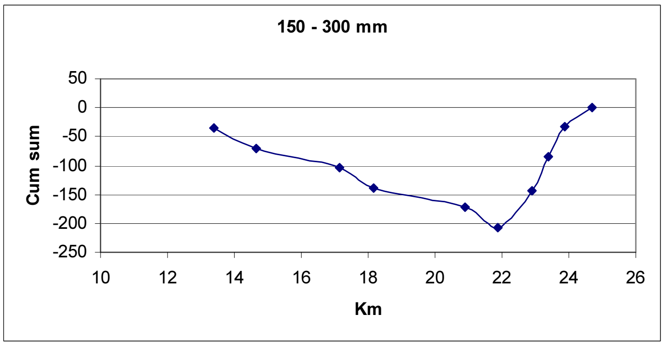

Figure 3. Cumulative sum plot for material at depth of 150 to 300 mm.

0 – 150 mm depth

The proposed subbase material is included in this layer, which showed much more variation than the other layers. A cumulative sum approach was again used to identify uniform sections. It should be noted that it is based on only 10 results and for better definition of uniform sections it would have been advisable to use DCP data along the centre-line from at least 500 m intervals or preferably 200 m intervals.

The results of the cumulative sum analysis (Figure 4) show three distinct uniform sections, probably related to the use of three different borrow pits along the road during recent regravelling operations.

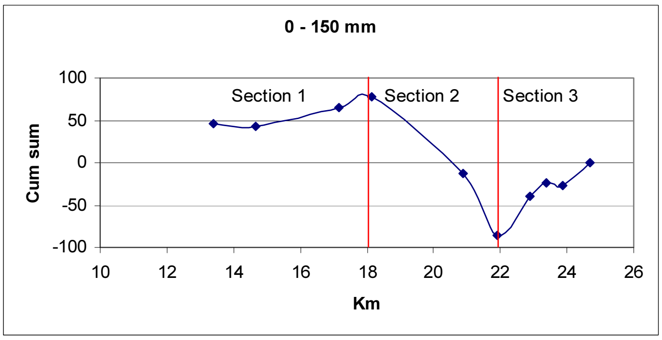

Figure 4. Cumulative sum plot of DCP strengths between 0 and 150 mm depth.

The proposed designs of the three sections were as follows:

- Section 1: km 13.4 – 18.16

This section has an average in situ CBR of 91% (25th percentile of 82) indicative of a suitable G6 subbase material. Local ripping and re-compaction of the upper 75 to 100 mm to refusal was advised in some areas shown by the DCP plots.

- Section 2: km 18.16 – 21.89

This section has an average in situ CBR of 192% (25th percentile of 188) indicative of a suitable G6 subbase material.

- Section 3: km 21.89 - 24.7

This section has an average in situ CBR of 89% (25th percentile of 79) indicative of a suitable G6 subbase material, very similar to the first section. Local ripping and re-compaction of the upper 75 to 100 mm to refusal was advised in some areas.

Base

On top of the sub-structure described above, a base course with a suitable thickness and strength would be necessary. This would typically be 150 mm of G4 or an equivalent layer of stabilized or bitumen treated material.

3.2. *Eastern Cape example*

The length of the road was 20 km and 98 DCP tests were carried out. Although the moisture environment was described as dry during the survey, the testing was carried out during the rainy season and some seepage was seen on bedding planes in the shales and sandstones. Rather to err on the conservative side, the 20th percentile has been used for the CBR estimations (the DCP software used did not allow computation of the 25th percentile).

The DCP data was analyzed in 2-km sections. The standard deviation and percentile values were examined to determine whether the sections were uniform. In all cases the sections were surprisingly uniform with very small standard deviations of the DCP determined CBR. Analysis of the average profile was then carried out using an overlay of the proposed pavement structure and the 20th percentile DCP values for each section. The results are summarized in Table 3.

Table 3. Suitability of existing road cross-section

Chainage	Uniformity	Support layer	Subbase	Base
0.2 – 1.8	√	√	√	X
2.0 – 3.8	√	√	√	X
4.0 – 5.8	√	√	√	X
6.0 – 7.8	√	√	√	X
8.0 – 9.8	√	√	X	X
10.0 – 11.8	√	√	√	X
12.0 – 13.8	√	X	X	X
14.0 – 15.8	√	√	X	X
16.0 – 17.8	√	√	X	X
18.0 – 19.8	√	√	√	X

An analysis of all of the DCP results confirmed the findings of the individual sections. The Redefined Layer Strengths show a G6 subbase quality layer to 192 mm (20th percentile in situ CBR 32%), and generally good support beneath this (20th percentile CBR of 27 to 30% down to 272 mm).

The following designs were thus applied.

Km 0 – 8, 10 – 12 and 18 -20:	Shape existing wearing course Import 150 mm G4 base
Km 8 – 10 and 14 – 18:	Rip and re-compact 150 mm as subbase

	Import 150 mm G4 base
Km 12 – 14:	Windrow top 300 mm of material from road Rip and re-compact underlying 150 mm Mix and replace windrowed material in two 300 mm layers Import 150 mm G4 base

4. Conclusions

The DCP design technique has been shown to be highly appropriate for the design of low volume roads. Testing is quick, cheap and non-destructive. Two roads designed using this technique have been described, the latter having been successfully built to this design 7 years ago. It is, however, important that the designer has a good understanding of the in situ moisture and density conditions at the time of the DCP testing and understands the relationships between the field (design) and laboratory test (standards and specification) results for the materials involved.

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