New age pavement design solutions using stone-age technology

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Introduction

The 2012 Austroads pavement design guides, which have been developed over a number of years, provide comprehensive guidelines for the design and rehabilitation of road pavements. These guidelines, with its appropriate amendments by road authorities, have been well established in Australia and used successfully in the past. These design and rehabilitation methods rely upon good information of the existing pavement structure and condition. In many cases, this information can be obtained by various means, including deflection tests, test pits and laboratory testing.

However, in some cases this information is difficult, or expensive to obtain, particularly for projects in more remote locations. This has been a particular problem following the 2011 Queensland floods, where pavement rehabilitation of short lengths of pavement was required in remote areas spanning a vast area. In the absence of information, designers often assume certain default values based on experience or very limited information. This can often lead to conservative pavement designs to account for uncertainties as a result of a lack of existing pavement information.

This paper presents an alternative pavement rehabilitation design method using the Dynamic Cone Penetrometer (DCP) to assess the quality of the individual pavement layers and develop an appropriate pavement design that would be required for the particular pavement under consideration. The design method, developed in Southern Africa during the 1970's and early 1980's, is fundamentally based on the CBR cover design method, also known as the empirical design method in Austroads. Although the method was developed for traffic volumes up to 10 million Equivalent Standard Axles (ESA's), it has been widely and successfully used on pavement with traffic volumes up to 30 million ESA's. This paper also presents guidelines and case studies for the use of DCP tests to obtain information regarding the existing pavement structure, i.e. pavement layer thickness, variability and in situ layer strength, without the need for expensive testing.

Background

The DCP device was initially developed in Australia by Scala (1956) in response to the need for a simple and rapid device for the characterization of subgrade soil. The device used by Scala included a 20 pound (9kg) hammer with a dropping distance of 20 inches (508 mm) using a 5/8 inch (15.875 mm) rod. A 30 degree cone was used to penetrate 30 inches (762 mm) into the soil. During this study, Scala attempted to determine a correlation between the DCP measurements and CBR. The current standard DCP device as per AS1289 is based on these dimensions.

In the late 1960's, Van Vuuren (1969) continued the development of the device, with some minor differences in the dimensions. A 10 kg hammer was dropped from a height of 460 mm forcing a 30 degree cone connected to a 16 mm rod up to 1 m into the soil. Further correlations between CBR and DCP measurements were made.

During the early 1970's, the former Transvaal Roads Department (TPA) initiate a study to critically assess their current pavement design philosophy by studying the performance of pavements at least 10 years old at the time. The study was to be completed within a year and a simple and quick method to assess the in-situ condition of pavements was required. Due to the good correlation between CBR and DCP measurements, consideration was given to the use of the DCP device during the study (Kleyn: 1975, Kleyn, 1983).

The TPA study developed into the foundation of the DCP pavement design method, a method that was later validated by numerous Heavy Vehicle Simulator (HVS) tests (Kleyn: 1975, Marais et al: 1982, Kleyn, 1984).

Important concepts of the DCP pavement design method

The device

The device used in the TPA study adopted an 8 kg hammer dropped from a height of 575 mm, resulting in a similar amount of energy applied than the current AS1289 device. A 60° cone was also adopted as it was found that the 30° cones often break and become blunt very quickly, while the shorter 60° cone registered variations in material properties within the pavement layer more pronouncedly. Kleyn (1984) compared a large number of measurements between the 30° and 60° cones and determined a reduced equivalent CBR value of around 20% with the 60° cone over the 30° cone.

Pavement layers are more difficult to penetrate than subgrade materials and the device used in the TPA study was required to be more rigid to withstand the stresses induced on it during testing and recovery. Some modifications were required to improve the robustness of the standard device at the time.

Penetrations measurements were taken every number of blows (typically every 10 blows) as opposed to the number of blows per 100 mm penetration. This was to more accurately describe the penetration of the device through the pavement and identify individual layers and change in material properties..

The terminal penetration depth was 800 mm for pavements, a number later confirmed with a large number of HVS tests (Kleyn: 1984).

The DCP curve

The DCP curve is a visual representation of the progress of penetration of the DCP through the pavement as illustrated in Figure 1.

DCP number (DN)

The DCP Number (DN) is the rate of penetration through a specific pavement layer measured in mm/blow. The DN is the slope of the penetration on the DCP curve.

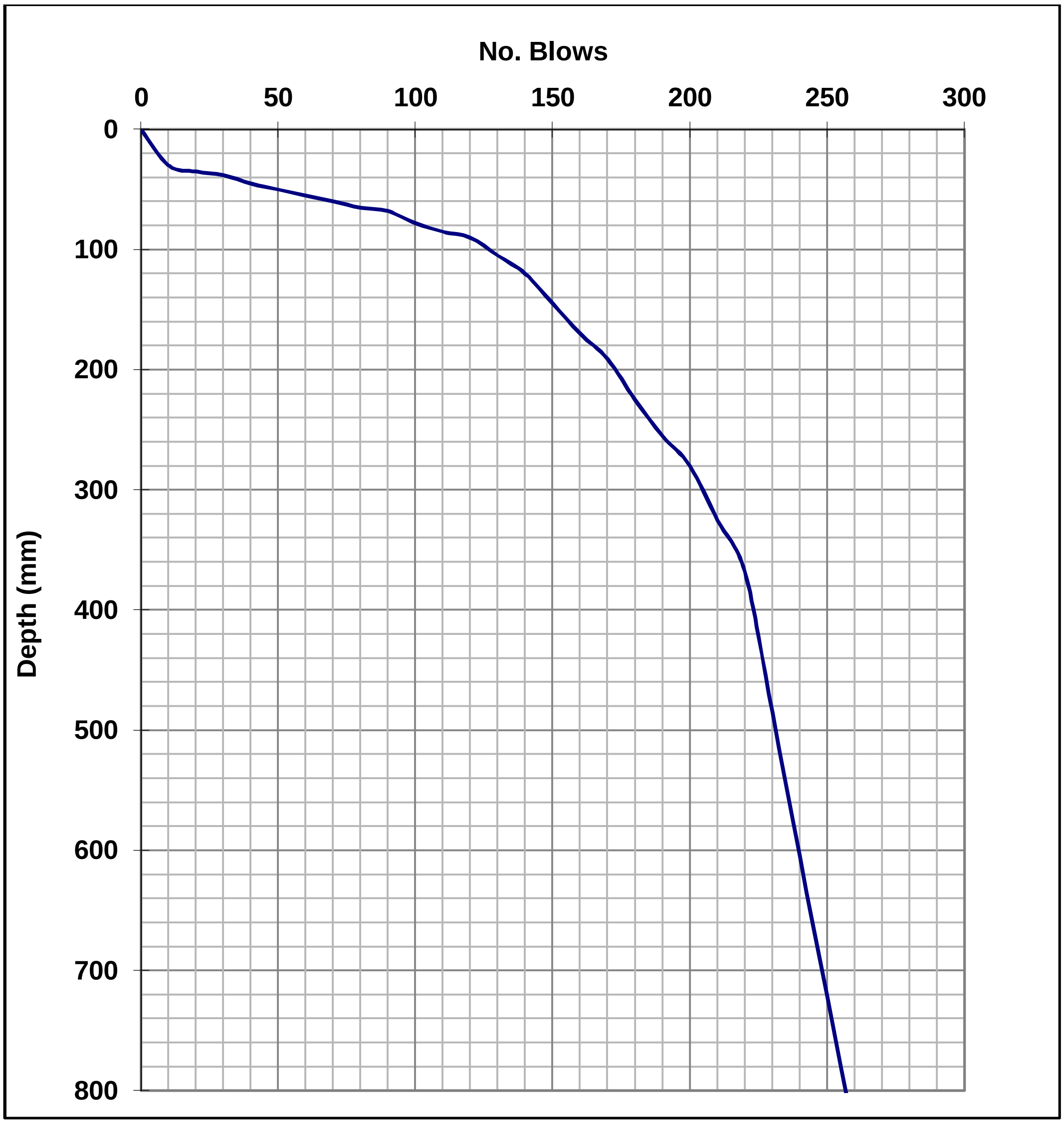

Figure 1. Typical DCP curve

Layer-Strength Diagram

The layer-strength diagram is derived from the DCP curve and is a visual representation of the DN with depth through the pavement structure as illustrated in Figure 2. It is possible to determine and illustrate the correlated in-situ CBR and UCS of a particular pavement layer using the known calibrations between DCP measurements, UCS and CBR. The Layer-Strength diagram can also indicate the required layer strength for a given design traffic loading.

DCP structure number

The DCP structure number is the number of DCP blows required to penetrate through a pavement structure or layer.

The DSN_{800} is the number of blows required to penetrate through a pavement structure up to a depth of 800 mm.

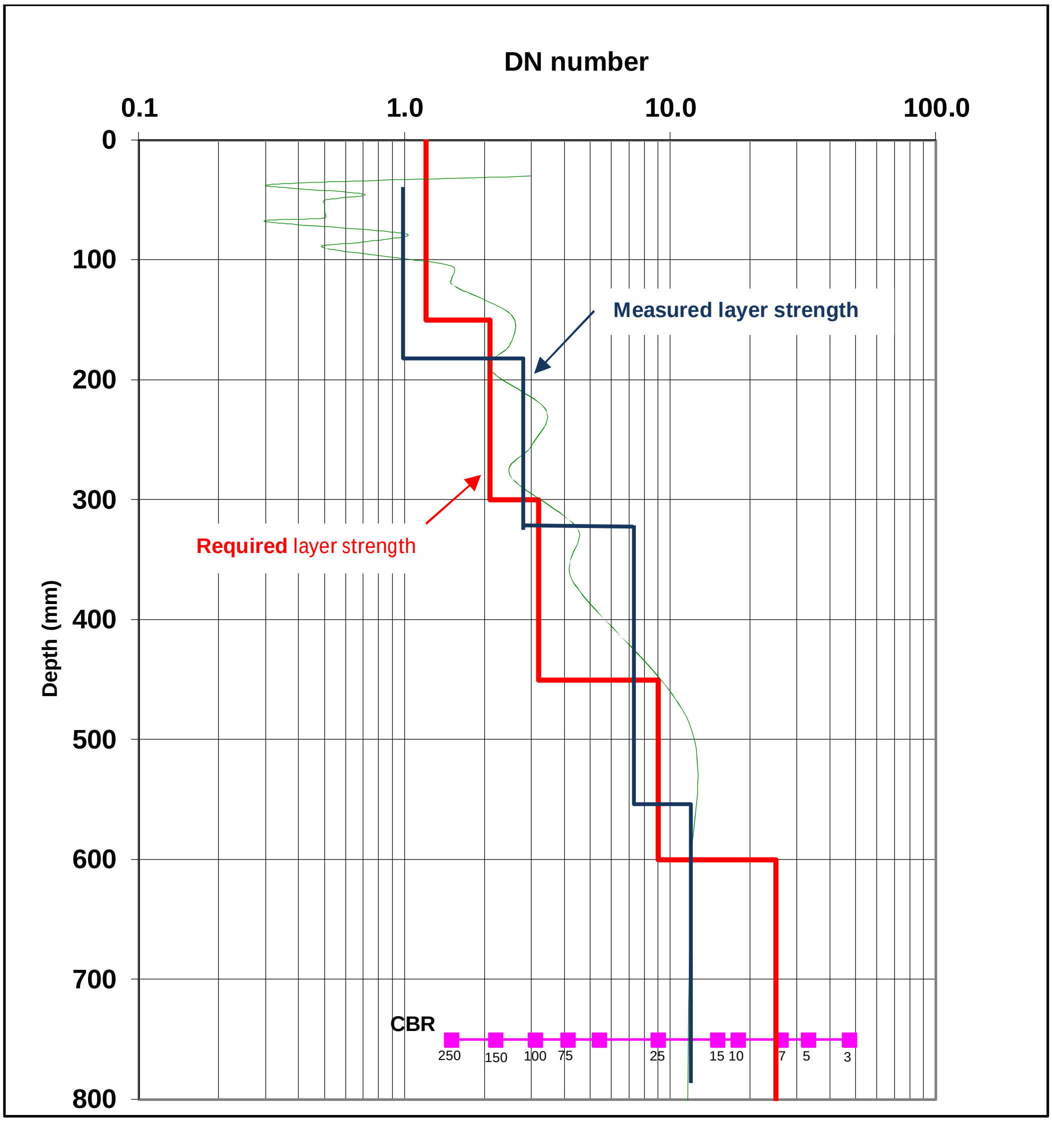

Figure 2. Typical Layer-strength diagram

Pavement strength balance

During the TPA study, Kleyn (1984) discovered that most pavements converge to a particular balance, or distribution of strength throughout the depth of the pavement structure. It became apparent that pavements that follow a particular balance, appear to behave more optimally in terms of performance and that the preservation of the pavement balance in pavement rehabilitation design should be considered.

The number of DCP blows required to reach a certain depth expressed as a percentage of the number of DCP blows to reach a penetration of 800 mm (DCP_{800}), is defined as the Balance Number (BN) at that depth.

The Pavement Balance Number (BN_{100}) is defined as the number that describes the balance of the pavement and is the Pavement Balance at a depth of 100 mm.

A set of standard balance curves are presented in Figure 3. Balance curves for pavements with a pavement balance between the illustrated values can be interpolated.

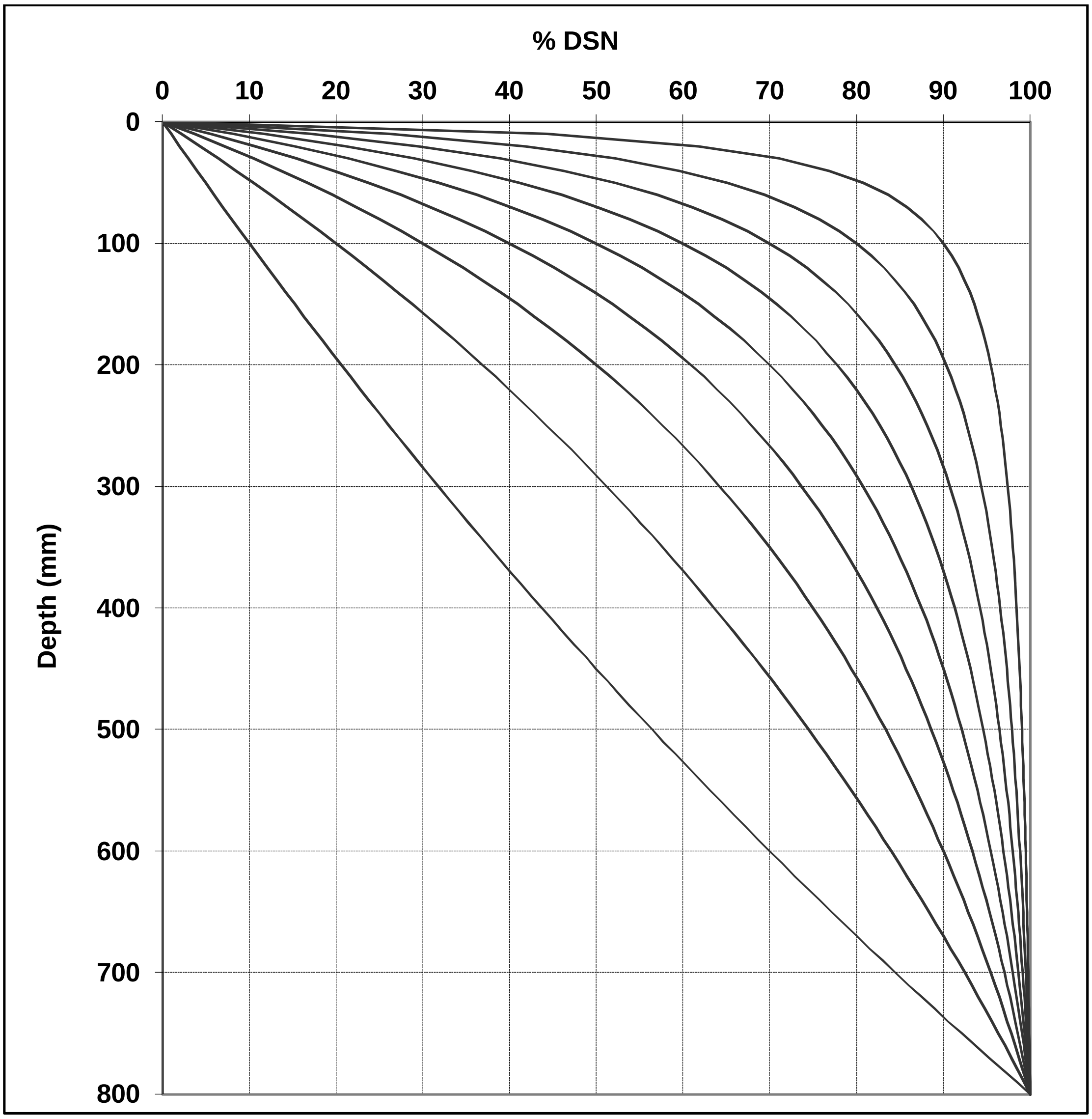

Figure 3. Standard balance curves (Kleyn: 1984)

Pavement strength-balance classification

De Beer et al (1988, 1990) developed a classification system for the strength-balance of thin surfaced flexible pavements and also described pavement behaviour in terms of the pavement strength-balance. Pavements that were well or averagely balanced (i.e followed a particular balance curve relatively closely) was divided into shallow and deep pavements. Pavements that did not follow a particular balance curve closely were classified as poorly balanced and pavements that have more strength in the lower layers than in the upper layers, were regarded as inverted pavements. Deep pavements are pavements that have a more equal distribution of strength throughout the depth of the pavement structure, while shallow pavements have more strength of the pavement towards the upper layers of the pavement. Figure 4 illustrates the typical balance curves of different types of pavements.

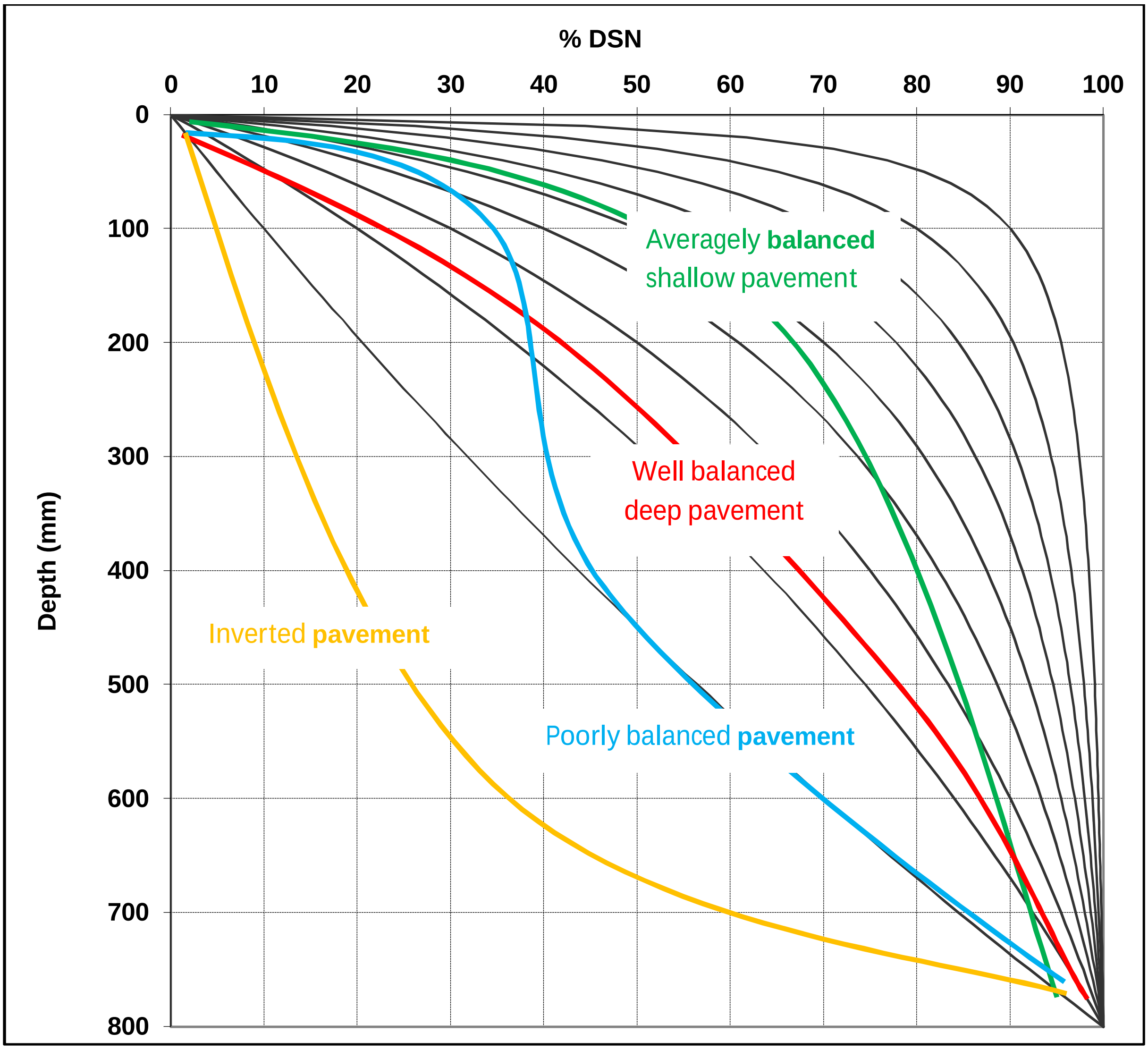

Figure 4. Typical pavement types classified in terms of pavement strength-balance

Principles of the DCP design method

The basic principles of the DCP pavement design method are based on the CBR cover design method, with the most important difference the measurement of in-situ material properties as opposed to laboratory CBR tests. In addition, the DCP design method currently in use in South Africa has been thoroughly calibrated with a large number of HVS and Long Term Pavement Performance (LTPP) tests.

Due to the nature of the test, the DCP is only useful in the analyses and design of pavements consisting of unbound gravel or lightly cemented pavement layers.

DCP data can be analysed and processed using the concepts described in the earlier section to provide an indication of the following:

- The adequacy of individual pavement layers
- The expected behaviour of the pavements

- The identification of individual layer thicknesses and interfaces.

<u>The adequacy of individual pavement layers</u>

By plotting the measured DCP data on a layer strength diagram (Figure 2), an indication of the in-situ CBR of the pavement materials with depth can be determined. This profile may then be compared to minimum specific standards to determine the adequacy of the various pavement layers in depth for the expected traffic loading. This could further assist the pavement designer in determining the existing cause and mechanism of distress in terms of historic cumulative traffic loading.

<u>Pavement behaviour</u>

The strength-balance curve (Figure5) together with the strength-balance classification provides useful information on the expected future behaviour of the pavements. This will allow the designer to evaluate each pavement layer relative to the rest of the pavement structure.

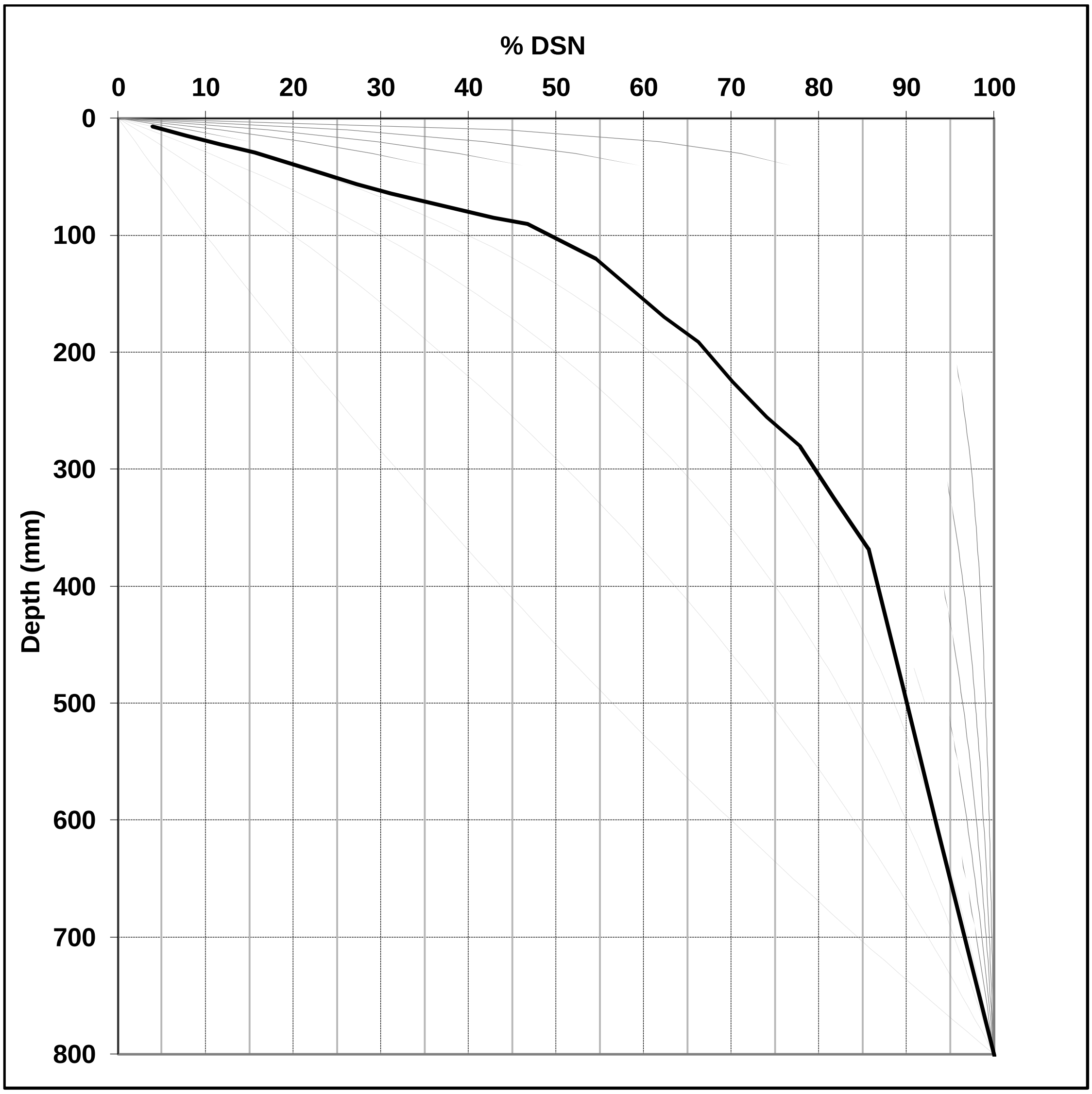

Figure 5. Typical balance curve of a well balanced shallow pavement (BN_{100} = 50)

Unbalanced pavements usually contain layers which are strong or weak relative to the rest of the pavement. These layers can be identified and the potential influence these layers will have on the rehabilitation design can be considered. In addition, this information may also add value in the mechanistic design of pavements, particularly with respect to backcalculations or explaining anomalies encountered during the backcalculation process.

Individual pavement layer thickness

The accuracy of as-constructed data varies considerably and it is often the case that the actual pavement structure varies considerably compared to as-constructed records. The most accurate way to determine individual layer thickness is by test pits, but this is expensive and cannot be repeated at high frequencies. The DCP provides a tool that makes it possible to distinguish between layers of similar quality. A combination between the original DCP curve (Figure 1) and a normalised strength-balance curve (Figure 6) often provide a good indication of individual pavement layer thickness.

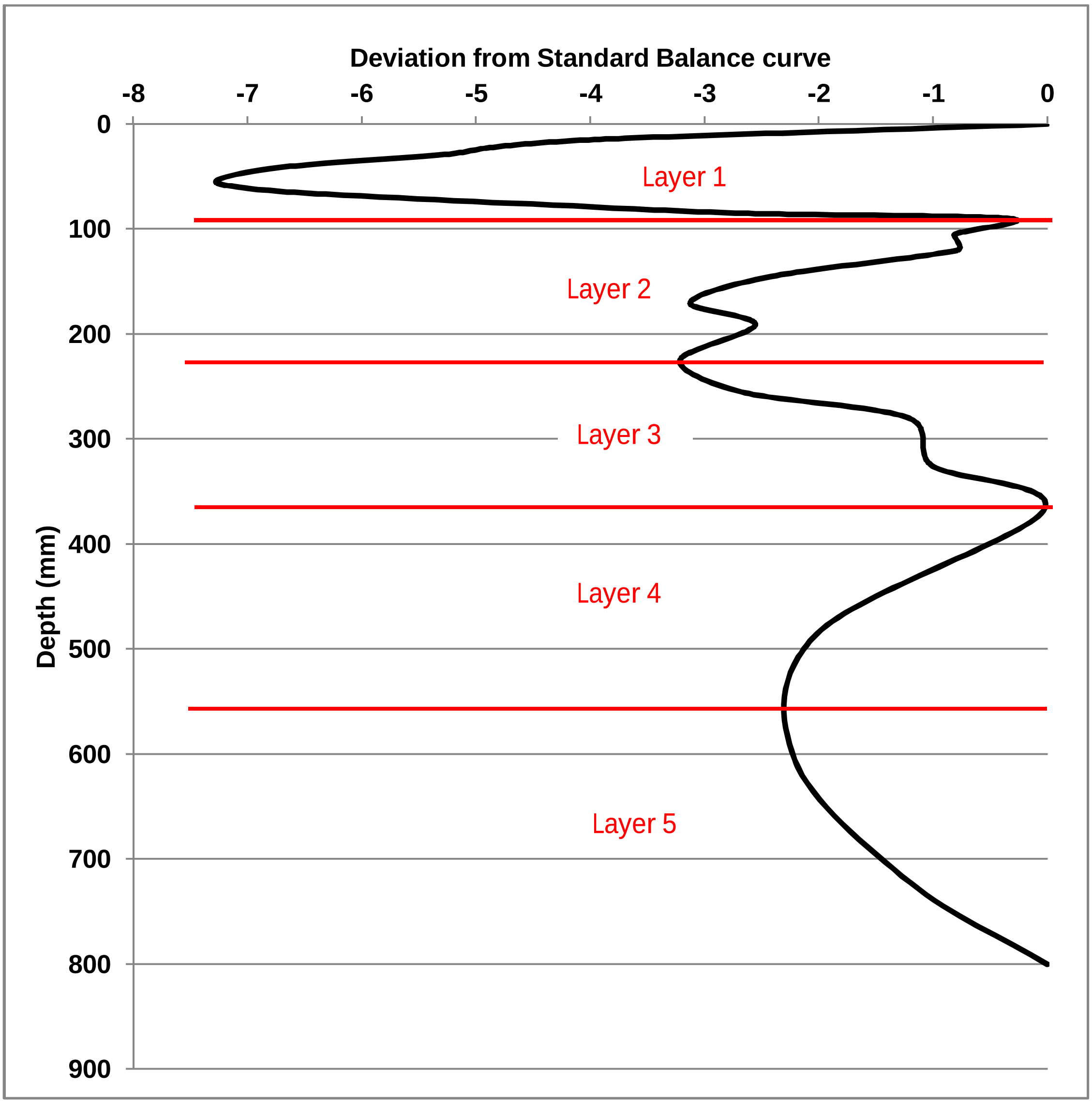

Figure 6. Normalise balanced curve with possible layers indicated

Correlation with CBR and UCS

Correlation between DCP measurements and CBR has been widely published and is still one of the primary uses of the device. Kleyn (1984) reported reasonable correlation between the data he studied and published relationships by Smith et al (1983) and Van Vuuren (1969). The relationship adopted for the DCP design procedure is presented by the following equation:

$CBR = 410 \times DN^{-1.27}$ (for DN > 2 mm/blow) (Eq 1)

where: CBR = In situ correlated CBR

DN = penetration rate (mm/blow)

A relationship between Unconfined Compressive Strength and DCP measurements for lightly cemented materials was developed by de Beer (1993) and the relationship adopted in the DCP design procedure is presented by the following equations.

$UCS = 15.x\ (403.3 \times DN^{-1.259})^{0.88}$ for DN>= 2mm/blow (Eq 2.1)

$UCS = 15 \times (66.66 \times DN^2 - 330 \times DN + 563.33)^{0.88}$ for DN< 2mm/blow (Eq 2.2)

where: UCS = In situ correlated CBR

DN = penetration rate (mm/blow)

Pavement structural capacity

The structural capacity of the pavement is the remaining life of the existing pavement before it reaches a critical level of distress. This is particularly important to determine when, or if, a particular strengthening measure will be implemented, or to assess the capacity of the existing pavement when a non-strengthening rehabilitation measure appears to be appropriate.

The assessment of the structural capacity of the pavement is dependent on the moisture regime of the pavement at the time of testing and the total number of blows required to penetrate the pavement to a depth of 800 mm (DSN_{800} number). Kleyn (1984) developed the following equation to determine pavement structural capacity:

$MESA = C_m \times 10^{-9}(DSN_{800})^{3.5}$ (Eq 3)

where: $MESA$ = Structural capacity in million standard axles

C_m = Moisture Regime: 6.5 for soaked conditions

14 for wet conditions

30 for optimum conditions

64 for dry conditions

DSN_{800} = Number of DCP blows to 800 mm penetration

This equation can be used to determine the traffic loading a pavement is able to carry before developing a rut depth of 20 mm. It should be noted that the existing rut depth of the pavement is to be taken into account in determining the remaining life of the pavement.

DCP measurements are dependent on the moisture condition of the pavement, and it is important to define the moisture state at the time of testing in order to correctly interpret and analyse the results. Generally pavements should operate in the optimum to dry categories depending on location and pavement drainage, but wet or saturated conditions may occur, particularly during investigations. Care should be exercised when designing pavements that operate in the wet or saturated state during its design life.

The rate of deformation for pavements with lightly cemented treated layers was described by de Beer (1990) as follows:

$$RL = \frac{DSN_{200}}{\left(\frac{10^{3.82806-DN_{50}}}{1.38572}\right)} \qquad \text{(Eq 4)}$$

where RL = increase in rut depth in mm per million ESA

DN_{50} = average rate of DCP penetration (in mm/blow) for the upper 50 mm of the pavement

DSN_{200} = number of DCP blows to penetrate to a depth of 200 mm into the pavement structure

With a known existing rut depth, the remaining life of the pavement can be determined until a terminal rut depth is achieved.

Pavement rehabilitation design using the DCP

The primary design philosophy for pavement rehabilitation design using the DCP is to achieve a balanced pavement design while optimise the utilisation of the in-situ pavement material strength. The following procedure (Kleyn: 1975, Kleyn et at: 1983, Jordaan: 1989) outlines the process for well or averagely balanced pavements. An example is included at the back of this paper to demonstrate the process:

1. With the future expected cumulative traffic loading and moisture regime known, the required DSN_{800} is calculated by using Equation 3.
2. The measured DCP data from the existing pavement is processed and plotted on a Pavement Balance graph. The Pavement Balance Number (BN_{100}) that closely resembles the pavement balance is selected.
3. The required pavement layer properties are determined by determining the percentage of pavement strength from the balance curve above a particular depth of the pavement. The number of blows to this depth can then be determined from the required DSN_{800} number.
4. Using the relationships between CBR and DN, or UCS and DN, the required material properties at various depth of the pavement can be determined to develop a required layer strength diagram.
5. The measured layer-strength of the pavement and the required layer strength of the pavement are superimposed on each other and the rehabilitation needs of the pavement can be

determined. If the required strength is higher than the measured strength at a particular depth, strengthening of the pavement is required.

6. Strengthening, if required, can be achieved by either improvement of the material quality, overlaying the pavement with a good quality material, or a combination of both.

For poorly balanced pavements, the process is similar, except that a standard layer strength diagram for a particular traffic level can be used to determine the required pavement layer properties as discussed in step 3 above.

Recent Practical Applications

Two recent projects in Australia are presented below where the DCP was used to obtain valuable information regarding existing pavement structures, i.e. pavement layer thickness, variability and in situ layer strength.

Pavement Assessment of a Regional Airport

This case study provided a practical example of the benefits of using DCP tests to characterise existing pavement structures and subgrade materials.

<u>Background</u>

A pavement assessment and rehabilitation design of a runway and taxiway at a regional airport in western Queensland was undertaken. The project involved evaluating the structural condition of the existing runway and recommending appropriate remedial / strengthening measures. Sections of the runway started to exhibit signs of structural distress soon after the runway was used by an Hercules C130 to provide flood relief during the 2010/2011 floods. Generally, the visual condition of the runway was variable, with some sections still in a relatively good condition and other sections in a very poor condition. The following defects were noted during the visual condition assessment of the runway:

- Pavement rutting
- Longitudinal and transverse cracking
- Loss of shape
- Mechanical damage

The pavement rutting observed along sections of the runway is typically associated with either an overstressed pavement structure or overstressed subgrade (refer photo 1).

The narrow width of the pavement rutting observed indicated that the distress most likely originated within the upper pavement layers rather than the subgrade. It was essential to obtain detailed information regarding the existing pavement profile and structural condition In order to determine the likely cause of distress. Given the remoteness of the location and highs costs associated with establishing more sophisticated testing equipment, such as FWD devices, it was decided to excavate a limited number of test pits and perform a number of DCP tests through the runway to characterise the existing pavement structure.

Photo 1 Pavement Rutting along Runway

Pavement Investigation

Three test pits were excavated within the runway to determine the profile of the existing pavement structure and obtain samples from the pavement layers and subgrade for laboratory testing. The test pits revealed the following pavement structure:

- Multiple bituminous sprayed seals
- 200 mm – 300 mm thick natural sandy gravel base layer
- Varying thickness selected layer comprising of a sand
- In situ sandy clayey subgrade

Samples were taken from the base layer, selected layers and subgrade to determine the grading, in situ moisture content, Atterberg Limits and California Bearing Ratio (CBR) of the materials.

In addition to the test pits, ten DCP tests were done adjacent to the centreline of the runway at a nominal spacing of 150 m. These DCP tests were done in an attempt to determine the in situ strength of the pavement layers and subgrade, as well as identify any potential variability in the condition or profile of the pavement along the runway. A 60° cone was used for the DCP investigation to enable the use of published guidelines and data from South African experience. Given that the DCP was being used to characterise the thinner pavement layers, the penetration was recorded after every 5 blows.

Investigation Findings

Base Layer

The penetration rate of the DCP typically varied between 0.9 mm/blow and 6.1 mm/blow through the base layer, indicating large variability in the structural condition of the base layer along the length of the runway. This variability in the penetration rate was consistent with the variability in the visual condition of the runway. Furthermore, the test locations with a higher penetration rate generally coincided with the sections of the runway that showed signs of structural distress. Some of the DCP penetration curves measured along the runway is shown in Figure 7.

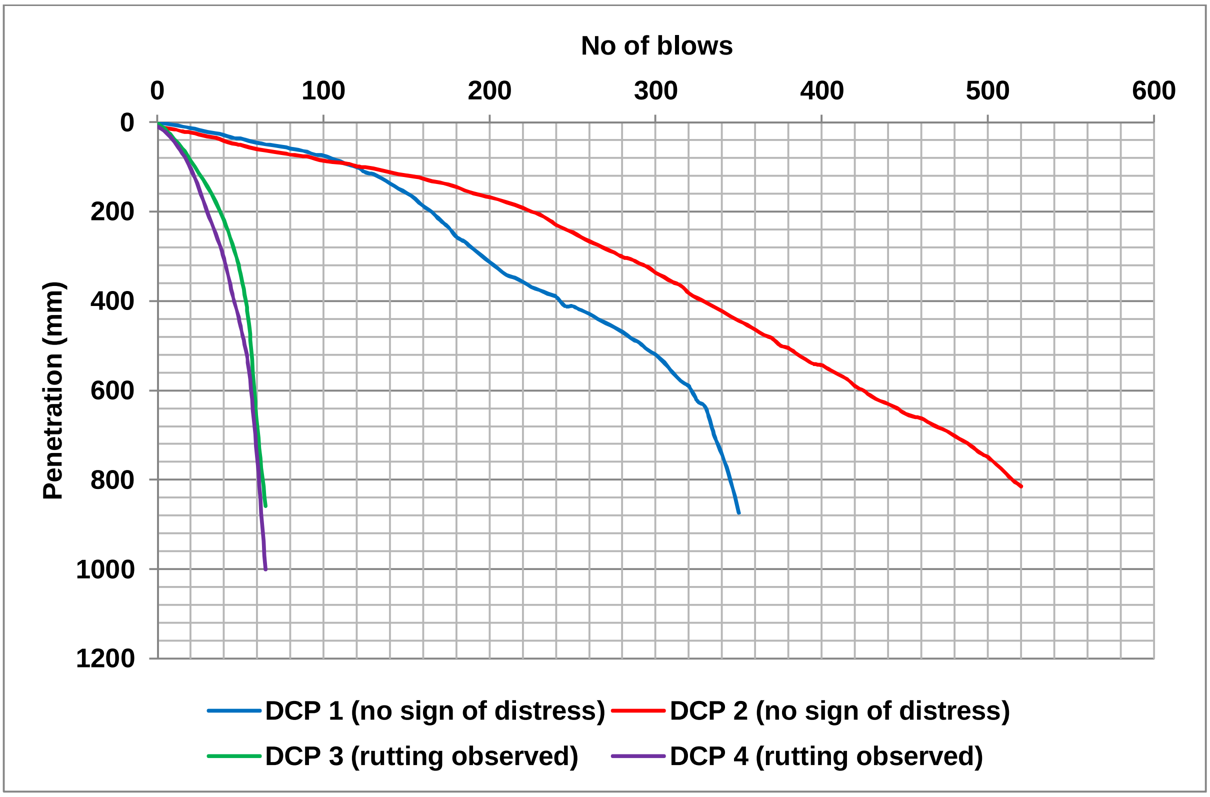

Figure 7 DCP Penetration Rate

Typically, a penetration rate of between 0.8 mm/blow and 1.5 mm/blow is considered as being acceptable for good quality base layers in road pavements (Jordaan, 1994). The authors are not aware of any published data for an acceptable DCP penetration rate through base layers in runway pavements, but given that materials with similar material strength properties are used for both applications, a penetration rate of approximately 1 mm/blow was considered to be acceptable.

The four day soaked CBR of the base layer material varied between 10 % and 15 % and is indicative of a very low strength pavement material.

The DCP results confirmed that the base layer along sections of the runway were in a structurally poor condition and this correlated well with the rutting observed and low soaked CBR values measured on samples taken from the pavement.

In addition to determine the in situ strength of the base layer, the DCP measurements were also used to determine if there were any significant variability in the thickness of the pavement layers along the runway. The slope of the DCP penetration curve was used to get an indication of pavement layer thicknesses. A change in the slope of the curve indicates a change in the in situ shear strength of the pavement structure. This change in strength could be as a result of either a change in material type, compaction or in situ moisture condition. Information regarding the existing pavement profile obtained from test pits, bore holes or as-constructed drawings can then be used to determine if the change in strength is most likely as a result of a change in material type, change in moisture state, presence of a weak zone or traffic related deterioration. Information obtained from the three test pits indicated that the pavement comprise of a 200 mm to 300 mm thick base layer. With this in mind, the DCP penetration curves measured along the runway are shown in Figure 8.

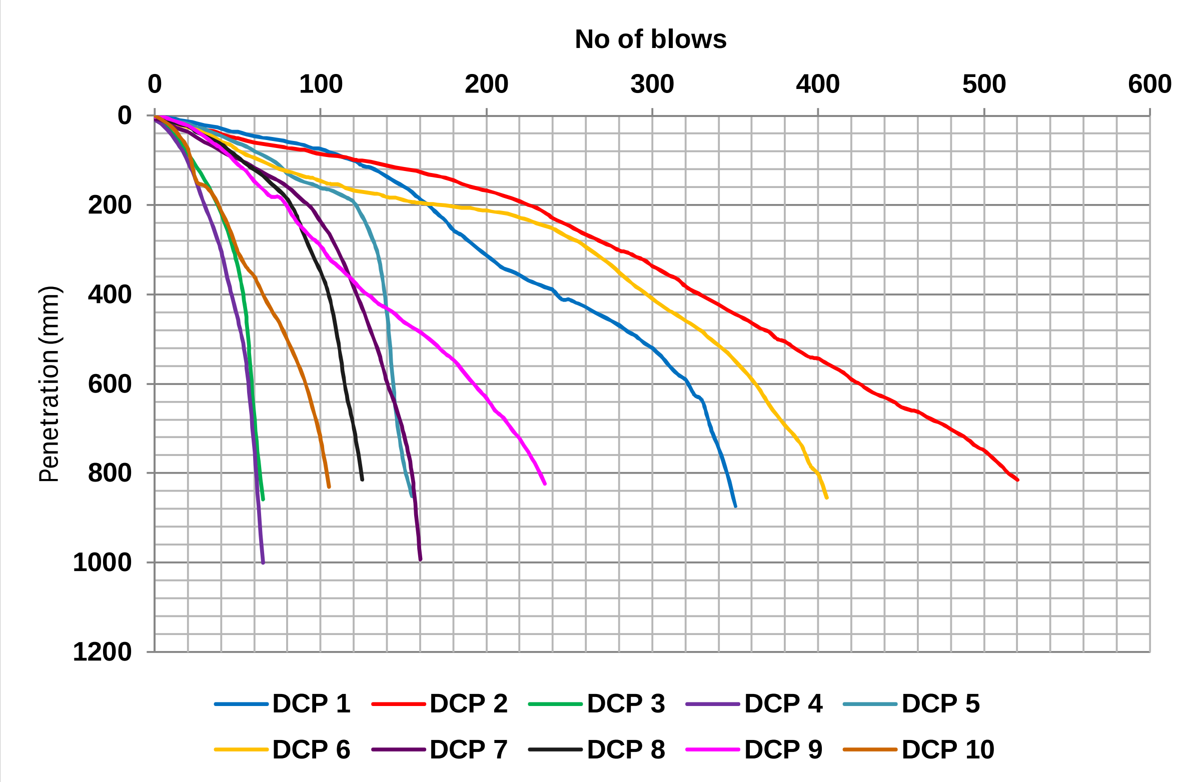

Figure 8 Layer Thickness Estimated from DCP Penetration Rate

One can clearly observe a significant change in the slope of the penetration curve at a depth of between 150 and 220 below the surface, correlating well with the base layer thicknesses observed in the test pits. As such, the DCP measurements could therefore be used with a high degree of confidence to estimate the base layer thickness in the areas where there was no test pits excavated.

Select Fill Layer

The DCP penetration rate measured through the select fill layer along the runway varied between 2.1 mm / blow and 30 mm/blow, which correlated to an estimated in situ CBR of between 5 % and greater than 80 %. The CBR estimated from the DCP measurements taken at the three test pits varied between 7 % and 22 %, compared to a soaked CBR of 5 % and 10 % determined from the samples taken at the test pits. The DCP measurements showed a good correlation with the laboratory soaked CBR results.

Subgrade

The DCP penetration rate through the subgrade varied between 25 mm/blow and 70 mm/blow, correlating to a 10th percentile in situ CBR of approximately 2.5 %. Again, this correlated well with a soaked CBR of 3.5 % measured on a sample taken from the test pits.

Rehabilitation measure

From the DCP investigation it became apparent that the major cause of failure of the pavement is related to the condition and strength of the base layer. The proposed rehabilitation design measures included an unbound granular overlay option, or an option to improve the quality of the existing base layer by in-situ stabilisation.

Industrial Pavement Failure

Background

The potential cause of premature pavement failures at a heavy duty industrial facility was recently investigated. The industrial pavement comprised of concrete pavers overlying a cement modified base and cement stabilised subbase layers. The cement modified base comprised of a good quality crushed rock modified with 1 % cement to achieve a seven day Unconfined Compressive Strength (UCS) of approximately 1.2 MPa. Severe pavement rutting started to occur soon after construction. Excavation of test pits confirmed that the rutting was limited to the cement modified base layer (refer Photo 2) with no visible distress in the underlying stabilised layers..

Photo 2 Rutting Limited to Base Layer

Visual observations during the pavement investigations revealed a potentially weak upper zone in the cement modified base layer, typically between 20 mm - 50 mm thick, which could easily be excavated by hand. This weak upper zone was observed in both the trafficked and un-trafficked areas. Even though this weaker upper zone was visually visible, it was important to confirm the extent and condition of this zone with some kind of structural testing. DCP testing has been widely used in South Africa to characterise the in situ strength of lightly cemented materials. Lightly cemented materials, in the South African context, are defined as materials with a low percentage of cement and typically with an UCS of less than 3 MPa (Jordaan, 1994). These lightly cement stabilised materials were therefore similar to the cement modified base layer being investigated as part of this project. As such, the DCP was considered to be an appropriate tool to determine the in situ strength and structural condition of the modified base layer.

DCP Investigation

Subsequently, DCP tests using a 60° cone were performed through the modified base layer in the un-trafficked areas. The results from the DCP tests were analysed, processed and compared to results from HVS studies by de Beer (1993) on pavements before HVS testing (un-trafficked) and pavements subjected to HVS tests (trafficked). The average DCP penetration rate versus depth measured at the industrial facility (with the effect of bedding in removed), as well as the data obtained by de Beer data are shown in Figure 9 (Litwinowicz, 2010).

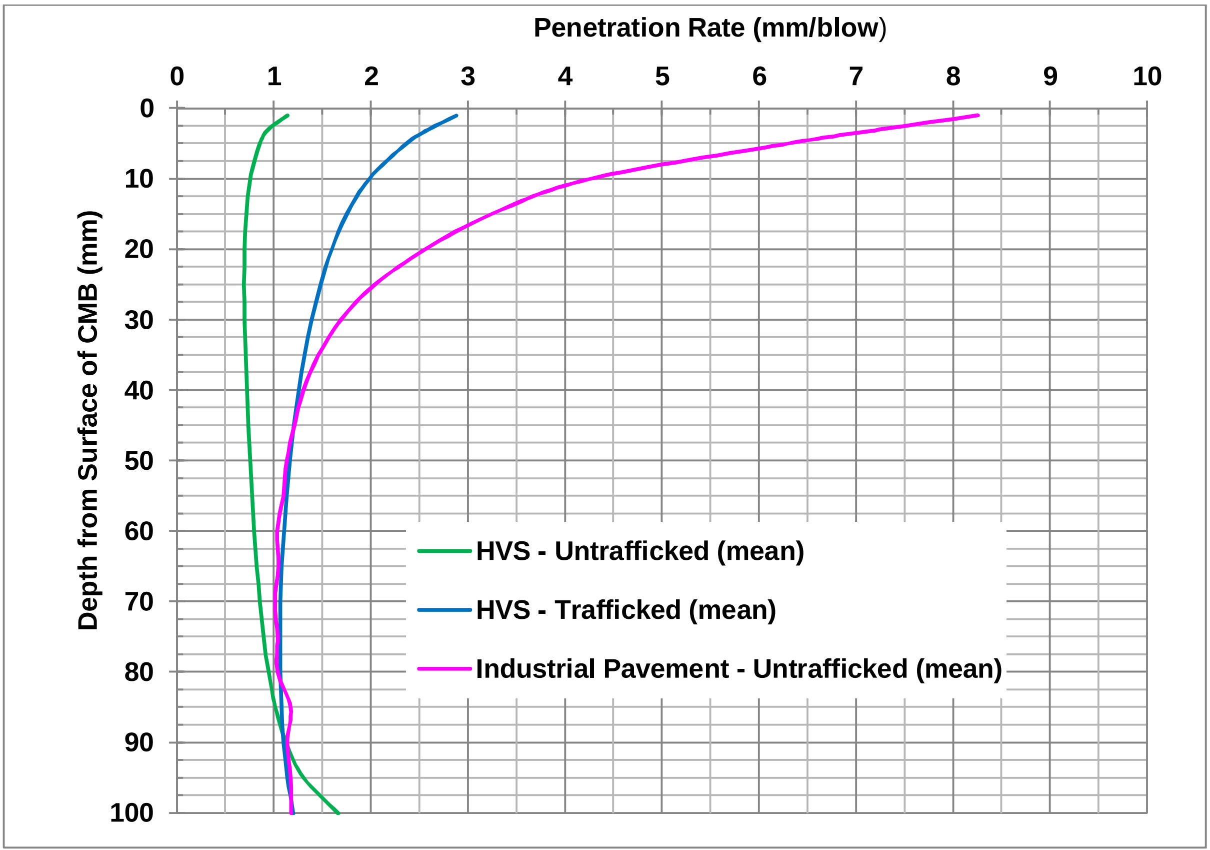

Figure 9. Comparison of DCP penetration rate of upper 100 mm between Industrial pavement and HVS test pavements.

The data published by de Beer clearly shows the impact of traffic on the in situ strength of the upper zone of a lightly cement stabilised base layer, also known as crushing. The DCP penetration rate through the top 30 mm of the base layer after trafficking is significantly higher than the penetration rate before trafficking, indicating a reduction in the in situ strength of the material. It is however interesting to note that the DCP penetration rate measured through the upper zone of the base layer in the un-trafficked areas of the industrial facility was significantly higher than the penetration rate of the de Beer data for a base layer that has been trafficked. This suggested that the in situ strength in the upper zone of the cement modified base layer at the industrial facility where significantly lower than what would typically be expected from an un-trafficked pavement and confirmed the presence of a weaker upper zone.

Using the correlation between UCS and DN from equations 2.1 and 2.2, the average UCS estimated near the surface was less than 0.5 MPa, compared to an average UCS of 2 MPa deeper down in the base layer (Litwinowicz, 2010). Again, these results confirmed the presence of a weak upper zone in the cement modified base layer that could have adversely affected the pavement performance.

This case study demonstrated the potential to use DCP tests to characterise the structural condition of lightly stabilised pavement layers. The DCP was successfully used to identify a weak upper zone in the pavement structure, even at thicknesses less than 50 mm.

Conclusions

Although initially developed in Australia, the use of the DCP in Australia is mainly limited to geotechnical investigations and subgrade characterisation. This paper highlighted some of the research conducted during the 1970's and 1980's into the development of a pavement design procedure that may be adapted to assist in the structural rehabilitation design of lower volume roads when the availability of sophisticated testing are not be available.

The method illustrated in this paper is simple, based on sound principles and can be implemented at relative low cost. When analysed, DCP data can assist the pavement designer in gaining a better understanding of the behaviour of the pavement, the presence of substandard materials in the pavement structure and the expected behaviour of the pavement structure during its design life.

It should be noted that the data, relationships and examples illustrated in this paper is not necessarily calibrated to account for Australian conditions and experience and it is recommended that the necessary calibrations be conducted before the device can be used with confidence as a pavement rehabilitation design tool in Australia.

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Annexure A. Pavement rehabilitation design example

This example is based on real DCP values obtain from tests conducted on a road pavement in the Western Cape, South Africa. The example is to illustrate the principles of the method and should not be used as a guideline on the methods itself as some of the details have been omitted to reduce complexity. The reader should consult the necessary design manuals and guidelines (Jordaan: 1989) for full details on the use of the design method.

Expected future cumulative traffic loading: 6.0 x 10^6 ESA

Expected moisture regime during pavement life was assumes as optimum, therefore C_m = 30

From Eq 3: Required DSN_{800} = 235

The measure DCP data from the pavement are presented in Figure A1 in the form of a DCP curve and layer strength diagram. The average penetration rates for the uniform layers within the pavement structure are also illustrated on the layer strength-diagram.

The measured DSN_{800} number of the pavement structure was 190, which at optimum moisture conditions would have a remaining life of 2,8 million ESA.

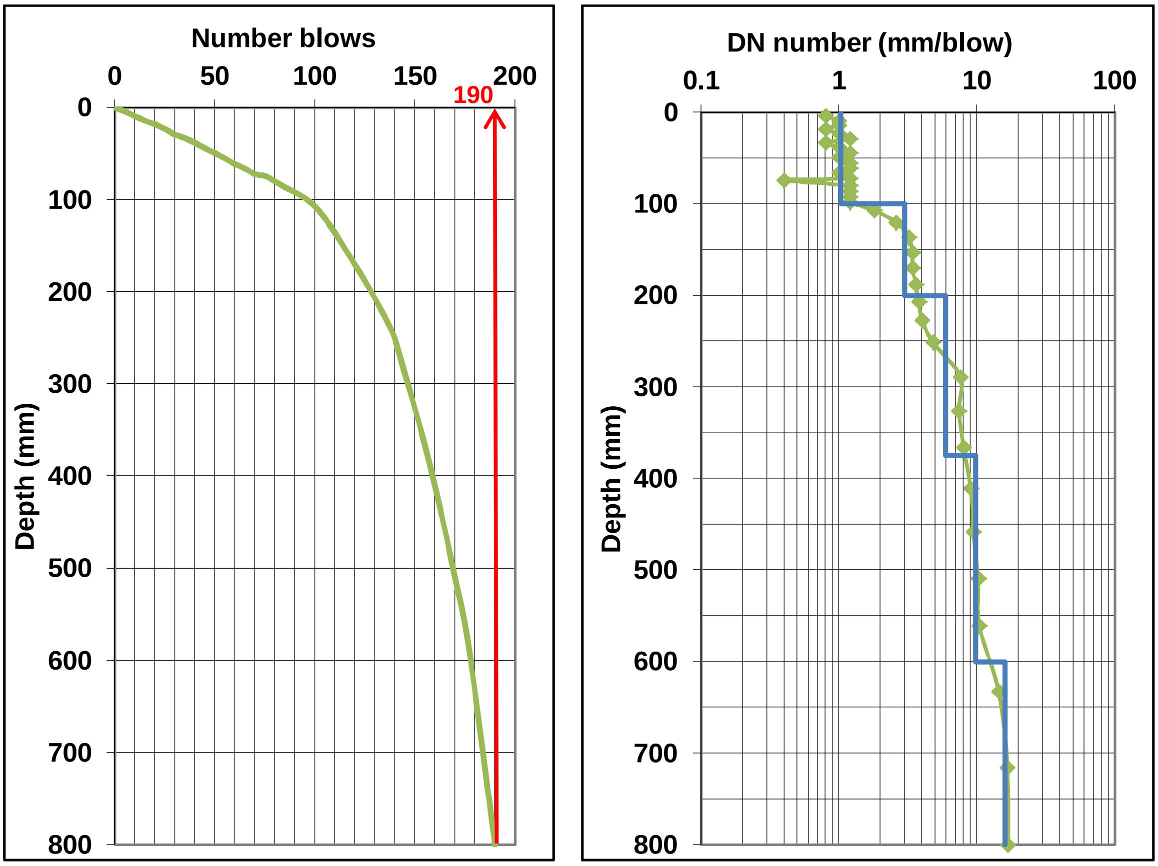

Figure A1. DCP curve and layer strength diagram for measured DCP data

The balance of the pavement is calculated and plotted on a pavement balance curve. The pavement balance curve indicates the cumulative strength of the pavement at a particular depth. From the balance curve in Figure A2, it appears, by inspection, that this pavement closely resembles a BN_{100}=48 balance.

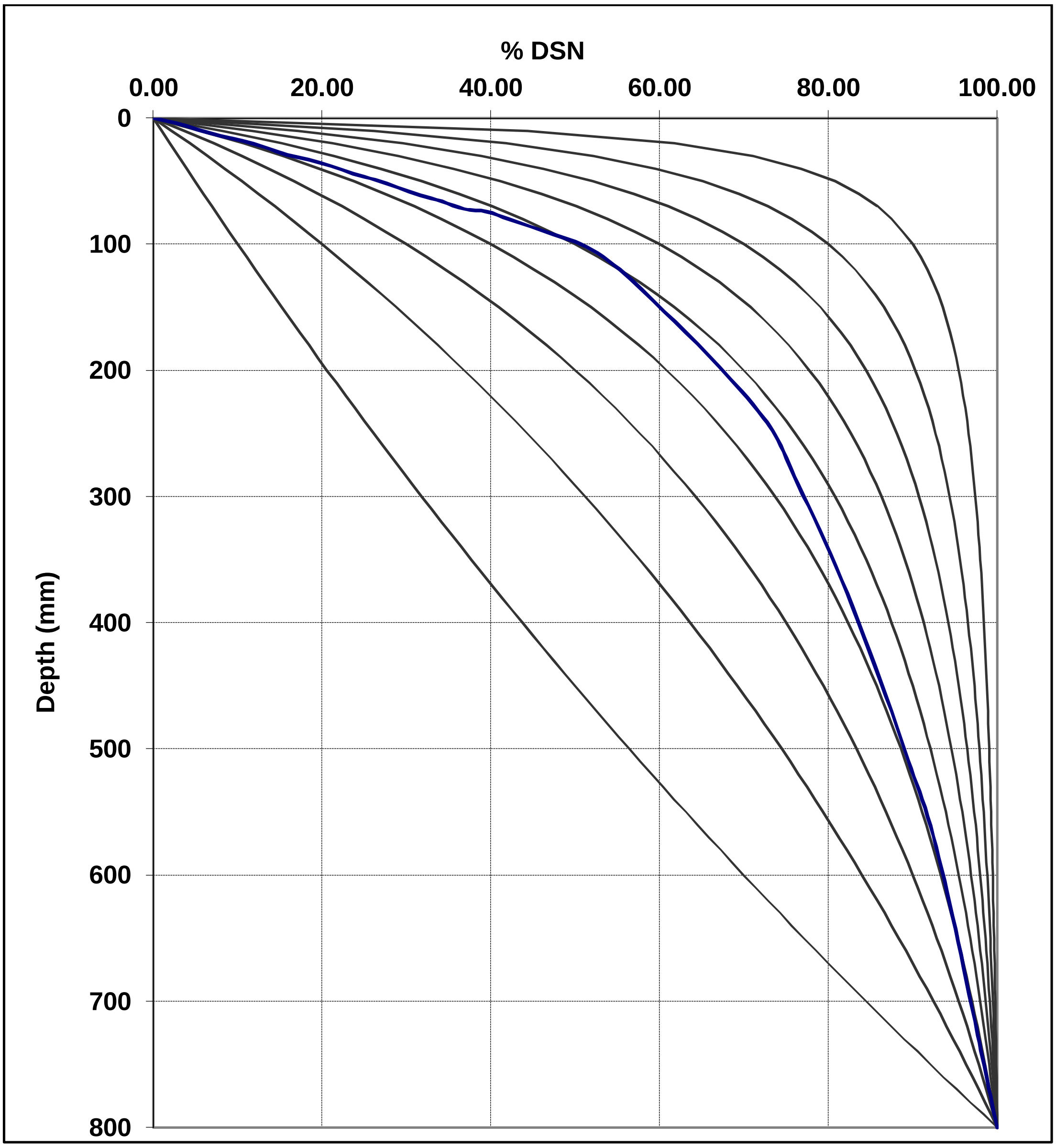

Figure A2. Pavement balance curve

The objective is to maintain the existing pavement balance, therefore the cumulative number of blows at a certain depth of the pavement is determined from the BN_{100}=48 balance curve graph as indicated in Figure A3. The required penetration rates for the required pavement strength are then calculated as per Table A1.

The example assumed a required base and subbase layer thickness of 150 mm each with a 200 mm selected fill layer thickness.

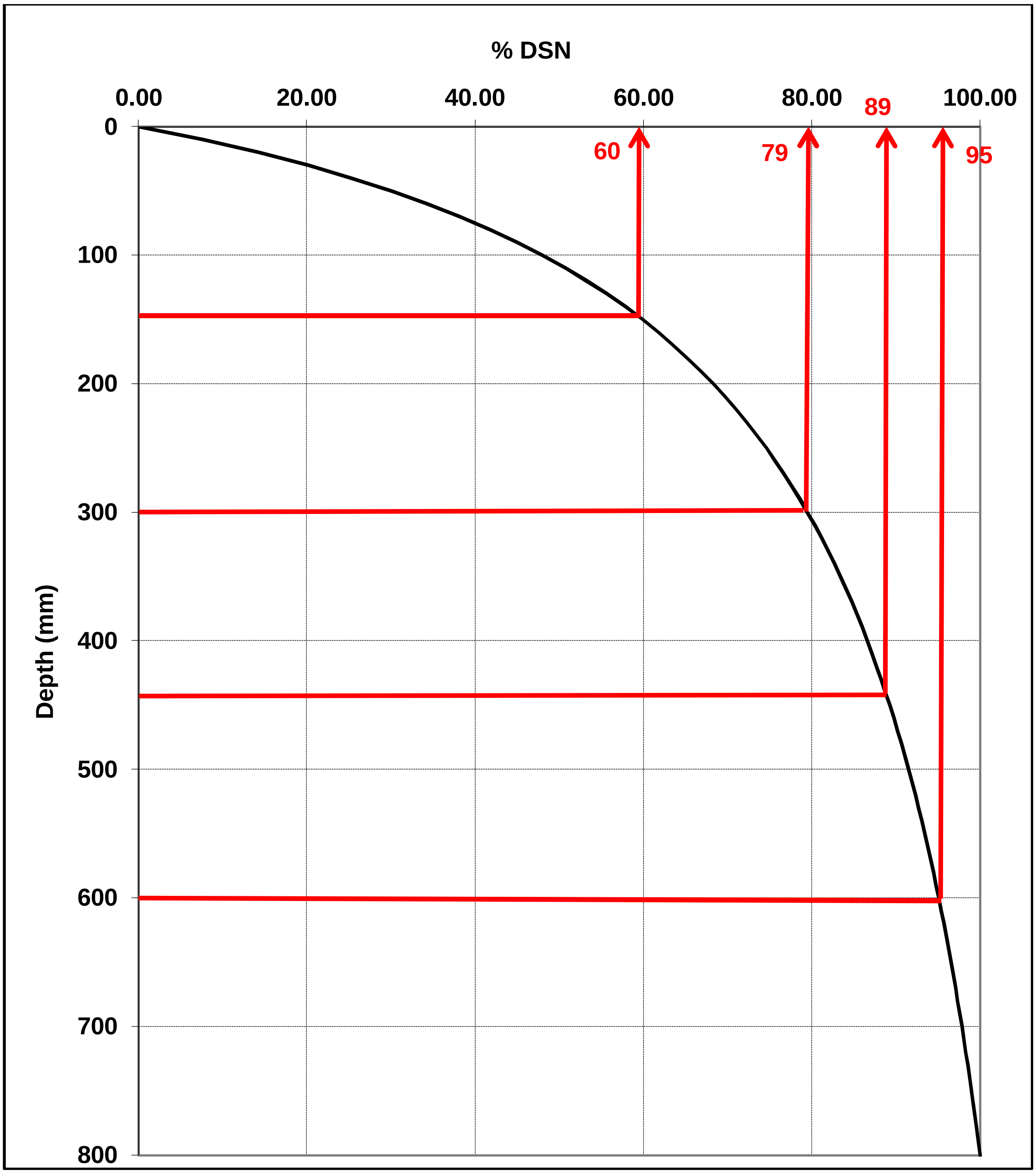

Figure A3. Determine required pavement layer properties from Balance curve.

Table A1. Calculation of required pavement layer properties.

Depth (mm)	Strength required %	Required blows	Required DN (mm/blow)
0	0	0	-
150	60	141	1.06
300	79	187	3.26
450	89	210	6.52
600	95	223	11.53
800	100	235	16.67

The required DN for each layer is then superimposed on the layer-strength diagram of the pavement as illustrated in figure A4.

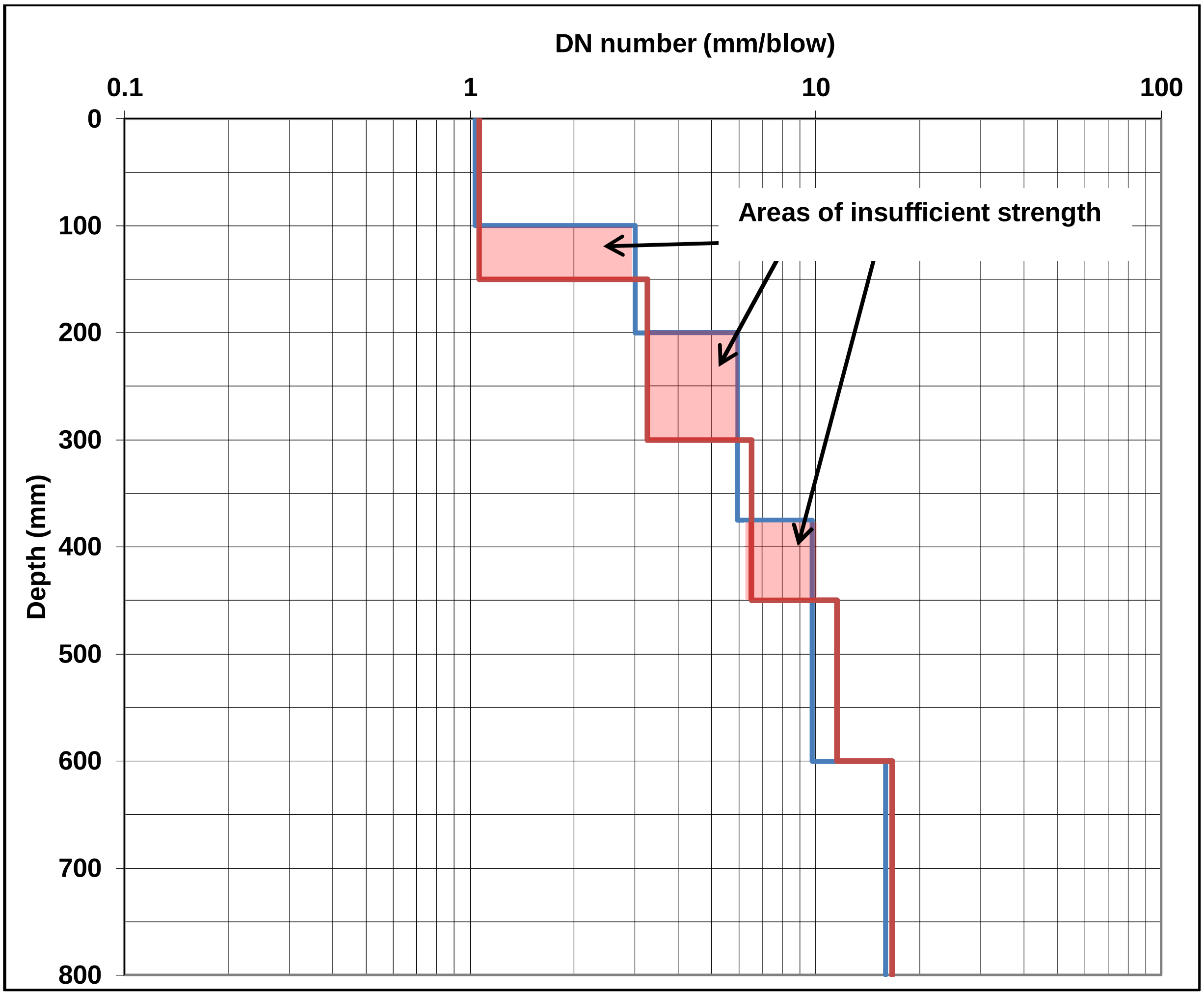

Figure A4. Existing and required layer strength diagrams

By inspection, areas within the pavement that are of insufficient strength can be identified where the existing Layer Strength Diagram (blue) is to the right of the required Layer Strength Diagram (maroon). In the example above these areas are (coloured in red in Figure A4):

- 100 to 150 mm from the surface
- 200 to 300 mm from the surface
- 375 to 450 mm from surface

This enables the designer to determine the areas within the pavement that would require strengthening and present the opportunity to consider various rehabilitation alternatives. One such alternative is the addition of a new 100 mm unbound granular overlay. This is illustrated by shifting the required layer strength diagram up by 100 mm as illustrated in Figure A5.

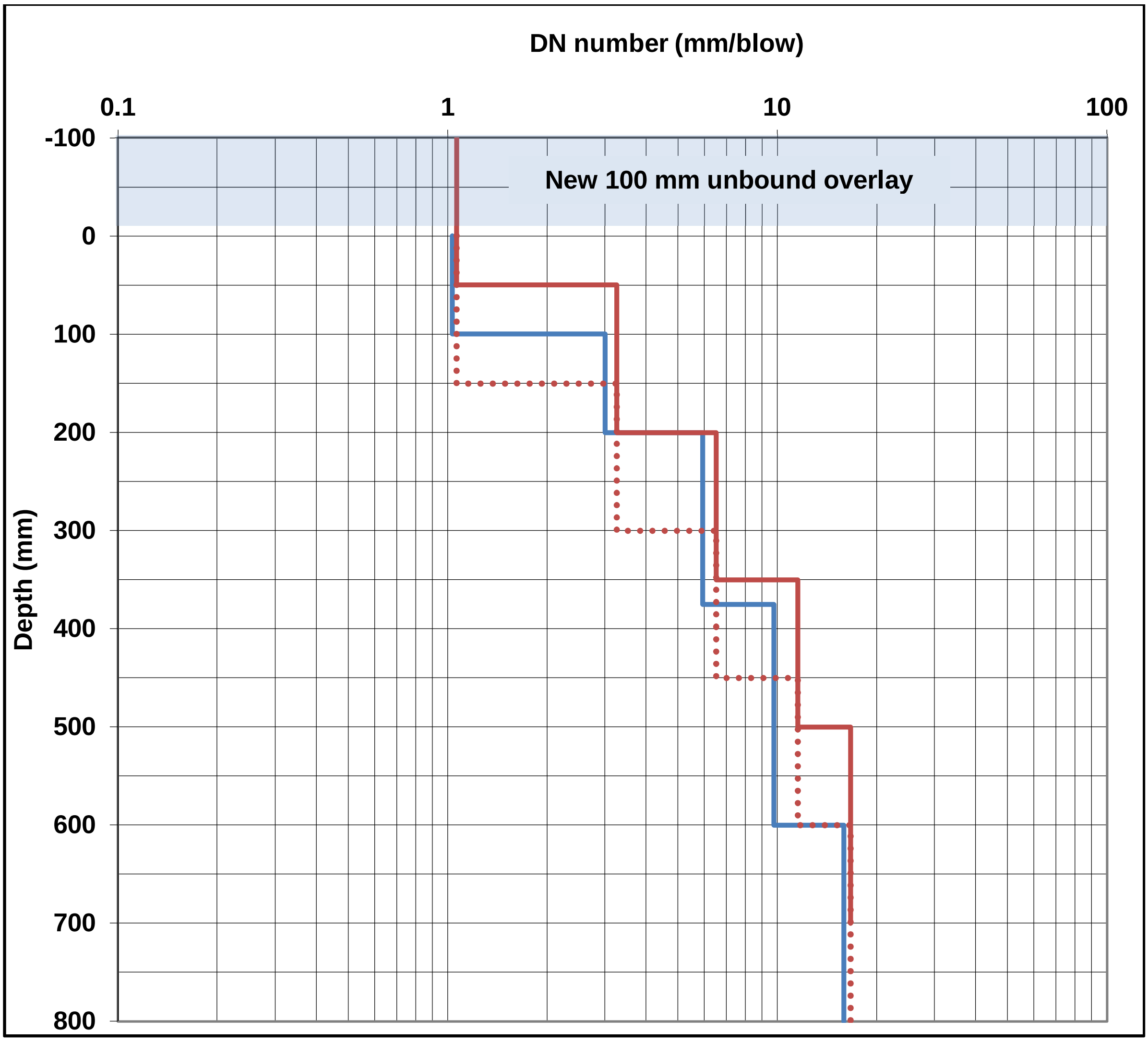

Figure A5. Rehabilitation alternative: 100 mm unbound granular overlay

By the addition of 100 mm of unbound granular material, the required layer strength diagram shifts up by 100 mm and it can be seen that all the pavement layers now have sufficient cover. For this example, reworking of the base layer was not a viable option as the deficiencies in the pavement strength was deeper down in the pavement.

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