# Effect of Vertical Confinement on Dynamic Cone Penetrometer Strength Values in Pavement and Subgrade Evaluations

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The Dynamic Cone Penetrometer (DCP) has become one of the most useful testing devices in pavement evaluation in Israel and other parts of the world. Consequently, a reliable true meaning and interpretation of the results are needed. Research work dedicated to studying the effects of vertical confinement on the DCP strength values of the granular pavement layers and subgrade is summarized. Specifically, four major effects were studied: vertical confinement of granular layers, vertical confinement of cohesive layers, vertical confinement of rigid structural layers, and the effect of vertical confinement of upper asphalt layers on the DCP strength values of the granular layers below them. Based on engineering analysis and experimental testing in the laboratory and in the field, the following conclusions were made. (a) No vertical confinement effect by rigid pavement structure, the upper granular layers, or the upper cohesive layers on the DCP strength values of lower cohesive subgrade layers was found. Any differences in the results between the confined and unconfined DCP values can be explained by the friction that developed in the rod during tilted penetration. (b) However, vertical confinement effects by upper asphalt layers on the DCP values of the granular pavement layers exist. Since this is the true effect of the pavement structure, any DCP measurement for pavement evaluation purposes should be performed through a narrow boring in the asphalt layers and not after removal of a wide strip of asphalt. Generally, these confinement effects decrease the DCP values, and thus increase the structural strength measured. These confinement and friction effects, which can be evaluated quantitatively, should be taken into consideration when using the DCP method to evaluate existing pavements.

During the last decade, the Dynamic Cone Penetrometer (DCP) test has been increasingly used in many parts of the world for pavement and subgrade evaluation through its relationship with the in situ California Bearing Ratio (CBR). This is because of its economy, simplicity, and capability of providing rapid measurements of the in situ strengths of subgrades and pavement layers without excavation of the existing pavement, as in the in situ CBR test (*1–9*).

Extensive work with DCP testing and the experience gained in Israel have shown that, in addition to the CBR-DCP correlation, some other factors that have an influence, such as vertical confinements, should be taken into consideration (*10*). For example, a question occasionally arises, that is, whether DCP results, obtained from the subgrade by means of the rod's penetration through the structural layers, are identical to the results obtained from the same subgrade after removal of the pavement structural layers. In other words, are the subgrade DCP results affected by the presence of the flexible structure? Similarly, the question can be applied to an all–asphalt pavement whose subgrade was examined following drilling of a small-diameter hole in the asphalt structure. These issues are considered to be related to vertical confinement.

Since the DCP has become one of the most useful testing devices in pavement evaluation in Israel, a reliable true meaning of the results and an interpretation of the results were required. Consequently, research work was dedicated to studying the effects of vertical confinement on the DCP values. Specifically, the following effects were studied:

1. Effect of vertical confinement of granular structural layers on clay and silt subgrade DCP values;
2. Effect of vertical confinement of cohesive layers on clay subgrade DCP values;
3. Effect of vertical confinement of rigid structural layers (an all-asphaltic structure) on clay subgrade DCP values; and
4. Effect of the vertical confinement of upper asphaltic layers on the DCP values of the granular layers below them.

The study of these effects is important for use of the DCP in the reliable evaluation of existing pavements. This paper presents the theoretical background for vertical confinement, as well as an analysis of the results obtained from both laboratory and field tests designed to study the effects mentioned earlier.

## DCP TEST IN PAVEMENT EVALUATION

The DCP, as developed in South Africa (*11*), consists of a steel rod with a cone at one end. It is driven into the pavement or the subgrade with a sliding hammer, and the material resistance to penetration is measured in terms of millimeters per blow. The cone is angled at 30 degrees, with the larger diameter of the cone being 20 mm. The hammer weighs 8 kg, and the dropping sliding height is 575 mm (Figure 1).

The DCP was originally designed and used to determine the strength profile of the flexible pavement structure and subgrade (*12–14*). Usually, pavement testing at a given point involves the extrusion of a 4-in. circular core from the top asphalt layers only and penetrating the DCP from the top of the base course layer down to the required pavement or subgrade layer. The properties of the asphalt layers are directly evaluated in the laboratory by a proper mechanical test (resilient modulus, diametrical test, splitting test, Marshall test, or others). The pavement parameters are continuously measured and recorded with depth by the DCP. Immediately at the test's conclusion, the shallow 4-in. hole is easily filled with either portland cement concrete (regular or fast curing) or a proper cold asphaltic mixture. In case of only subgrade evaluation for pavement

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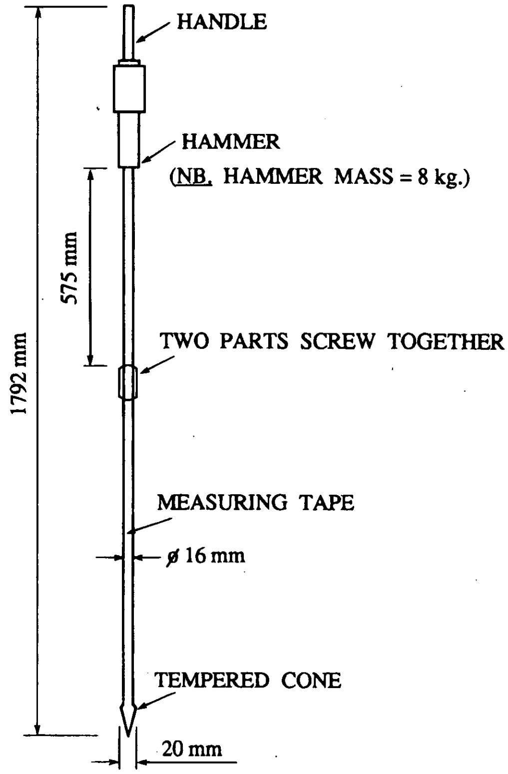

**FIGURE 1 General details of South African DCP.**

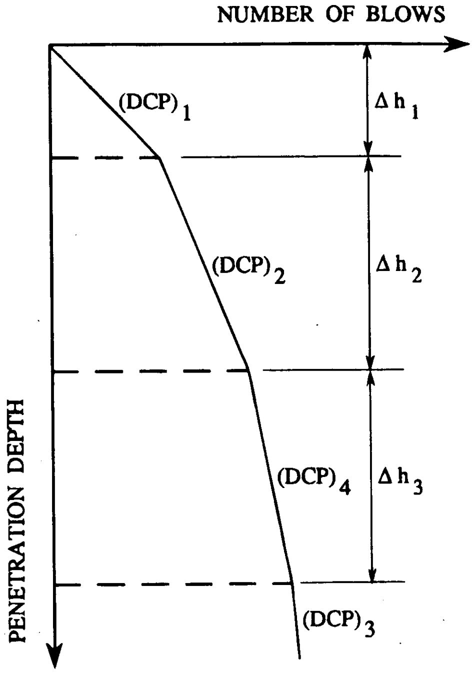

**FIGURE 2 DCP test output.**

design purposes, the DCP is penetrated down from the top of the natural soil or compacted subgrade.

During testing the number of blows versus depth is recorded. The DCP value is defined as the slope of the blows-versus-depth curve (in millimeters per blow) at a given linear depth segment (Figure 2).

## CORRELATION BETWEEN DCP AND CBR

To be able to relate DCP values to the structural parameter of the pavement under the local pavement design and evaluation technology, an extensive controlled laboratory and field test was carried out to correlate DCP to CBR (*10,15*). In the laboratory conventional and DCP tests were performed on a wide range of undisturbed and compacted fine-grained soil samples with and without saturation. Compacted granular soils were tested in flexible molds with variable controlled lateral pressures. Field tests were made on natural and compacted layers representing a wide range of potential pavement and subgrade materials. Pavement evaluation tests were also performed for pavement and material evaluation and for correlation with pavement condition.

The correlative laboratory and field testing program resulted in a quantitative relationship between the CBR of the material and its DCP value as follows (Figure 3):

$$\log \mathrm{CBR} = 2.20 - 0.71\,(\log \mathrm{DCP})^{1.5}\ (R^2 > 0.95) \tag{1}$$

where the DCP is the penetration ratio in millimeters per blow.

This relationship, which was initially formulated in 1985, was based on 56 comparative test results. Later, this correlation was checked as data accumulated over several years (10). Finally, on the basis of 135 tests the total equation, which was based on old and new data, is formulated as follows (Figure 3):

$$\log \mathrm{CBR} = 2.14 - 0.69\,(\log \mathrm{DCP})^{1.5}\ (R^2 = 0.876, N = 135) \tag{2}$$

From a practical standpoint, both Equations 1 and 2 yield almost identical results (*10*).

Several other agencies and researchers around the world have also tried to develop correlations between DCP and CBR values (*3,8,11,16*). Webster et al. (*8*) compared some of these correlations (Figure 4). It is evident that general agreement was reached between

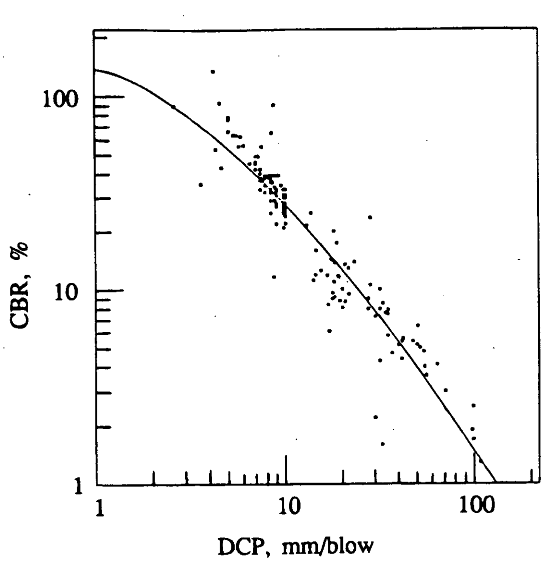

**FIGURE 3 Relationship between CBR values and DCP values (*10,15*).**

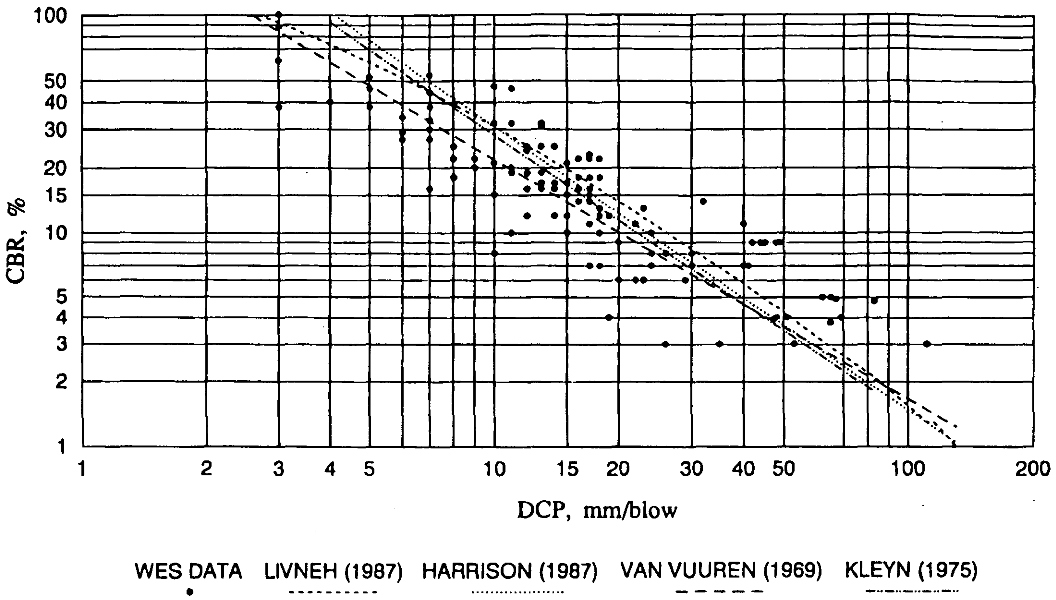

**FIGURE 4 Universal data for relationship between DCP and CBR (*8*).**

the various sources of information. On the basis of these results the following equation was selected as the best correlation:

$$\log \mathrm{CBR} = 2.46 - 1.12\,(\log \mathrm{DCP}) \quad (3)$$

It can be seen that a universal correlation exists between the DCP and CBR for a wide range of pavement and subgrade materials, testing conditions, and technologies.

## ENGINEERING BACKGROUND OF VERTICAL CONFINEMENT EFFECT

In the context of the basic bearing capacity approach, a plastic failure mechanism can be adopted to describe soil behavior under cone-shaped penetrometers. This approach was adopted by Livneh (*17*) and Livneh and Greenstein (*18*) to find the effects of lateral pressure on CBR values in granular materials. Similarly, few analytical or numerical solutions for wedge and cone-shaped penetrometers, which account for both cone apex-angle and roughness, are given in the literature (*19–21*).

Durgunoglu and Mitchell (*20*) proposed three types of failure mechanisms relevant to deep foundations that can also be adopted for penetration tests (Figure 5). On the basis of actual test results with variable apex-angles and cone roughness, they concluded that the failure mechanisms described in Figure 5(*b*) and 5(*c*) are inappropriate, whereas the failure mechanism represented in Figure 5(*a*) closely represents the actual failure surface associated with wedge penetration.

On the other hand, Meyerhof (*19*) provided solutions for both cohesive and cohesionless soils for certain conditions assuming the failure mechanism shown in Figure 5(*b*), whereas Nowatzki and Karafiath (*21*) used a finite-difference technique for limited conditions and obtained some penetration resistance values for cohesionless soils assuming the failure mechanism shown in Figure 5(*c*). It should be noted that this mechanism is only possible in the situation in which the ratio $D/B$ is larger than 4 to 10. For the DCP device this ratio means depths of more than about 10 cm.

In this context it is important to show that the state of deep foundation is defined by Meyerhof (*19*) as follows:

$$D = 4\sqrt{N_\phi}B \quad (4)$$

where

$$N_\phi = \tan^2\left(\tfrac{1}{4}\pi + \tfrac{1}{2}\phi\right) \quad (5)$$

and

$D$ = the foundation depth,
B = the width or diameter of the foundation, and
$\phi$ = the material's internal angle of friction.

Here, for cohesive soils (where $\phi$ is equal to 0), Equations 4 and 5 lead to the ratio of $D/B$ equal to 4, whereas for cohesionless soils (where $\phi$ is $> 0$) a deep foundation is defined at a depth of $D$ greater than $4B$.

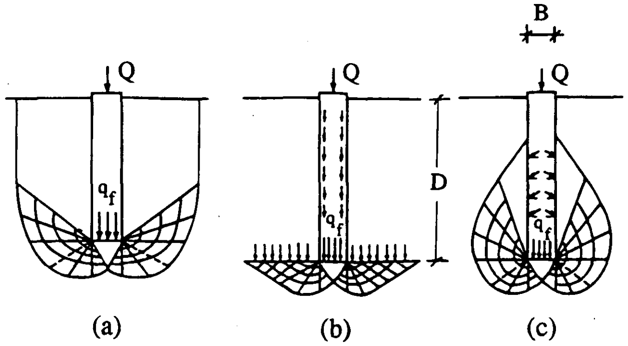

**FIGURE 5 Different failure mechanisms proposed for penetration test (*20*).**

To investigate the vertical confinement effect one should look at the Terzaghi's basic bearing capacity formula. Under this concept the penetration resistance $q_u$ can be defined as follows:

$$q_u = K_c C N_c + K_\gamma \gamma B^{1/2} N_\gamma + \gamma D N_q \tag{6}$$

where

$q_u$ = the unit tip resistance,
$C$ = the unit cohesion,
$\gamma$ = the material density,
$D$ = the depth of the penetrometer tip,
$N_c$, $N_\gamma$, $N_q$ = Terzaghi's bearing capacity coefficients (Figure 6), and
$K_c$, $K_\gamma$ = the shape factors.

The question then asked is whether DCP test results obtained at a depth of 10 cm and more below the clay subgrade, when the test is conducted in the clay subgrade after drilling into the pavement, are different from the results obtained from a similar subgrade at a depth of 10 cm and more below the surface, when the test is conducted following the removal of a wide strip of pavement. In other words are DCP test results obtained at a depth of 10 cm and more still subject to the possible effects of vertical confinement?

The answer according to Meyerhof (*19*) is negative when cohesive subgrade is concerned. If one looks at Figure 6 (which presents the bearing capacity coefficients as a function of the angle of internal friction), it can be seen that for $\phi$ equal to 0, the value of $N_c$ remains constant, commencing from a depth equal or greater than that expressed in Equation 4. Brinch-Hansen (*22*) also provide a negative answer since, commencing from a certain value of $D$, the increase in $N_c$ as a consequence of the continued increase in $D$ is negligible. This is reflected in the following equation:

$$d_c = 1.0 + \frac{0.35}{\frac{B}{D} + \frac{0.6}{(1 + 7tg^4\phi)}} \tag{7}$$

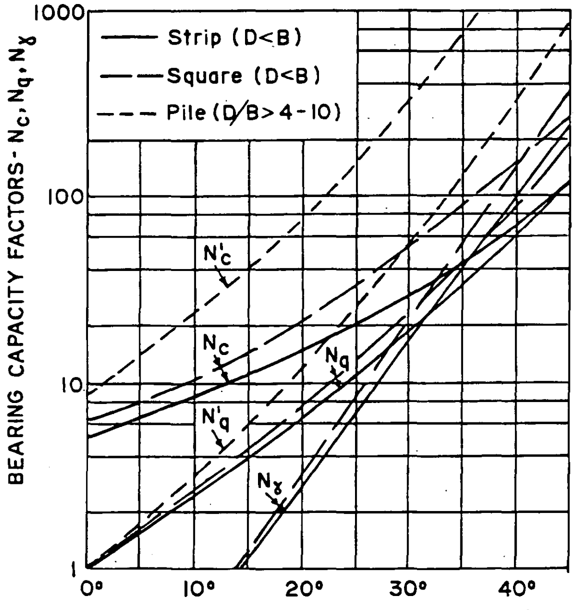

**FIGURE 6 Bearing capacity factors for spread and pile foundations (*16*).**

where $d_c$ is the increase factor of $N_c$ depending on the foundation depth.

Theoretically, vertical confinement is mainly possible because of the bearing capacity component $\gamma D N_q$ (Equation 6). In cohesive soils, when $\phi$ is equal to 0, $N_q$ is equal to 1.0, and thus, this component is quite negligible. Hence, it can be seen that for clay subgrades the values of both $N_c$ and $N_q$ in Equation 6 eliminate the effect of vertical confinement in deep penetration measurements of the DCP.

On the other hand, for granular materials (where $\phi$ is $> 0$), both $N_q$ and $N_c$ possess significant values that increase with depth. Therefore, the vertical confinement of the upper layers will be significant and will increase with the depth of the DCP tip.

This situation of a very deep foundation is similar to a position in which the foundation is not as deep but the soil surface is bound by a rigid structure (as, for example, in an all-asphalt structure). On the basis of the preceding discussion, it can be concluded that the DCP results obtained from a penetration depth of 10 cm or more from the surface of the clay subgrade will be only negligibly affected by the presence of a rigid structure on the subgrade's surface or will be totally unaffected.

These conclusions are derived from the engineering analysis, and they are compared with the empirical testing described later in this paper.

## EFFECT OF CONFINEMENT BY GRANULAR STRUCTURE

The effect of confinement by the granular structure on the subgrade's DCP values was studied on the basis of an analysis of actual DCP test data (*10*). The analysis presented in this section is based on 11 DCP test locations. The DCP test was conducted following the drilling of asphalt cores at these points. The subgrade DCP values obtained by this method are referred to as the confined values, that is, $\text{DCP}_{\text{con}}$. These values are compared with the DCP values derived from the subgrade values described earlier following removal of all structural layers (i.e., after the digging of test pits). The DCP values obtained from the exposed subgrade are referred to as the unconfined values, that is, $\text{DCP}_{\text{unc}}$.

The test results obtained are presented in Figure 7. It can immediately be seen from Figure 7 that the two test populations are not identical, as also verified statistically. Thus, for example, a statistical $t$-test of the results showed that the mean unconfined DCP ($\bar{x}$) is larger than the mean confined DCP ($\bar{y}$) at a confidence level of 95 percent.

Moreover, a linear $y = a + bx$ type of regression analysis leads to the following results:

$a = 21.03$ ($S_a = 6.42$), $b = 0.103$ ($S_b = 0.158$), $R^2 = 0.45$, and $\sigma^2 = 46.21$

where

$S_a$ and $S_b$ = standard deviations for $a$ and $b$, respectively;
$\sigma^2$ = mean square error (MSE); and
$R$ = correlation coefficient.

A statistical $F$-test of this regression leads to the conclusion that at a confidence level of 95 percent, the regression is not significant or, in other words, that there is no correlation between $x$ values and $y$ values. The analysis according to Grubbs (*23*) leads to the conclusion that the systematic error related to measuring $x$ values is sig-

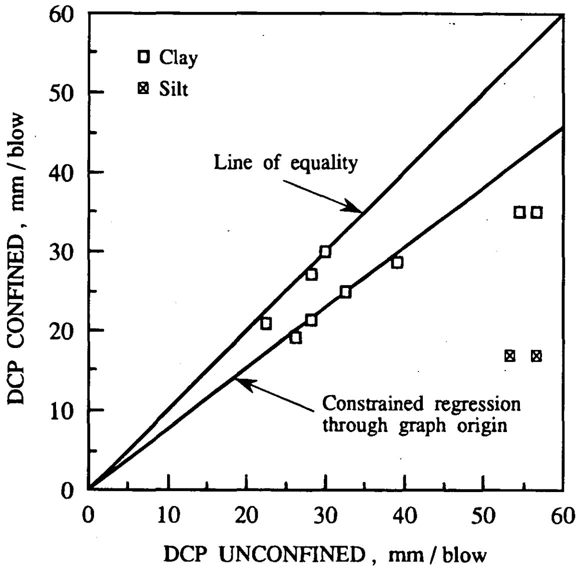

**FIGURE 7 DCP test results for subgrade beneath granular structure.**

nificantly different from the systematic error related to measuring $y$ values. At the same time, the precisions of the readings in both tests (as expressed by the standard deviation of the random error) can be considered identical. This analysis proves once again that the two test populations are not identical, and thus indicates the possible existence of vertical confinement.

Now, attention should be given to the two silt points in Figure 7. Since in the silt $\phi$ is $> 0$ on the basis of the discussion in the engineering background, it is conceivable that the two test points in the silt are indeed related to the phenomenon of vertical confinement, whereas there is no reason for the confinement effect to take place in the rest of the test points, which are in clay. For this reason the character of the two populations should be reexamined following exclusion of the two silt test points (marked separately in Figure 7).

The hypothesis that the two silt points do not belong to the population was examined by similar linear regression without the two points described earlier. The regression led to the following parameters:

$$a = 12.10\ (S_a = 3.199),\ b = 0.418\ (S_b = 0.086),\ R^2 = 0.771,\ \text{and}\ \sigma^2 = 9.005$$

An $F$-test of this regression leads to the conclusion that at a confidence level of 95 percent the model is significant and a linear correlation between $x$ and $y$ does exist.

The conclusion is that the two points do not belong to the same population, because without them there is a significant linear correlation. Finally, it can be assumed that the difference between the two populations $(x,y)$ is a result of the friction created in the rod during tilted penetration of the DCP rod through the granular material (as will be discussed later or of the friction created in the rod during a collapse of the granular material on the rod surface during penetration. A constrained regression through the graph origin was conducted to obtain the extent of the friction's effect on the results, and the following correlation was obtained: $y = 0.73x$. This leads to the following relationship:

$$\mathrm{DCP}_{\mathrm{unc}} = 1.34\ \mathrm{DCP}_{\mathrm{con}} \tag{8}$$

In other words when the DCP test is conducted through granular layers, an error of 34 percent magnitude may occur. In this specific case the DCP values of the clay subgrade should be increased by about 34 percent to obtain the true reduced strength of the material beneath the granular structure.

Finally, it should be mentioned that the effect of friction created in the rod (either by tilted penetration or by material collapse) can be quantitatively evaluated by torque measurement in the DCP device during penetration intervals. This work is being done and will be reported in the near future.

## EFFECT OF CONFINEMENT BY CLAY LAYERS

It is also important to examine whether conducting the DCP test on the surface of the clay subgrade and conducting the DCP test through this subgrade (commencing from a certain depth) lead to identical results. The results of the 27 tests are presented in Figure 8. The method was to conduct a DCP test on the surface and then dig a 0.5-m-deep test pit and conduct the DCP test again, commencing from the pit bottom downward.

The DCP value in the first test, which corresponds to a depth of 0.5 to 0.7 from the soil surface, is compared with a DCP value in the second test, which corresponds to a depth of 0.0 to 0.2 from the pit bottom. The first test provides the value of the confined DCP (the $x$ values), and the second test provides the value of the unconfined DCP (the $y$ value).

To test whether the two test populations are identical, a statistical analysis similar to that described earlier was performed. According to the statistical $t$-test results, both populations are identical. However, this result should be accepted with caution because there is no assurance that in the test population (derived from various sites with a wide range of strengths) the condition requiring that the standard deviation from the mean does not change with the change in the number of sites is indeed obtained.

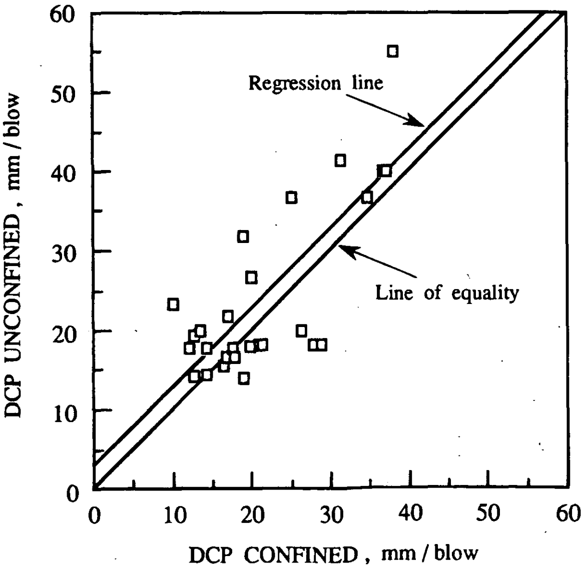

**FIGURE 8 Correlation between confined and unconfined DCP within clay subgrades.**

A regression analysis of the linear $y = ax + b$ type leads to the following results:

$$a = 2.86\ (S_a = 3.75),\ b = 0.98\ (S_b = 0.16),\ R^2 = 0.59, \text{ and } \sigma^2 = 48.23$$

Examination of the confidence interval for the parameters $a$ and $b$ at a confidence level of 95 percent leads to the acceptance of the hypothesis that $a$ equals zero and $b$ equals *1*, that is, that there is no additive or multiplicative bias. Hence, the calculated values for $a$ and $b$, 2.86 and 0.98, respectively, are not significant.

An analysis by the method of Grubbs (*23*) also indicates that both the systematic error and the standard deviation of the one population's random error are identical to those of the other population.

The final conclusion is that despite the variations shown in Figure 8, it seems that the two populations are identical. In other words the effects of the penetrating rod's surface friction are not felt in this case. This is logical, since in clay material (in contrast to granular material) the chances of preserving the gap between the sides of the hole created with the cone's penetration and the penetrating rod's surface, whose radius is smaller, are better.

## EFFECT OF CONFINEMENT BY RIGID STRUCTURE

An examination of the DCP values of a clay subgrade confined beneath a 50-cm-thick all-asphaltic pavement has yielded deviant strength results compared with the CBR values obtained by direct testing. The DCP test was conducted in the subgrade following drilling of the core for the entire depth of the all-asphalt structure. The results are presented in Figure 9.

When the regression is restrained through the graph zero of Figure 9, the equation is:

$$\text{CBR}_D = 1.75\ \text{CBR}_s \qquad (9)$$

or

$$\text{DCP}_s = 1.55\ \text{DCP}_D \qquad (10)$$

where $\text{CBR}_D$ is the CBR value calculated from the DCP test conducted through the all-asphalt structure, and $\text{CBR}_s$ is the direct CBR value.

To test whether the increase in strength presented in Equations 9 and 10 is the result of vertical confinement caused by the rigid all-asphalt structure, a special series of tests was conducted in the laboratory as described in the next paragraph.

In the test series clay samples (liquid limit, 66 percent; plasticity index, 43 percent) were compacted by 12 blows (4 samples) and 26 blows (18 samples) in the standard CBR mold. The moisture contents were higher than the plasticity limit. These clay samples were not saturated with water. Each pair of samples was tested with the DCP instrument both without vertical pressure (free top surface) and with the surface restrained by means of a thick metal plate with a 3-cm-diameter hole. At the end of the test it was clearly observed that when the sample was unrestrained there were vertical movements and cracking around the area of penetration, whereas in the case of the restrained samples, the upper soil surface remained smooth and uncracked and without any vertical movement.

All of the various statistical tests indicate that restraining the samples does not affect the DCP results. This can also be seen from the plotted results presented in Figure 10. The regression model leads to the following parameters:

$$a = 1.26\ (S_a = 3.51),\ b = 1.01\ (S_b = 0.114),\ R^2 = 0.90, \text{ and } \sigma^2 = 8.73$$

For a confidence level of 95 percent, $a$ equals zero and $b$ equals 1. This analysis does not follow the trend of results presented in Figure 9. The explanation for this can be given by assuming that friction forces do develop along the penetrating rod as a result of nonvertical penetration rather than because of the artificial restraining of the clay in the laboratory or its restraint by the all-asphalt pavement at the site. To test this assumption a series of tests was conducted in which the rod was inserted both vertically and at an angle of 15 degrees.

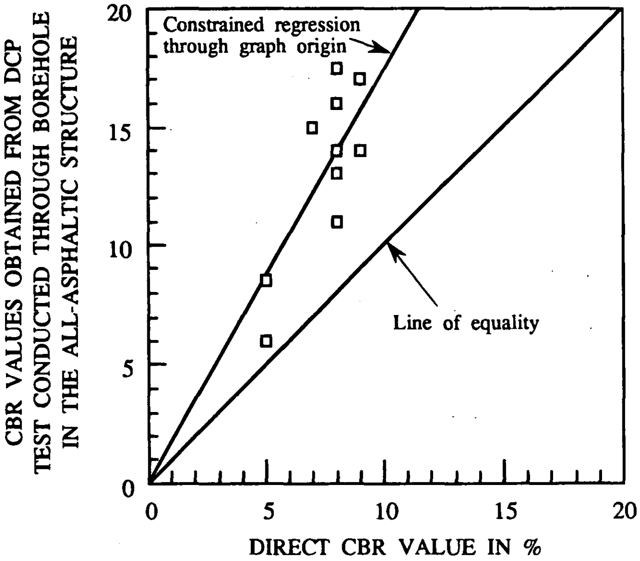

**FIGURE 9 CBR results from clay subgrade beneath 50-cm-thick all-asphalt structure.**

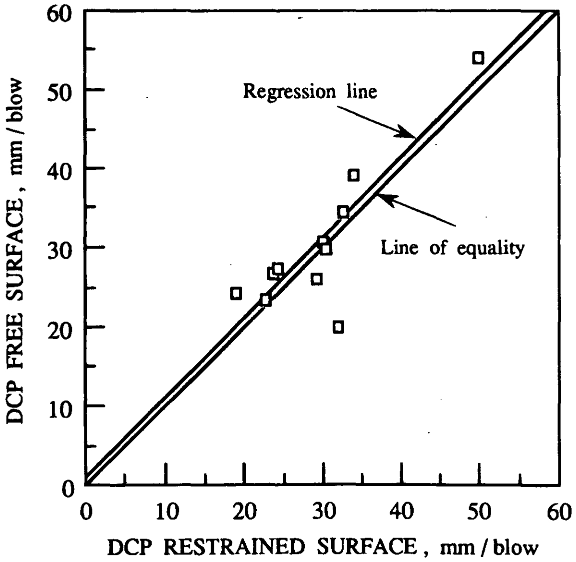

**FIGURE 10 Effects of restrained sample surface on DCP values.**

The statistical analysis indicates that there is a difference between the two tests. The mean $CBR_v$ value for the vertical penetration is 6.6 percent, whereas the $CBR_t$ value for penetration at a 15-degree angle is 8.9 percent. A constrained regression through the origin produces the following correlation (Figure 11):

$$CBR_v = 0.78\ CBR_t \qquad (11)$$

The meaning of this above regression is that the DCP value decreases (the strength increases) when the penetrating rod is inserted at an angle. This fact can be used to explain the results presented in Figure 9, since in many cases under actual deep DCP penetration, the rod tends to tilt at an angle of up to 15 degrees. It should be noted that the tilted penetration can be avoided by penetrating the DCP rod through a vertical supporting frame. This is accomplished by the regular DCP device or by an automated DCP device (*24*).

## EFFECT OF CONFINEMENT BY ASPHALT LAYERS

The effect of confinement by the asphalt layers on the granular pavement layers was examined by conducting DCP tests on the base course materials after drilling an asphalt core and comparing the results with those obtained from performance of the DCP test on these materials following the removal of a wide asphalt strip from the same spot tested previously. In contrast to the case described in the preceding section, one can expect here an increase in the normal DCP value compared with the confined DCP values in granular materials, since the bearing capacity factor, $N_{\gamma q}$, is far greater than 1. Indeed, the results obtained indicate the following correlation, as can also be seen in Figure 12:

$$DCP_{unc} = 1.84\ DCP_{con} \qquad (12)$$

The difference between the DCP values is statistically significant, and thus, the asphalt does indeed have a confining effect on the state of the granular material. Since this effect has been shown to exist, it is now appropriate that the strength values of the granular material in the CBR or DCP field tests should be determined only after the drilling of asphalt cores and not after the removal of a wide strip of asphalt.

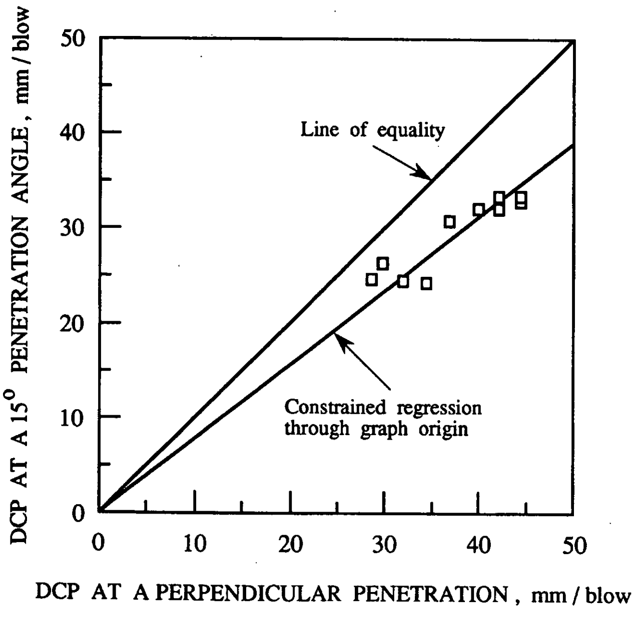

**FIGURE 11 DCP values from vertical penetration and penetration at a 15-degree angle.**

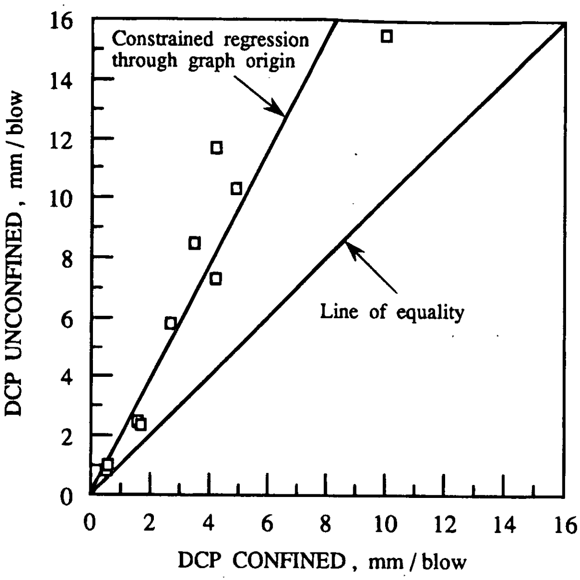

**FIGURE 12 Effects of asphalt confinement on DCP values in granular material.**

## SUMMARY

The DCP has become one of the most useful testing devices in pavement evaluation in Israel and other parts of the world. Consequently, a reliable true meaning of the results and an interpretation of the results were needed. This paper summarized research work that was dedicated to studying the effects of vertical confinement on the DCP values of the subgrade and the granular pavement layers. Specifically, four major effects were studied: vertical confinement of granular layers, vertical confinement of cohesive layers, vertical confinement of rigid structural layers, and the effect of vertical confinement of upper asphalt layers on the DCP values of the granular layers beneath them.

On the basis of the theoretical analysis, experimental testing in the laboratory and in the field, and statistical analysis, the following conclusions were made.

1. No vertical confinement effect by rigid pavement structure or by upper cohesive layers on the DCP values (or strength) of lower cohesive subgrade layers exists. Also, no vertical confinement effect by the upper granular layers on the DCP values of the cohesive subgrade beneath them exists. Any difference in the results between the confined and unconfined DCP values in the rigid structure case or in the case of the granular layers can be explained by the friction that developed in the DCP rod by tilted penetration or by a collapse of the granular material on the rod surface during regular penetration. This friction effect, which is also a function of the ratio between the cone tip and the rod diameters, can be quantitatively evaluated by torque measurements in the DCP device during penetration intervals.

2. A vertical confinement effect by the upper asphaltic layers on the DCP values of the granular pavement layers does exist. Generally, these confinement effects cause a decrease in the DCP values, thus increasing the structural strength measured. Since this is the true effect of the pavement structure, any DCP measurements for pavement evaluation purposes should be performed through a narrow boring in the asphalt layers and not after removal of a wide strip of asphalt.

3. The vertical confinement effects and the friction effects described earlier, which can be quantitatively evaluated, should be taken into consideration when using the DCP method in pavement and subgrade evaluation.

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