Evaluation of Trench Backfill at Highway Cross-Drain Pipes

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ABSTRACT

This paper presents the results from field and full-scale laboratory tests on different trench backfill materials in the construction of highway cross-drains. The purpose was to study the cause of "dip" problem in asphalt pavement over trenches. The Dynamic Cone Penetration (DCP), Dynamic Deflection Determination System (DYNAFLECT), Falling Weight Deflectometer (FWD), and Plate Load Test (PLT) were used in this investigation to measure the stiffness of backfill materials and adjacent subgrade soils, and to develop the correlations among different test devices. Three sets of cross-drain trenches with and without "dip" problems were selected for the tests. In addition, three full-scale trench sections were also constructed and tested in a laboratory site. The field test data indicate that pavements that have problems at cross-drain trenches have weaker backfill than the adjacent subgrade soils. Whether or not this kind of "dip" occurs is also affected by other factors such as the stiffness of pavement structures and the loading of truck traffic. It is found that sand backfills constructed under current specifications so far are generally weaker than the native subgrade soils in Louisiana. The results of this study also indicate good correlations among the test data from the DCP, DYNAFLECT, FWD, and PLT, which can be used in the future for the quality control of backfills.

KEY WORDS: Trench backfill, Dynamic Cone Penetration, DYNAFLECT, Plate Load Test, Falling Weight Deflectometer

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INTRODUCTION

Conduit structures are commonly used in the Louisiana highway system to deal with hydraulic drainage needs. These structures include pipe culverts, pipe arch culverts, storm drains, sewers, etc. Although the Louisiana Department of Transportation and Development (LA DOTD) has standard specifications for building these structures to guarantee their proper functions, unexpected settlements still occur at some of these locations. These settlements usually cause the deterioration of pavement ride comfort by forming "dips" in the pavement riding surfaces, as shown in the example of Figures 1-a, 1-b, and 1-c. Figure 1-a is a pavement profile at a problematic cross-drain pipe location on a newly constructed rural highway. Figure 1-b shows its corresponding pavement rutting profile, and Figure 1-c shows its rideability measured by the International Roughness Index (IRI) and Mean Roughness Index (MRI). Here, MRI is defined as the average of IRI values from the left and right wheel paths. Figure 1-d is the view of this problematic cross-pipe location. Even though the "dip" is not perceptible to the naked eye, it is noticeable in a vehicle and can be detected by a Profiler Van.

The problem illustrated by Figures 1-a through 1-d indicates that, under certain conditions, the current LA DOTD specifications cannot guarantee the quality of cross drain installation to preserve pavement ride quality. Because of this, the Louisiana Transportation Research Center (LTRC) has initiated a research project to address the issue.

Field investigation indicates that under the same traffic and environment conditions, pavement "dips" occur at some cross-drain pipe locations but not at others. This provides LTRC's research team a starting point to investigate the problem. To fully understand the reason why pavement "dips" occur, the research team conducted field tests at about 20 cross-drain locations with and without pavement "dips" in LA DOTD Engineering Districts 03, 08, 61, and 62. In addition, three full-scale trenches (without pipes) were also constructed by LTRC research team to verify the testing data from the 20 field sites and to investigate different backfill materials and techniques (compaction efforts).

FIELD TESTS AND PROCEDURE

The field-testing program included the Dynamic Cone Penetration (DCP) and Dynamic Deflection Determination System (DYNAFLECT). The DCP is a simple and effective tool that is used for the assessment of pavement layers and subgrade (1). It can provide continuous measurements of in-situ strength and stiffness of subgrade soils without sampling. The crew from the LTRC geotechnical laboratory conducted the DCP test in the field. In each test, the existing pavement structures were first cored through using a drill rig, and DCP tests were then started at the top of subgrade soil. During the test, the penetration for each hammer blow was recorded, which is referred to as the penetration rate (*PR*, in cm/blow). The DCP tests were conducted both in and out of trench backfill area at each pipe location for comparison.

DYNAFLECT is a trailer-mounted device that induces a dynamic load on pavement and measures the resulting deflections, as shown in Figure 2-a, by usually five geophone sensors. DYNAFLECT with Model Number 1000-8A was used in this study. The resilient modulus, M_R, of subgrade soil was determined according to a normal graph procedure developed by Kinchen and Temple (2). This normal graph procedure is based on a double-layer model shown in Figure 2-b. The LTRC pavement research crew conducted and interpreted the DYNAFLECT testing data.

DCP DATA REDUCTION

A typical DCP raw data profile in Figure 3-a shows the variation of penetration rate (*PR)* along the depth. This kind of profile emphasizes the weakness of soils. Larger *PR* values indicate weaker soils. To emphasize the stiffness of backfill materials, a penetration blow count, N_{DCP}, in blows/10 cm, is defined as the average blow counts over a 5-cm (2") thick soil layer, or

$$N_{DCP} = \frac{10}{\dfrac{\sum_{i=1}^{n} PR_i}{n}} = \frac{10 \cdot n}{\sum_{i=1}^{n} PR_i} \qquad \textit{(blows / 10 cm)} \qquad (1)$$

Here, n is the number of *PR* readings in a 5-cm (2") thick soil layer. If n = 0 in equation (1), N_{DCP} will be

$$N_{DCP} = \frac{10}{PR_{adjacent}} \qquad \textit{(blows / 10 cm)} \qquad (2)$$

Here, $PR_{adjacent}$ is the penetration rate from the soil just above the 5-cm (2") thick soil layer considered. Stiffer soils will have higher N_{DCP} values.

The selection of the 5-cm thickness mitigates reading errors that might occur during the DCP tests, and the coefficient of 10 is also empirically selected with a reference to previous studies (1, 3). Webster et al. (3) suggested that

$$CBR = \frac{292}{DCP^{1.12}} = \frac{292}{(10 \cdot PR)^{1.12}} = \frac{292}{10^{1.12} \cdot 10^{1.12}} \cdot \left(\frac{10}{PR}\right)^{1.12} = 1.68 \cdot (N_{DCP})^{1.12} \qquad (3)$$

where *CBR* is the California Bearing Ratio and *DCP* stands for the *DCP* index in mm/blow. In this way, N_{DCP} will have a simple correlation with other engineering parameters. It also reflects the normal range of DCP readings for subgrade soils. Consequently, the *PR* profile in Figure 3-a is converted to a N_{DCP} profile over the depth, as shown in Figure 3-b. A simple software program that transfers the *DCP* index profile in mm/blow or *PR* profile in cm/blow to the N_{DCP} profile is developed for DCP data processing and will be available on the LTRC website at www.ltrc.lsu.edu.

FIELD TESTING RESULTS

Field-test locations were selected after consulting with local LA DOTD district maintenance engineers and inspectors. The criteria for selecting the locations were based upon the severity of pavement "dips" at cross-drain trenches and the type of trench backfill material. Tests were conducted both in the backfills and adjacent subgrade for comparison. The following sections discuss the field test results.

Settlement Versus Non-Settlement

The first group of cross-drain trenches tested used sand as trench backfill and subsequent pavement "dips" developed. A common discovery from testing these locations is that the sand backfill is much weaker than the adjacent native subgrade soils. Figure 3-b discussed earlier shows a typical set of N_{DCP} profiles obtained from one such location that developed a "dip." In this figure, the average N_{DCP} value in the trench backfill is about 4 blows per 10 centimeters, which is much less than the average value outside the trench of 9 blows per 10 centimeters. DYNAFLECT tests indicate a resilient modulus of 38.6 MPa (5,600 psi) within the sand backfill and 47.6 MPa (6,900 psi) in the subgrade soil outside the trench.

The second group of test locations also used sand as backfill material, yet no pavement "dips" showed up. There were two types of situations at these locations. The N_{DCP} values in these sand backfilled trenches were either nearly the same as the values in the adjacent native subgrade soils with medium or high truck traffic, or less than the values from the adjacent native subgrade soils under very light or no truck traffic. Figure 4-a is a typical set of N_{DCP} profiles for the former cases and Figure 4-b is an example for the latter cases.

In Figure 4-a, the N_{DCP} values are almost the same within and outside the trench backfill with a N_{DCP} value of about 4. DYNAFLECT tests indicate a resilient modulus of 51 MPa (7,400 psi) within the sand backfill and 48 MPa (7,000 psi) in the subgrade soil out of the trench, which are very close results.

In Figure 4-b, the N_{DCP} values of sand backfill at one side of the pipe are about 6 with a resilient modulus of 33 MPa (4,800 psi) while the N_{DCP} values at the other side are about 11 with a resilient modulus of 56 MPa (8,100 psi). The N_{DCP} values outside the trench are about 17 with a resilient modulus of 76 MPa (11,000 psi). Even though the N_{DCP} values inside the trench are less than those outside the trench, pavement "dips" do not always occur. Other factors also influence pavement "dip" development. These results prove the belief that pavement "dips" at cross drain locations indicate much weaker backfills in the trenches than the adjacent subgrade soils. Pavement "dips" at cross-drain pipe locations can be prevented if the trench backfill is at least as strong as or stronger than the adjacent subgrade soils.

Native Subgrade Soils Versus Sand Backfill

Figures 5-a and 5-b are the scatter distributions of N_{DCP} values with depth for native subgrade soils and sand backfill, respectively. These two figures include all the data the research team collected for native subgrade soils and sand backfill material, regardless of pavement "dip" presence. They indicate that both native subgrade soils and sand backfill have a wide spectrum of variation with respect to N_{DCP} values. This variation is normal for native subgrade soils since they are the results of a natural process, but it is abnormal for the sand backfill as they were constructed under the same specifications designed to produce consistency. Statistically, the data in these two figures indicate that the sand backfill is in general weaker than the native subgrade soils, as shown in Figures 6-a and 6-b.

Hypothetically, if trench backfills can reach a stiffness corresponding to N_{DCP} of 10 blows per 10 centimeters (1 blow per centimeter) or larger, most pavement "dips" caused by backfill settlement could be prevented at these locations. This is because most native subgrade soils have N_{DCP} values less than 10 blows per 10 centimeters, as shown in Figures 5-a and 6-a. This finding is consistent with the DCP data for subgrade soils obtained by the Minnesota Department of Transportation (4). Pavement structures over trench backfill also have a function of "bridging" traffic loading over these weaker areas. Though this "bridging" function is not fully understood at this time, pavement structures distribute traffic loading over a larger area, and hence reducing settlement due to lower loading stresses.

The current LA DOTD specification allows poorly graded sand to be used as trench backfill as shown in Figure 7. The shaded area in this figure describes the current acceptable range of granular material used as trench backfill material. For the sand example given in the figure, the sand has the uniformity coefficient, C_u, of 2.7 and the coefficient of gradation, C_C, of 0.87. Generally, the sand specified by the current specification is difficult to compact and achieve the required densities.

Other Backfill Materials

The experience obtained with sand lead the research team out of current specifications and into different trench backfill materials. The maintenance crews at LA DOTD and in local cities have already used other backfill materials to replace cross-drain pipes. These materials include RAP (Recycled Asphalt Pavement), Mexican Limestone, and washed gravel. Their construction procedure can best be described as "dump in." No compaction was applied and traffic was allowed to compact the backfills. To gain some preliminary knowledge on the properties of these backfill materials, the research team selected those available locations as the third group. According to the maintenance crews, the RAP backfill was built within the past three to six months, and the washed gravel and Mexican limestone sections were built about a year ago. The DCP test results from these sites are shown in Figure 8. These data indicate that further testing is needed for these materials.

As another development in LA DOTD construction practice, flowable fill, also known as Controlled Low Strength Materials (CLSM), has been used as backfill in some districts. The research team tried to conduct DCP tests at these locations. As expected, they found flowable fill used as backfill to be much stronger than the adjacent subgrade soils. The DCP device could not penetrate through the flowable fill.

Correlation between N_{DCP} and M_R

A general correlation between the resilient modulus, M_R, determined by DYNAFLECT and DCP data is established as shown in Figure 9, including all the material types tested. Average values of N_{DCP} over 60 cm (2 ft) and 90 cm (3 ft) were calculated at each location and plotted against the resilient moduli of the same location. The difference between the two linear regressions is marginal for a practical purpose. With a correlation coefficient $R = 0.79$, the relationship is given as:

$$M_R = 3.48 \cdot N_{DCP} + 28.25 \qquad (3 < N_{DCP} < 30) \tag{4}$$

Here, M_R is in MPa and N_{DCP} is in blows per 10 cm, which is an average value of N_{DCP} over 90 cm (3 ft) depth. Equation 4 is quite different from the correlations suggested by other studies (4,5,6). This variation can be attributed to the different methods used to determine the resilient modulus, M_R.

FULL-SCALE CONTROLLED TESTS

So far in the field investigation, the DCP was used to test subgrade soils and different backfill materials with the intention of using it as a quality control tool in trench backfill construction. Literature review indicates that material types may have an influence on DCP test results (4,7,8,9). Therefore, full-scale controlled tests were conducted at the LTRC laboratory site to establish the correlation between the N_{DCP} and M_R for different materials. Another purpose of these tests was to explore the workability, strength, and stiffness of different materials as backfill at different compaction efforts.

Three test trenches, each 20 ft long, 4 ft wide, and 3 ft deep, were constructed at the laboratory site using three selected backfill materials: crushed limestone, RAP, and sand. Table 1 summarizes the test results for the trench sections. The gradations for these three materials were shown earlier in Figure 7. The average moisture content obtained from nuclear gauge reading was 3.7% for sand, 8.4% for RAP, and 5.1% for the crushed stone. The trenches were filled in three 12"-thick lifts. Each trench was divided into three equal sections with different compaction efforts: light, medium, and heavy. Light compaction was achieved from one compaction pass by a vibratory plate compactor (Wacker Packer, Model Number WP1550AW, 200 lb); medium compaction was achieved from four compaction passes by the vibratory plate compactor; heavy compaction was achieved from four Wacker Packer compaction (Model BS45Y 53kg, 117lb) passes in addition to four vibratory plate compactor passes. The bottom and sides of the trench were wrapped in geo-fabric to separate the backfill materials from native soils.

DCP Test Result

DCP tests were conducted after compaction of each lift during the backfill process. Figure 10-a is an example of the DCP data after each lift of backfill. This figure shows how penetration blow count, N_{DCP}, increases with the additional lifts. Figure 10-b shows all data points presented in percent increase of average N_{DCP} values in each lift. The left part of the figure shows the data when the first lift had one overburden lift above it, where

$$Percent\ Increase\ of\ N_{DCP} = \frac{average\ N_{DCP}\ with\ one\ overburden\ lift}{average\ N_{DCP}\ without\ overburden\ lift} \tag{5}$$

The right part of the chart is when the first lift had two overburden lifts above it, where

$$Percent\ Increase\ of\ N_{DCP} = \frac{average\ N_{DCP}\ with\ two\ overburden\ lifts}{average\ N_{DCP}\ without\ overburden\ lift} \tag{6}$$

In general, the first lift's average N_{DCP} is affected more by the placement and compaction of the second lift (one overburden layer) than by the third lift (two overburden layers).

Figure 10-c shows the correlation of average N_{DCP} values over backfills with their thickness for different material. This figure indicates that the average N_{DCP} values increases with the increase of backfill thickness, mainly due to the overburden effect discussed earlier. This figure also shows that sand was the least sensitive to compaction effort, next to RAP, since the increase of average N_{DCP} values resulting from different compaction efforts for sand is very limited due to its very poor gradation as already discussed and shown in Figure 7.

Other Tests and Their Correlations

Besides the DCP, the Plate Load Test (PLT), the Falling Weight Deflectometer (FWD), and DYNAFLECT were also conducted after the construction of each trench to evaluate the strength and stiffness of the backfill materials. The following is the discussion of the correlations among these test results.

I. DCP versus PLT

The PLT is a standard field test used to determine the bearing capacity of soils and to evaluate the strength/stiffness properties of pavement layers and subgrade. A circular plate of 25.4 cm (12") diameter was used in this study. The test procedure followed ASTM D1196.

Figure 11-a shows a typical loading and reloading curve obtained from a PLT from which a reloading elastic modulus, E_{PLT}, is calculated. For a rigid plate, the second reloading elastic modulus is defined as:

$$E_{PLT} = \frac{2 \cdot \left(1 - \mu^2\right)}{\pi \cdot \delta_2} \cdot \frac{P}{R} \qquad (7)$$

where, P is the applied load; μ is the Poisson's ratio; R is the radius of plate; and δ_2 is the deflection under the second loading cycle of the plate.

Figure 11-b is the general correlation of average N_{DCP} values over a 90-cm layer with the reloading elastic modulus obtained from PLT for different backfill materials. This figure indicates that the different studied backfill materials generally follow the same trend with regard to their mechanical properties, and that a higher N_{DCP} value means a higher reloading elastic modulus, E_{PLT}, of soils. With a regression correlation coefficient of $R = 0.92$,

$$E_{PLT} = -0.34 \cdot \left(N_{DCP}\right)^2 + 13.97 \cdot N_{DCP} - 13.67 \qquad (2 < N_{DcP} < 15) \qquad (8)$$

Here, N_{DCP} is in blows per 10 cm and E_{PLT} is in MPa. Figure 11-b also shows the correlation suggested by Konard et al. (10) given as

$$\begin{aligned} \log\left(E_{PLT}\right) &= -0.884 \cdot \log\left(10 \cdot PR\right) + 2.906 = -0.884 \cdot \log\left(\frac{100}{N_{DCP}}\right) + 2.906 \\ &= 0.884 \cdot \log\left(N_{DCP}\right) + 1.138 \end{aligned} \qquad (9)$$

Where, PR is in cm/blow and N_{DCP} is in blows/10-cm, and E_{PLT} is in MPa. The correlations described by Equations 8 and 9 are quite close to each other as shown in the figure.

II. DCP versus FWD

The FWD is a trailer-mounted device that delivers an impulse load to the surface to be tested. DYNATEST 8002 FWD was used in this study and a computer program ELMOD4 was used to back-calculate the resilient modulus (M_{FWD}) of the trench backfills tested at PRF.

The average values of N_{DCP} over 90 cm (3 ft) were correlated with the resilient modulus, M_{FWD}, determined by the FWD, as shown in Figure 12. With a regression correlation coefficient of $R = 0.92$,

$$M_{FWD} = -0.14 \cdot \left(N_{DCP}\right)^2 + 10.61 \cdot N_{DCP} + 17.11 \qquad (2 < N_{DCP} < 15) \qquad (10)$$

The units in Equation 10 are the same as in Equation 9. Figure 12 also shows the correlation suggested by Chen et al. (7) as

$$M_{FWD} = 338 \cdot (10 \cdot PR)^{-0.39} = 338 \cdot \left(\frac{100}{N_{DCP}} \right)^{-0.39} = 56.09 (N_{DCP})^{0.39} \tag{11}$$

Where, *PR* is in cm/blow and N_{DCP} is in blows/10-cm, and M_{FWD} is in MPa. The correlations described by Equations 10 and 11 are quite different. The resilient modulus, M_{FWD}, determined by Equation 10 is in general 30 MPa lower than the values determined by Equation 11.

III. DYNAFLECT, PLT, and FWD

Figure 13-a compares the moduli determined by DYNAFLECT, PLT, and FWD by re-plotting Equations 4, 8, and 10. It indicates that the moduli from FWD are much higher than the values from DYNAFLECT and the values from PLT are between them.

Figure 13-b shows a direct empirical correlation between FWD and PLT. With a regression correlation coefficient of $R = 0.89$,

$$M_{FWD} = 6.686 \cdot (E_{PLT})^{0.612} \qquad (10\,MPa < E_{PlT} < 120\,MPa) \tag{12}$$

where both M_{FWD} and E_{PLT} are in MPa.

Figure 13-c describes the direct empirical correlations between DYNAFLECT and PLT, and between DYNAFLECT and FWD. The abscissa in Figure 13-c is $\alpha = W_1/SPD$, where W_1 is the maximum deflection read by first sensor as shown in Figure 2-a. *SPD* stands for percent of spread that is equal to the average of all sensor readings divided by the reading of first sensor. Therefore,

$$\alpha = \frac{W_1}{SPD} = \frac{(W_1)^2}{\frac{\sum_{i=1}^{7} W_i}{7}} = \frac{7 \cdot (W_1)^2}{\sum_{i=1}^{7} W_i} \tag{13}$$

Here, W_i and α are in centimeters.

With a regression correlation coefficient of $R = 0.70$,

$$M_{FWD} = -80.79 \cdot \alpha + 209.36 \qquad (1 < \alpha < 2) \tag{14}$$

and with $R = 0.91$

$$E_{LPT} = -102.9 \cdot \alpha + 224.9 \qquad (1 < \alpha < 2) \tag{15}$$

Here M_{FWD} and E_{PLT} are in MPa. Figure 13-d is the analytic model of DYNAFLECT for subgrade soils in which Equations 14 and 15 are valid.

CONCLUSIONS

This paper presents the results from the first phase of the LTRC research project: Alternative Methods to Trench Backfill (03-3GT). The following conclusions are made from the work of this phase.

- Pavement "dips" will occur at cross-drain trenches where trench backfill is much weaker than the adjacent native subgrade soils. The occurrence of pavement "dips" is also affected by the magnitude of truck traffic loading and the stiffness of pavement structure. Further study on these factors will be conducted in the next phase of this study.
- The quality control of cross-drain trench backfill should consider and use adjacent subgrade soils of the trench as a reference to prevent possible pavement "dips" caused by the differential settlement of backfill materials.
- The DCP is a useful tool for the ultimate quality control of trench backfill construction. It has the advantage of providing a continuous profile of stiffness over the depth of both the backfill material in the trench (around the pipe) and the adjacent native subgrade soils. Alternately, FWD and DYNAFLECT can also be used for quality control and diagnostic tools because of their correlations with DCP data as shown in this paper and their swift testing procedures.
- The effect of different backfill materials on DCP results is marginal for a practical purpose.
- DCP results have a better correlation with PLT results than those from the FWD, possibly due to the characteristics of back-calculation for FWD results.

The correlations established from the field and full-scale controlled tests at the laboratory site are limited to the test methods, procedures, and conditions described in this paper. Cautions should be applied when one of them is selected to predict the moduli of subgrade soils for its suitability.

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REFERENCES

1. Kleyn, E.G. (1975), "The Use of Dynamic Cone Penetrometer (DCP)", Report 2/74, Transvaal Roads Department, Pretoria, South Africa.
2. Kinchen, R.W., and Temple, W.H. (1980), "Asphaltic Concrete Overlays of Rigid and Flexible Pavements", Report No. FHWA/LA –80/147, Louisiana Department of Transportation and Development.

3. Webster, S.L., Grau, R.H., and Williams, T.P. (1992). "Description and Application of Dual Mass Dynamic Cone Penetrometer", Geotechnical Laboratory, US Army Corps of Engineers, Instruction Report GL-92-3.
4. Burnham, T.R. (1997), "Application of the Dynamic Cone Penetrometer to Minnesota Department of Transportation Pavement Assessment Procedures", Report No. MN/RC – 97/19, Office of Minnesota Road Research, Minnesota Department of Transportation.
5. De Beer, M. (1991), "Use of Dynamic Cone Penetrometer (DCP) in the Design of Road Structures", Geotechnics in African Environment, Blight et al. (Eds), Balkema, Rotterdam, ISBN 90 5410 007 9.
6. Chai, G., and Roslie, N. (1998), "The Structural Response and Behavior Prediction of Subgrade Soils using Falling Weight Defelectometer in Pavement Construction", 3rd International Conference on Road & Airfield Pavement Technology.
7. Chen, J., H. Mustaque, and T. M. LaTorella, (1999), "Use of Falling Weight Deflectometer and Dynamic Cone Penetrometer in Pavement Evaluation", Paper Presented in the Transportation Research Board, Washington, D.C.
8. Harison, J.A., (1989), "Correlation Between California Bearing Ratio and Dynamic Cone Penetrometer Strength Measurements of Soils", Proceedings of In-situ Civil Engineers, Part 2.
9. Jayawickrama, P.W., Amarasiri, A.L., and Regino, P.E. (2000), "Use of Dynamic Cone Penetrometer to Control Compaction of Granular Fill", Transportation Research Record 1736, Paper No. 00-1416.
10. Konard, J.M. and Lachance, D. (2000), "Mechanical Properties of Unbound Aggregates from DCP and Plate Load Tests", Proceedings of the Fifth International Conference on Unbound Aggregate in Roads, Nottingham, United Kingdom.

Table 1. Summary of Full-Scale Trench Test Information

Trench Number	Material	Section Number	Compaction Effort	Standard Proctor γ_d (kN/m^3)	Field Moisture Content (%)	Field Dry Density γ_d (KN/m^3)	Average N_{DCP} (Blows per 10 cm)	Modulus E_{PLT} (MPa)	Modulus M_{FWD} (MPa)
1	Sand	1	Light*	16.8	3.7	16.1	1.5	15.38	27
		2	Medium**			17.1	3.6	40.03	77
		3	Heavy***			17.2	5.3	-	-
2	RAP	1	Light	18.4	8.4	15.8	3.3	18	44
		2	Medium			16.9	6.2	32	78
		3	Heavy			18.0	14	105.2	139
3	Crushed Limestone	1	Light	21.4	5.1	18.9	2.8	29.95	40
		2	Medium			19.1	4.7	35.17	70
		3	Heavy			21.1	17.5	96.5	92

* : One pass of vibratory plate compactor

** : Four passes of vibratory plate compactor

*** : Four passes of vibratory plate compactor + four passes of Wacker Packer compaction

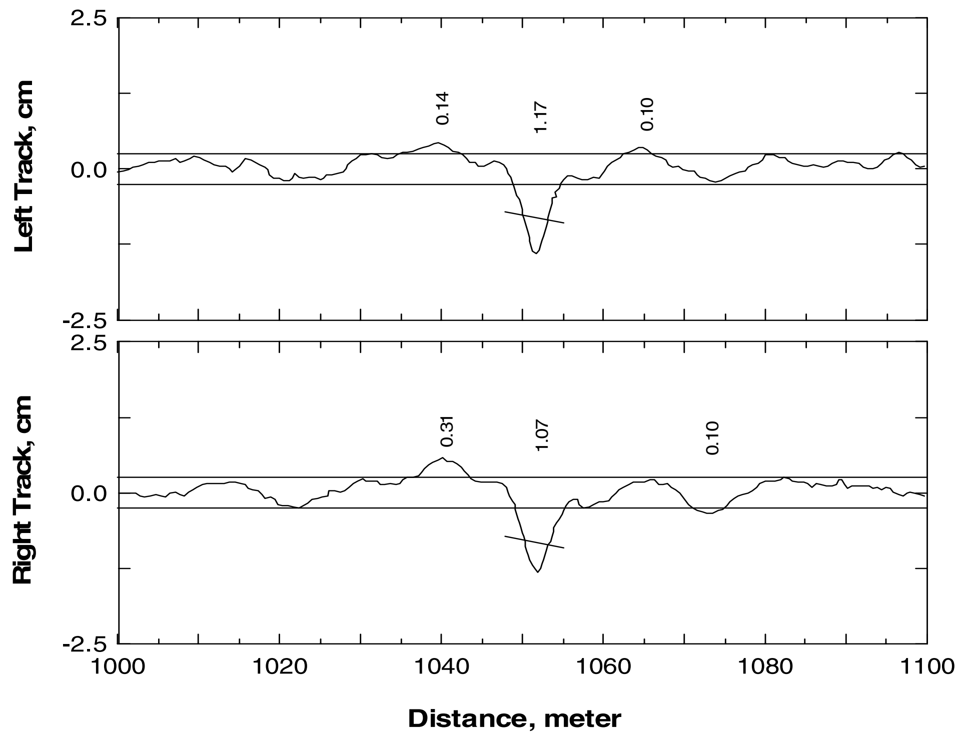

Figure 1-a. A Pavement Profile at a Problematic Cross-Drain Pipe

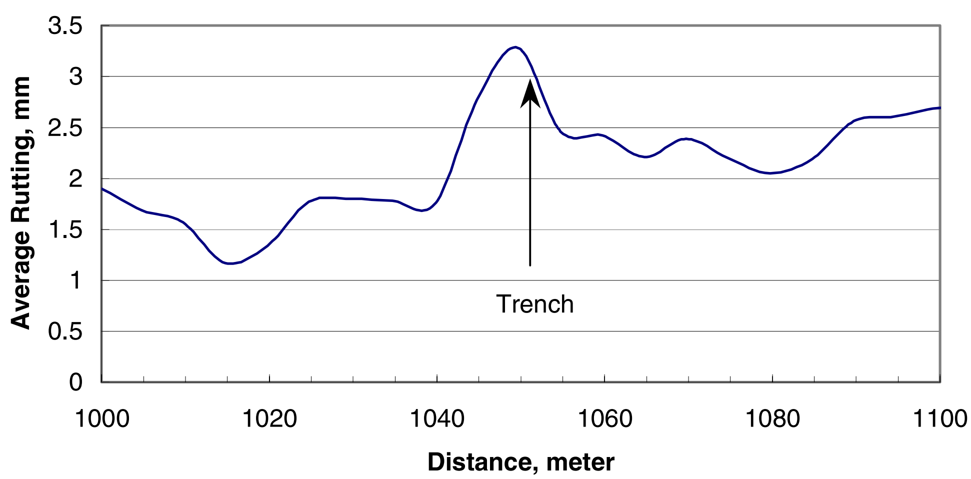

Figure 1-b. A Pavement Rutting Profile at a Problematic Cross-Drain Pipe

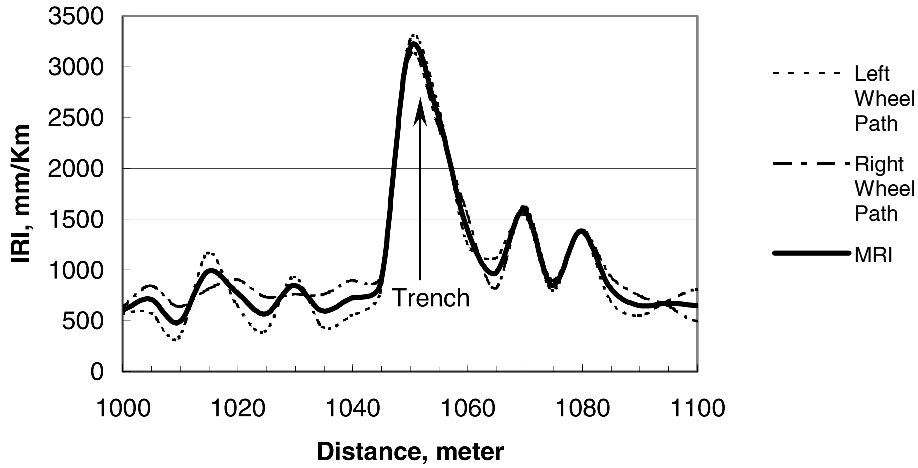

Figure 1-c. Rideability at a Location of a Problematic Cross-Drain Pipe

Figure 1-d. A Photo for the Problematic Cross-Drain Pipe Location on a Newly Constructed Highway

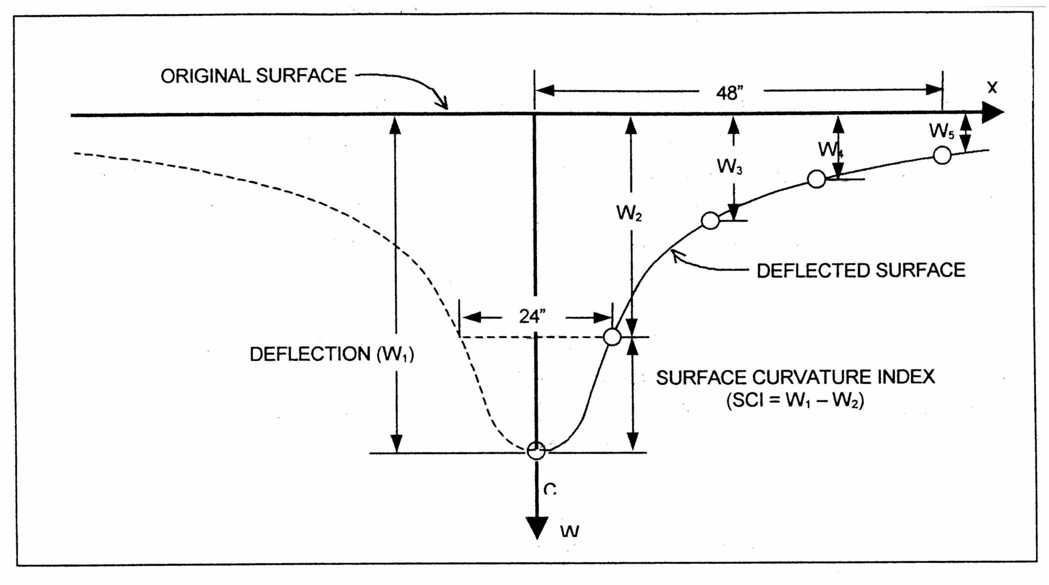

Figure 2-a. Typical DYNAFLECT Deflection Basin

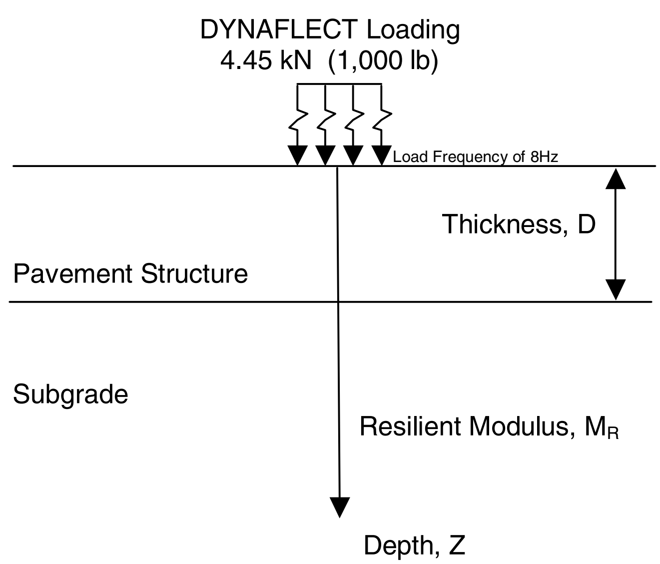

Figure 2-b. The Analytic Model of DYNAFLECT for Pavement

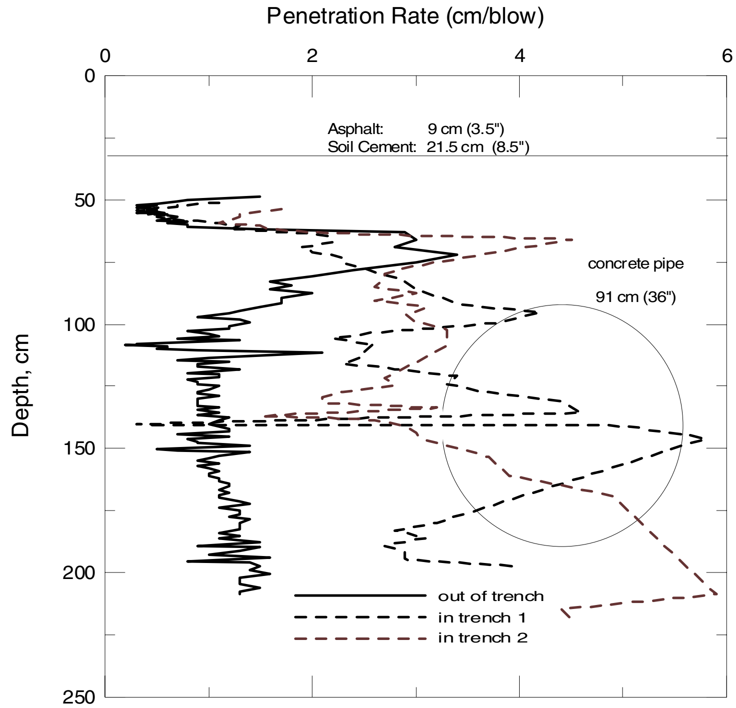

Figure 3-a. A Raw DCP Test Profile

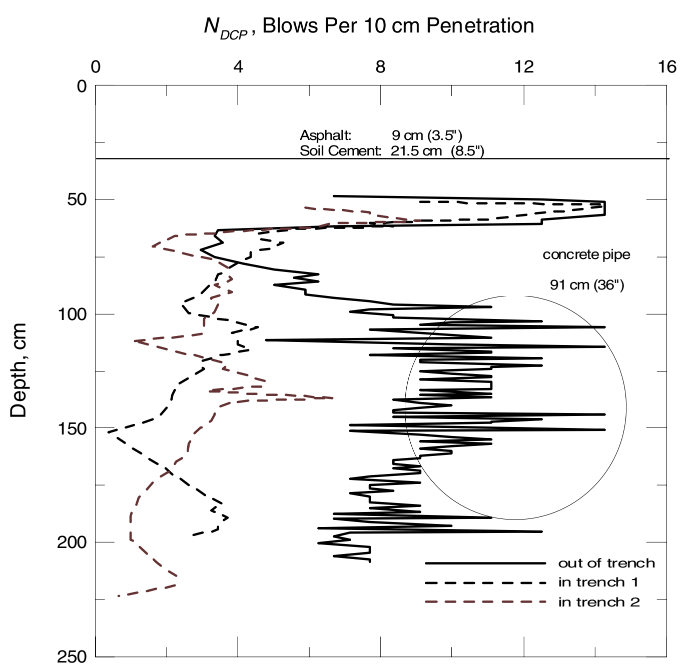

Figure 3-b. The Reduced DCP Profile with Pavement Settlement

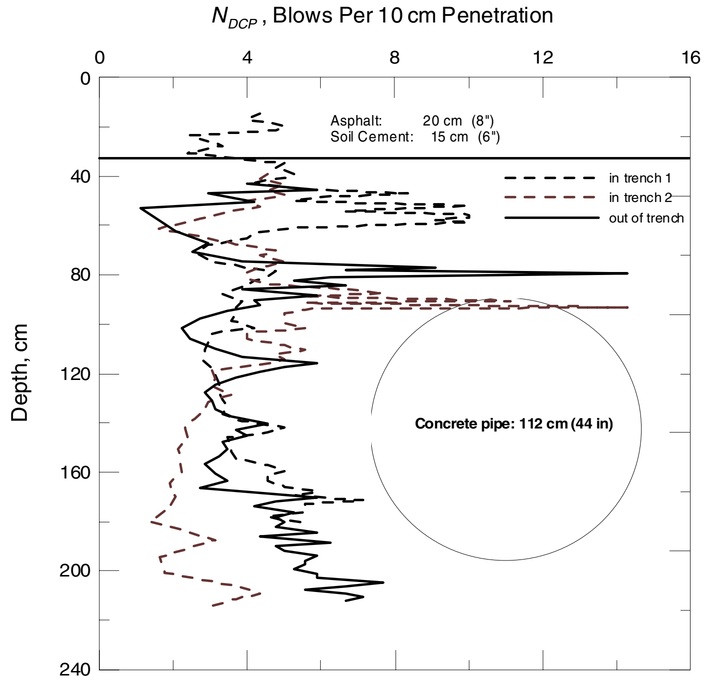

Figure 4-a. A N_{DCP} Profile without Pavement Dip under Truck Traffic

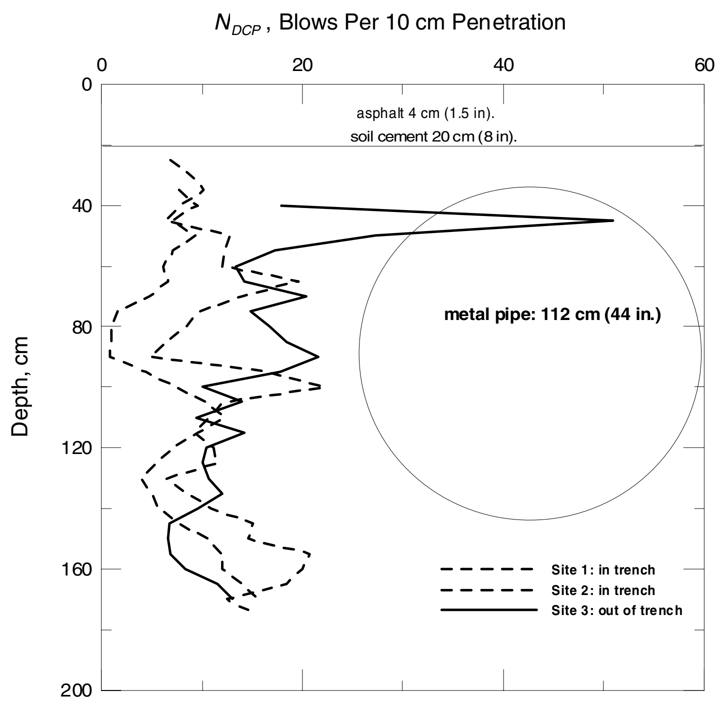

Figure 4-b. A N_{DCP} Profile without Pavement Dip Under No Truck Traffic

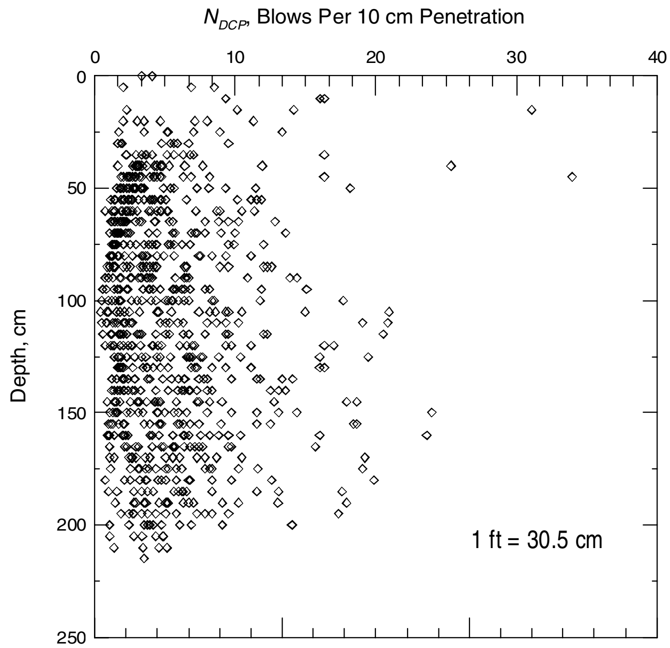

Figure 5-a. The Scatter Distribution of N_{DCP} for Native Subgrade Soils

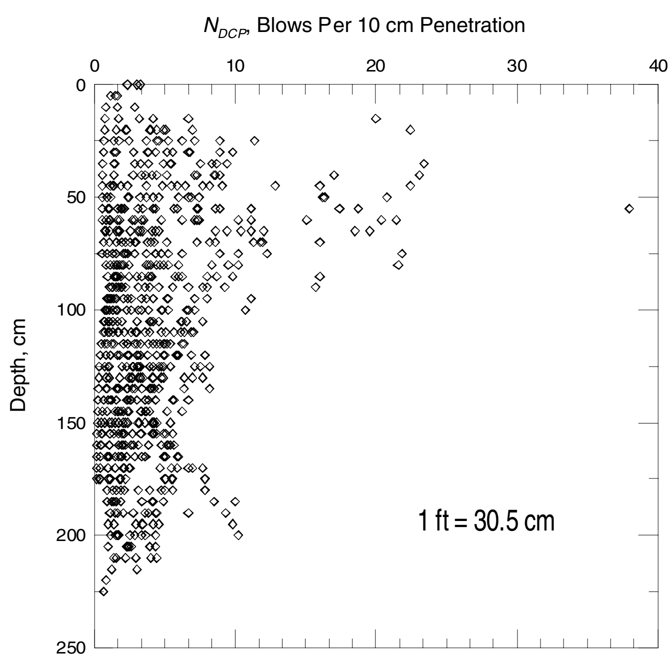

Figure 5-b. The Scatter Distribution of N_{DCP} for Sand Backfill

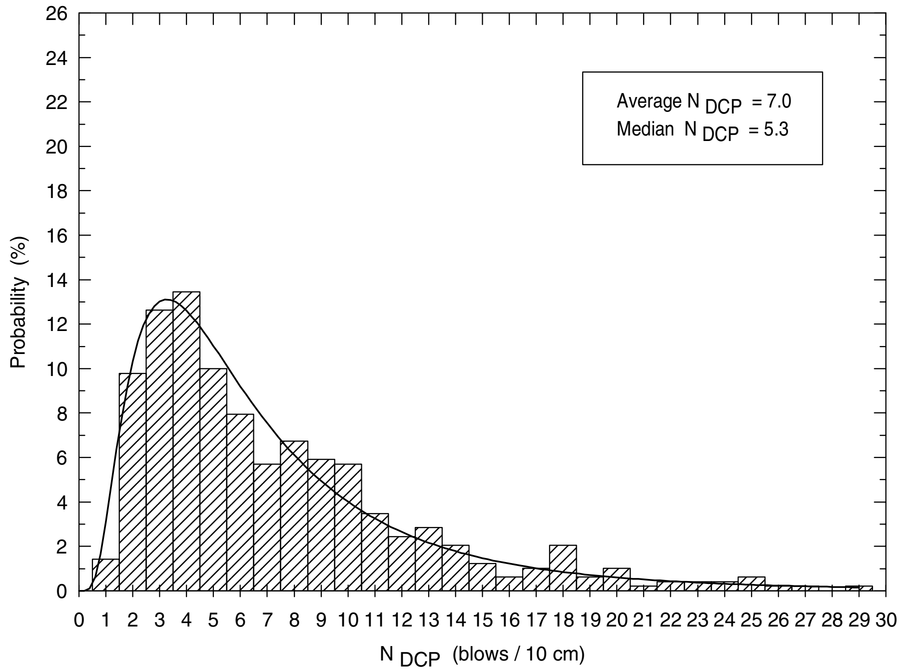

Figure 6-a. Histogram of N_{DCP} for Subgrade Soils

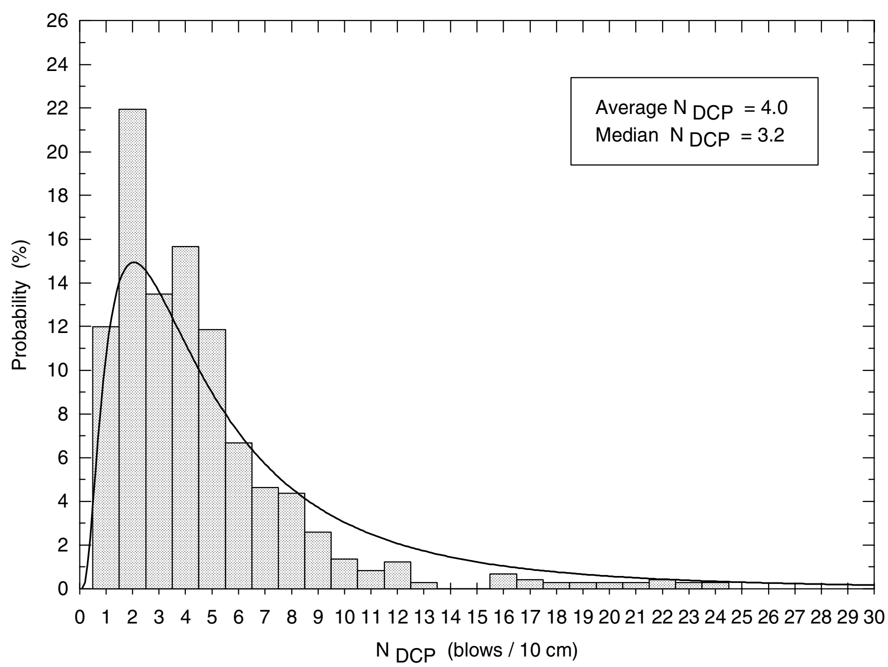

Figure 6-b. Histogram of N_{DCP} for Sand

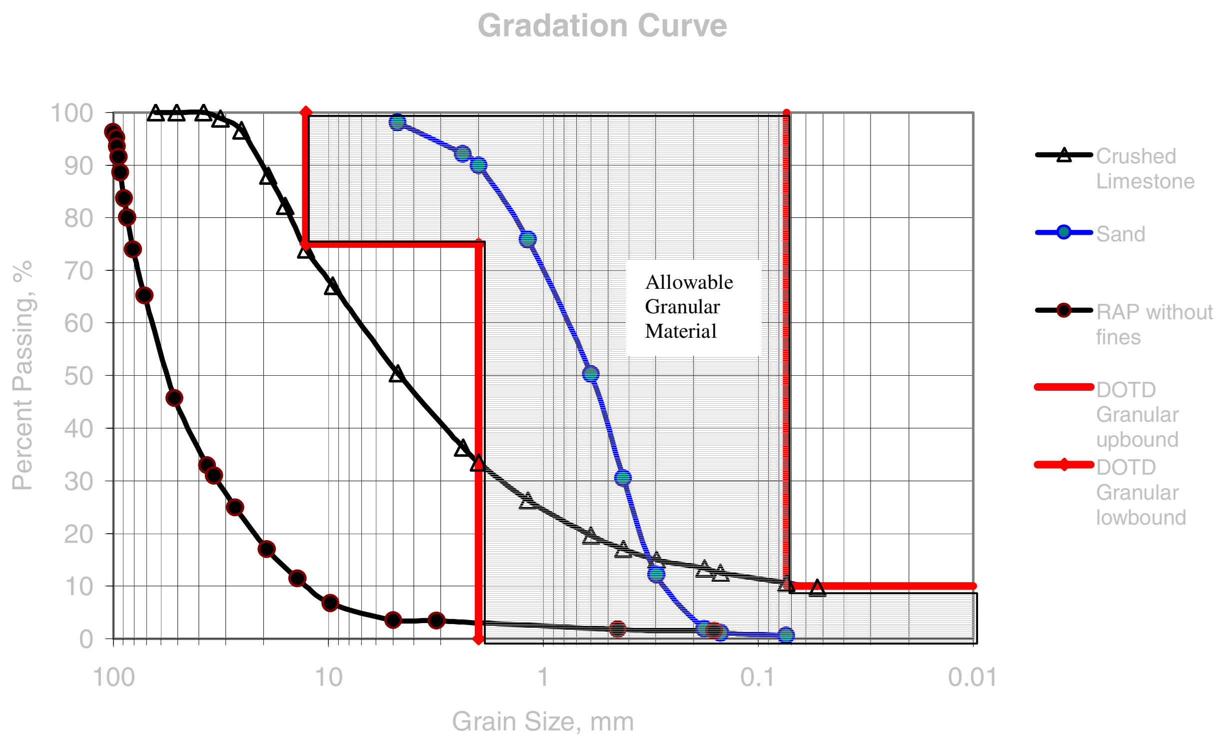

Figure 7. Louisiana DOTD Specification on Granular Material

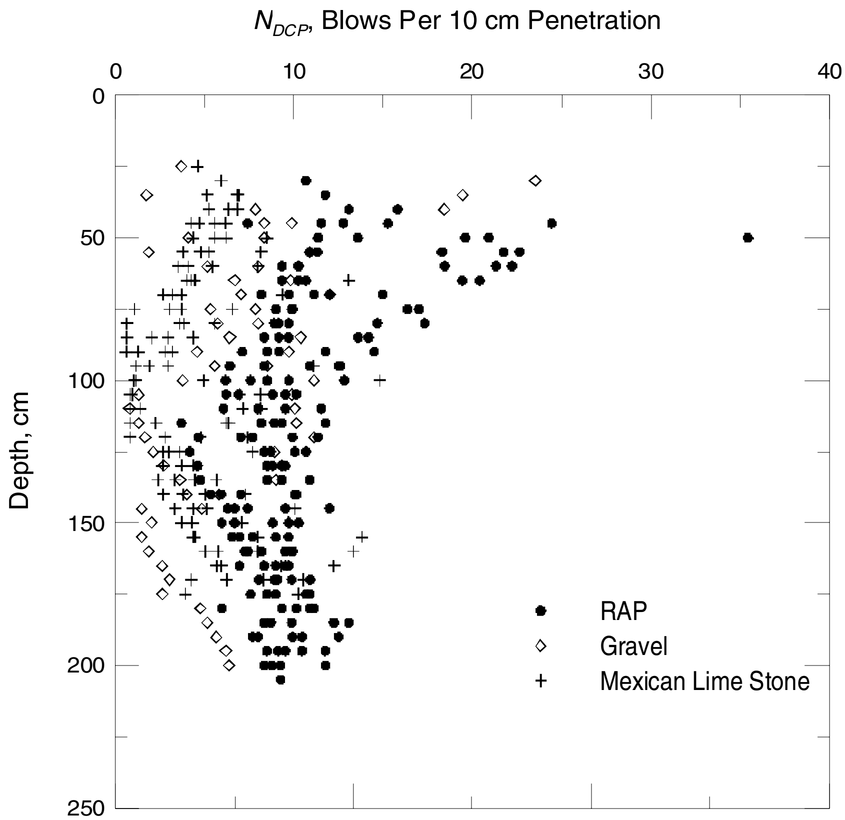

Figure 8. Scatter Distributions of N_{DCP} for Different Materials

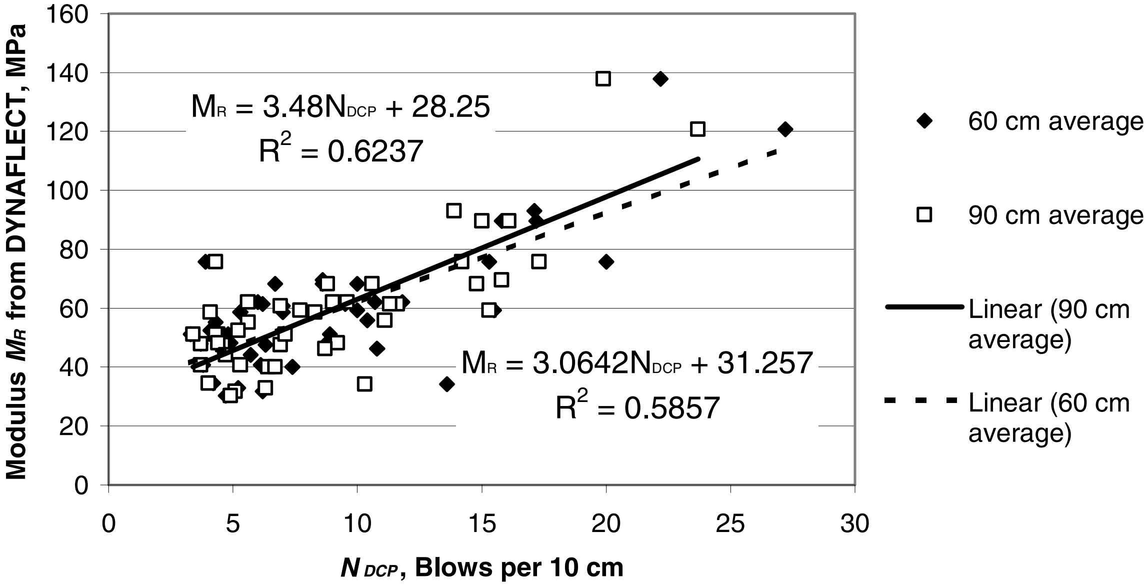

Figure 9. Correlation of N_{DCP} with the DYNAFLECT Resilient Modulus, M_R

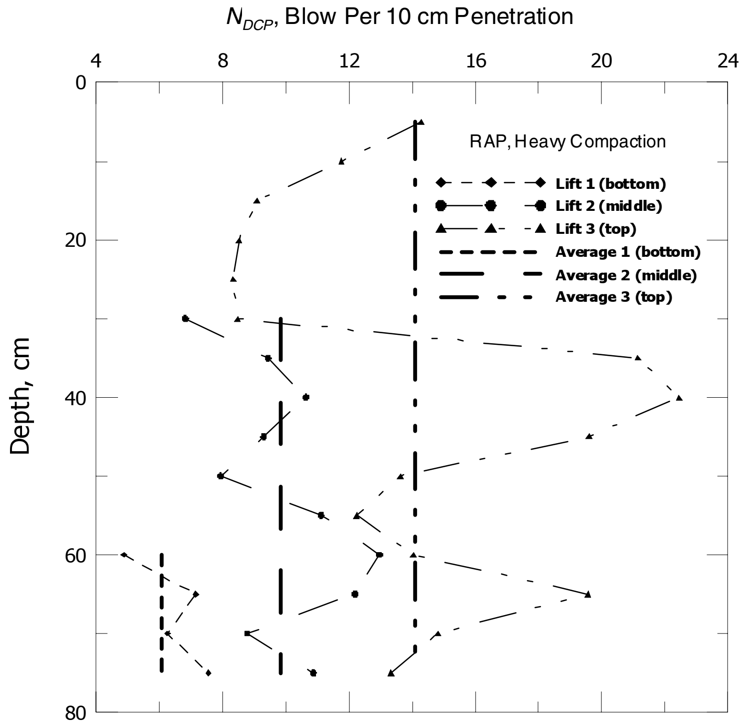

Figure 10-a. N_{DCP} Profiles after Each Lift for RAP Material

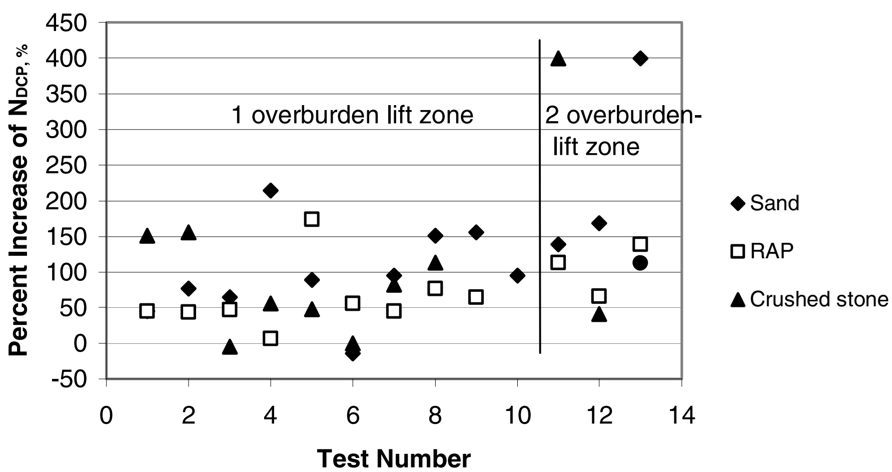

Figure 10-b. The Percent Increase of Average N_{DCP} Values in Each Lift

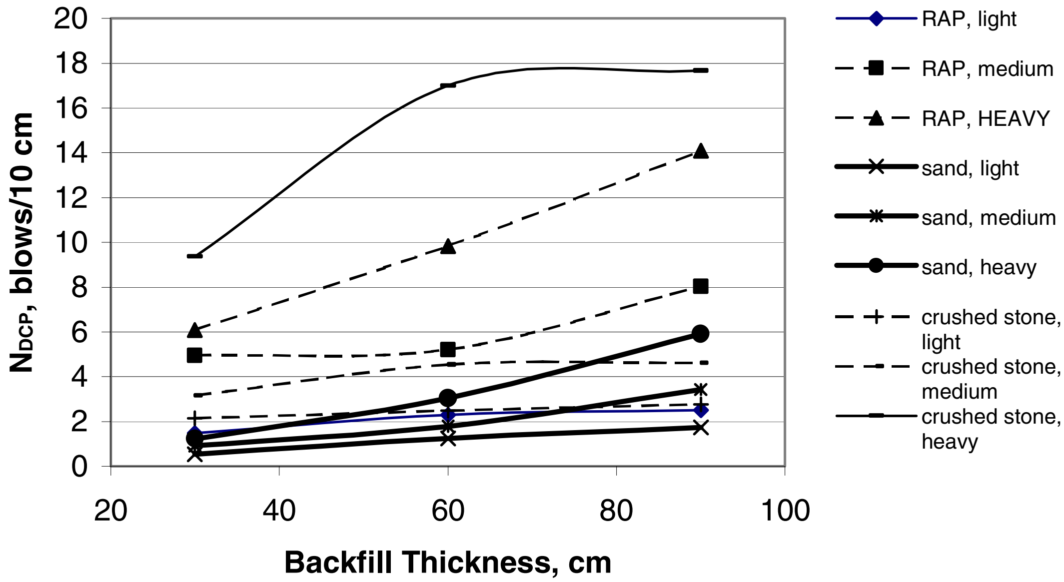

Figure 10-c. Correlation of Average N_{DCP} Values in a Backfill with Its Thickness

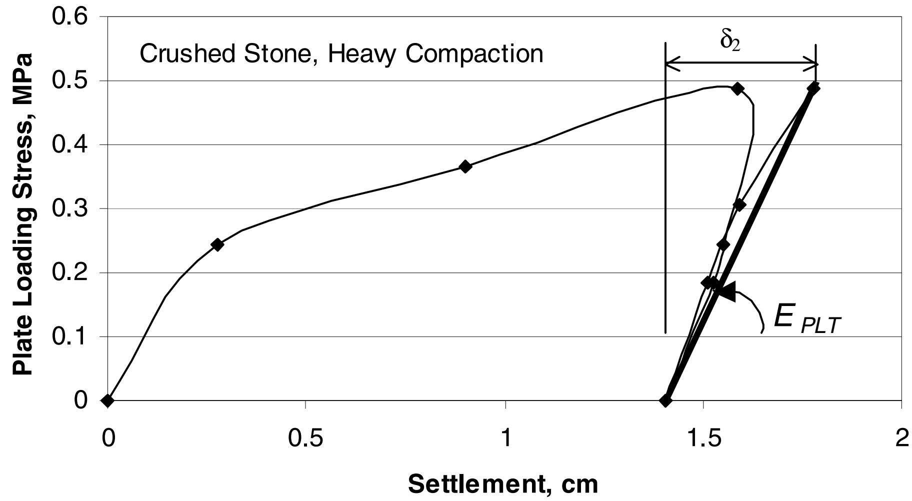

Figure 11-a. A Loading and Reloading Curve of PLT for Crushed Stone

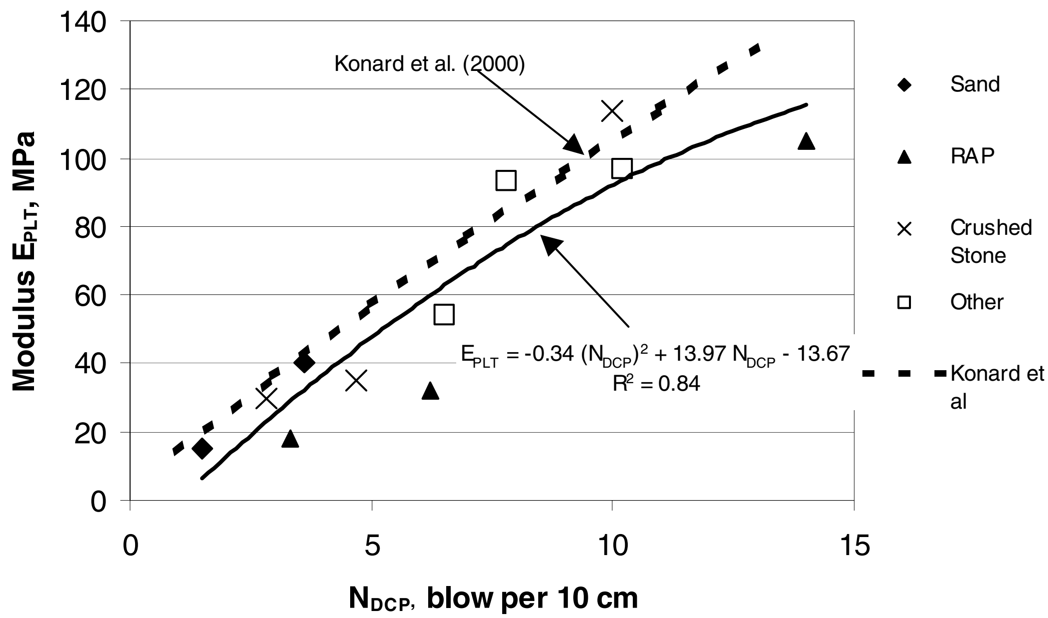

Figure 11-b. Correlation of Average N_{DCP} Values over a 90-cm Layer with E_{PLT}

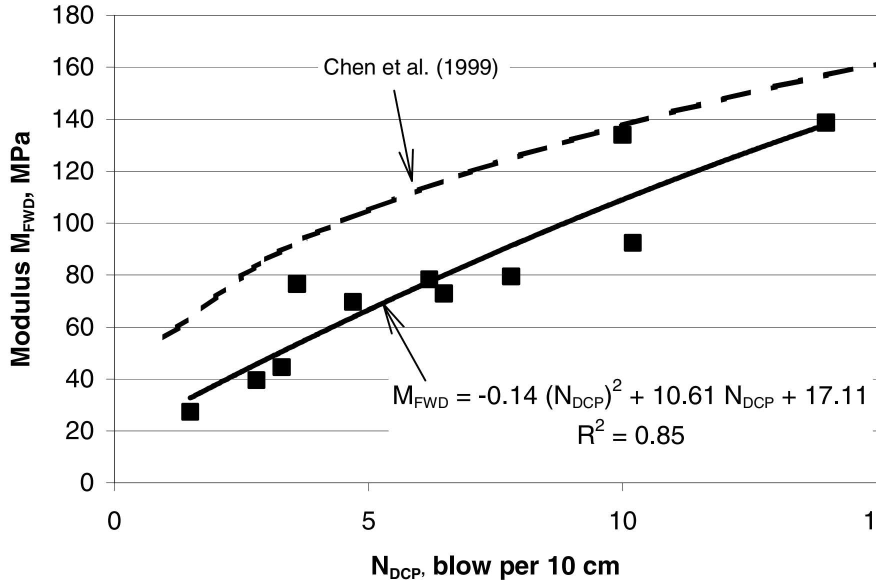

Figure 12. Correlation of Average N_{DCP} Values over a 90-cm Layer with M_{FWD}

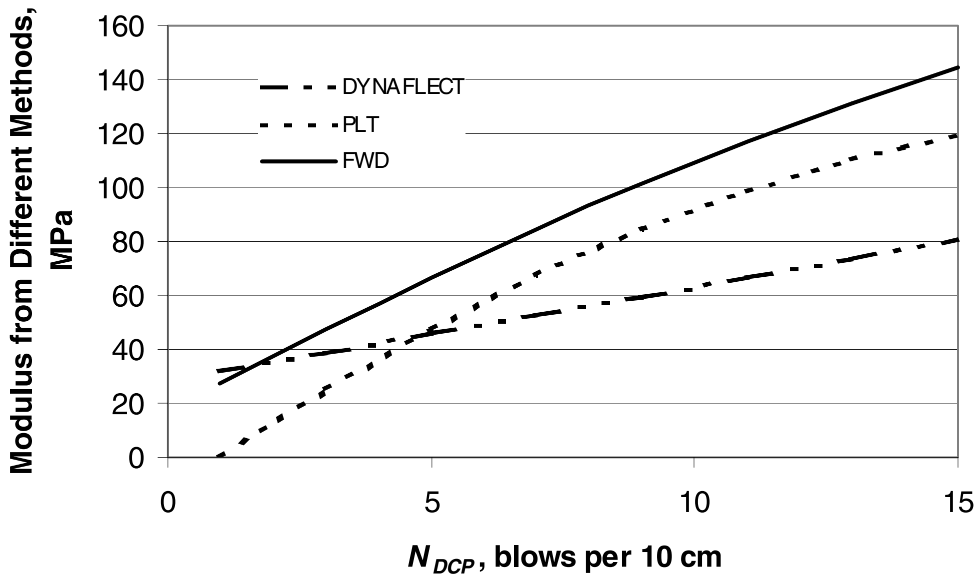

Figure 13-a. Relationship among Moduli by Different Methods

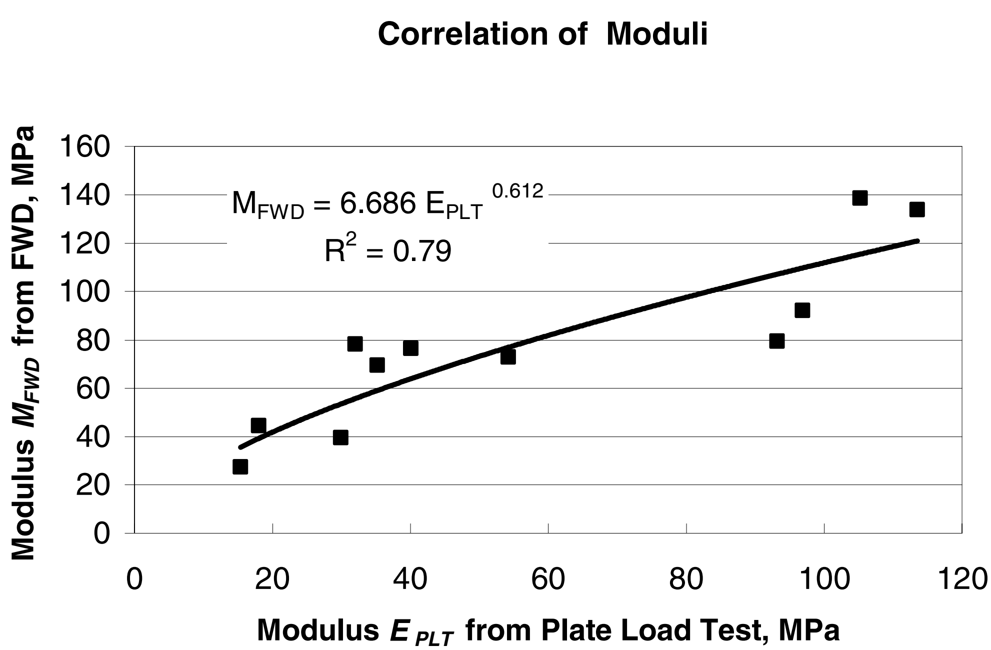

Figure 13-b. Direct Correlation of E_{PLT} with M_{FWD}

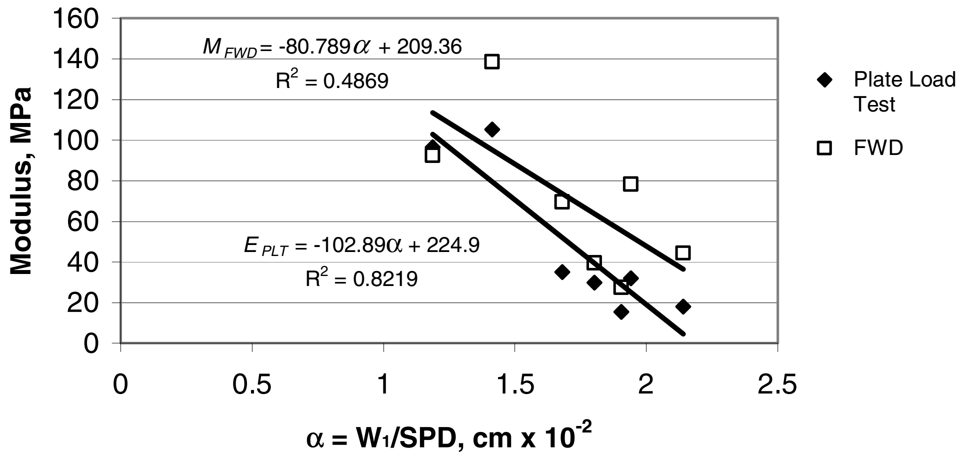

Figure 13-c. Correlation between DYNAFLECT Reading and Moduli

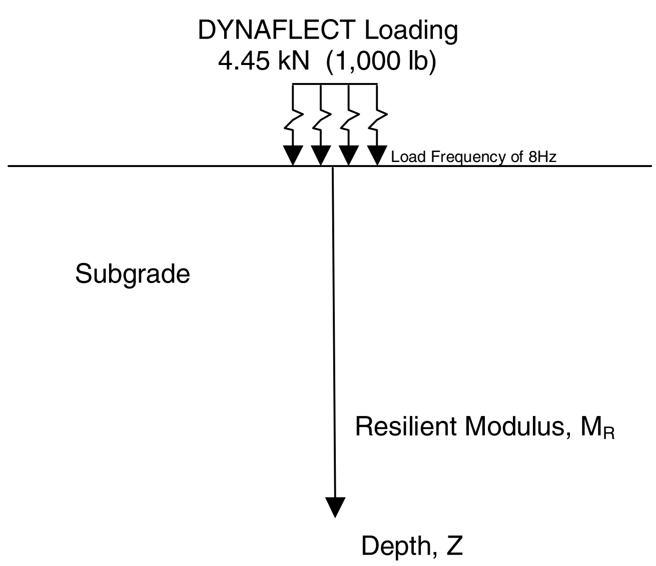

Figure 13-d. The Analytic Model of DYNAFLECT for Subgrade