

Rapid Shear Strength Evaluation of In Situ Granular Materials

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Dynamic Cone Penetrometer (DCP) and rapid-loading (1.5 in./sec) triaxial shear strength tests were conducted on six granular materials compacted at three density levels. The granular materials were sand, dense-graded sandy gravel, AREA No. 4 crushed dolomitic ballast, and material No. 3 with 7.5, 15, and 22.5 percent FA-20 material. (FA-20 is a nonplastic crushed-dolomitic fines material—96 percent minus No. 4 sieve : 2 percent minus No. 200 sieve.) DCP and triaxial shear strength data (including stress-strain plots) are presented and analyzed. The major factors affecting DCP and shear strength are considered. DCP-shear strength correlations are established and algorithms for estimating in situ shear strength from DCP data are presented. To the authors' knowledge, this is the first study in which the shear strength of granular materials has been related to DCP test data. Such relations have significant potential applications in evaluating existing transportation support systems (railroad track structures, airfield and highway pavements, and similar types of horizontal construction) in a rapid manner. A DCP test can be conducted to a depth of 2 to 3 ft in a matter of minutes. Several tests can be conducted to establish the variability of the in situ material.

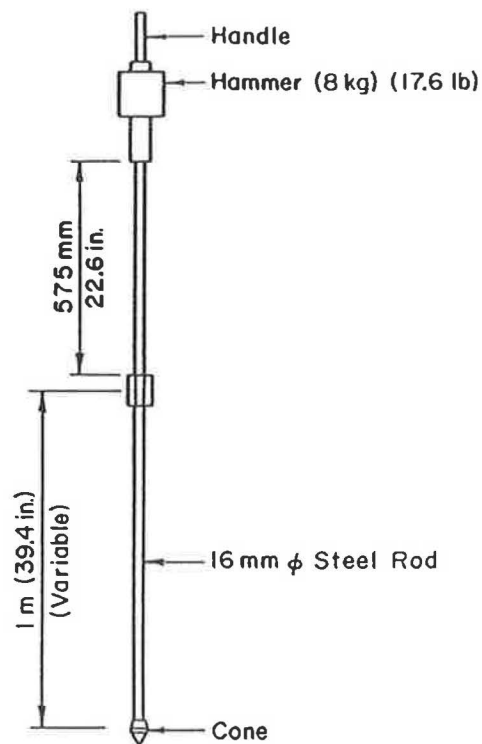
Characterization of in situ shear strength of granular materials and fine-grained soils in transportation support systems evaluation is an expensive and time-consuming endeavor. Test excavations, laboratory analysis of bulk field samples, and in situ tests [i.e., plate bearing and California bearing ratio (CBR)], have all been used. Because of the expense involved, however, testing is generally quite limited.

The high variability associated with most soil types and the number of soil types typically encountered in a project necessitate a test method that is inexpensive and rapid. The trade-off has been either a cursory survey with limited results or an in-depth characterization of a limited number of sites.

Several rapid test methods are available for evaluating in situ strength. The dynamic cone penetrometer (DCP)(1), the Clegg hammer, the U.S. Army Waterways Experiment Station penetrometer (commonly referred to as the "WES cone penetrometer"), the dynamic portable penetrometer (DPP)(2), and the vane shear apparatus are examples of devices currently in use. Device limitations include the inability to differentiate layers or detect zones of weakness (Clegg hammer), incompatibility with large particle sizes (vane shear apparatus), the inability to penetrate high-strength materials (WES cone), and the lack of strength correlations for granular materials with large-sized aggregate (DPP).

The DCP does not have these limitations. It can be used for a wide range of particle sizes and material strengths and can characterize strength with depth.

The DCP, as used in this study, consists of a 17.6-lb sliding weight, a fixed-travel (22.6 in.) weight shaft, a calibrated stainless steel penetration shaft, and replaceable drive cone tips (Figure 1). Test results are expressed in terms of the penetration rate (PR), which is defined as the vertical move-



THE CONE

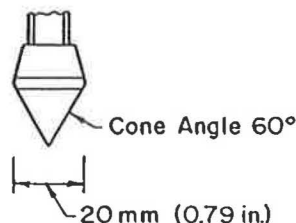


FIGURE 1 Dynamic cone penetrometer.

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FIGURE 2 DCP utilization.



ment of the DCP cone produced by one drop of the sliding weight (inches/blow).

The DCP has many advantages. It is adaptable to a wide range of material types, can be conducted rapidly (approximately 5 to 10 min per test site), is portable, and is relatively inexpensive to construct and maintain.

The DCP is particularly well suited for in situ strength evaluation of railroad track beds, highway and airfield pavements, and unpaved areas. Figures 2 and 3 show the DCP evaluation of a railroad system and a typical depth-blow count relation. The differentiation in layer strengths is evident in Figure 3. Note, the total blow count to a given depth is indicative of overall strength.

There are existing DCP-CBR correlations (3,4), as illustrated in Figure 4. DCP use has been limited in part because of a lack of correlations relating DCP penetration values with fundamental material properties such as shear strength (cohesion, c , and the angle of internal friction, Φ). These properties are essential inputs to many mechanistic-empirical analysis and design procedures including ILLI-PAVE (5), ILLI-TRACK (6,7), and similar procedures using Mohr-Coulomb failure criteria. This paper establishes DCP-shear strength correlations for a range of granular materials.

OBJECTIVE AND SCOPE

The primary objective of this study is to evaluate the efficacy of the DCP for estimating the shear strength of granular materials. A simple, quick, and economical field procedure is desired to evaluate the structural adequacy of ballast through the use of RAILER, the railroad track maintenance management system under development at the U.S. Army Construction Engi-

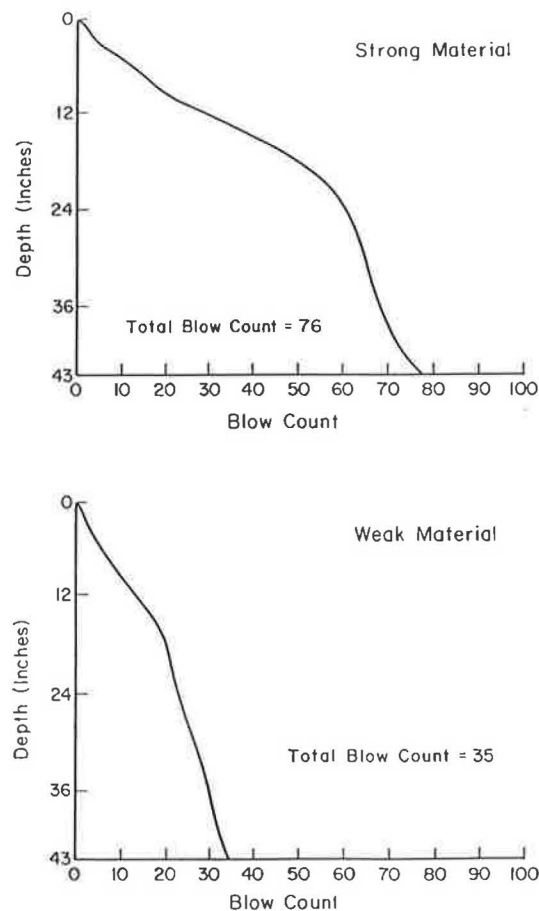


FIGURE 3 Typical DCP blow count-depth relationships.

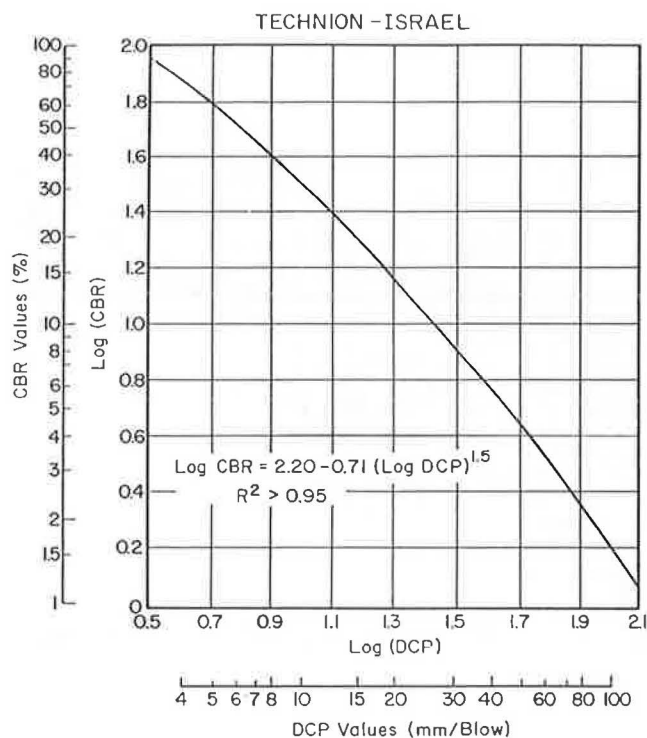


FIGURE 4 CBR-DCP algorithm (3).

neering Research Laboratory (USA-CERL). To the authors' knowledge, no currently available correlations establish a relationship between the DCP-PR and granular material shear strength.

Therefore, a two-phased study was conducted to establish the desired correlations. In Phase 1, typical track section materials including sand, sandy gravel, crushed dolomitic ballast, and ballast with varying amounts of nonplastic fines were evaluated with the DCP to obtain a general understanding of the factors involved in the test procedure. Phase 2 focused on determining the shear strength and associated parameters for each of the materials previously tested with the DCP apparatus. Phase 2 test results were statistically analyzed to establish regression equations relating PR and shear strength.

MATERIALS

The materials evaluated were sand, dense-graded sandy gravel (Rokey), crushed dolomitic ballast (AREA No.4), and ballast with varying amounts of nonplastic crushed dolomitic fines (minus No.4 sieve, FA-20). Inclusion of these materials produced a broad data base for establishing overall trends and correlations. Pertinent material properties are summarized in Tables 1 and 2.

SPECIMEN PREPARATION

Specimen preparation procedures were standardized to reduce variability. General procedures [see Ayers and Thompson (1) for details] are as follows:

1. The material was separated into size fractions and recombined to the proper gradation.
2. The moisture content was determined (where applicable) and adjusted as necessary.
3. The materials were compacted in three increments (lifts) to predetermined maximum, minimum, and intermediate densities. Compaction was accomplished by use of a vibratory hammer with a full-face compaction head.
4. The DCP specimens were compacted in a 12-in. diameter by 18-in. deep steel mold with attached bottom plate. A study of mold size effects (1) indicated that a mold diameter is less than approximately 8 times the maximum aggregate size was significant. Mold size effects are attributed to sample confinement and wall friction and are further documented by Green and Knight (8).
5. Standard practices were followed for preparing the triaxial specimens (6-in. diameter by 12-in. depth). The specimens were compacted on the base plate of the triaxial cell (Figure 5). Two membranes were used (31-mil neoprene compaction membrane, plus a second 25-mil latex membrane).

DCP TESTING

A recent study (1) indicated that operator error was minimal and did not significantly affect DCP results. Examples of operator error include vertical misalignment of the device (significant only in extreme cases), incorrect reading of the penetration rod, and incorrect recording of the data (generally evident during data review). In this study, a test platform was used to maintain vertical alignment of the DCP apparatus and maximize reproducibility. The test apparatus is shown in Figure 6. Test data (blow count and penetration depth) were manually recorded.

Material density, gradation, and fines content (in the case of ballast materials) were the primary factors evaluated in the DCP series. Other material parameters (such as void ratio, effective grain size, coefficient of curvature, coefficient of uniformity, and maximum aggregate size) were calculated or measured for subsequent use.

TRIAXIAL TESTING

The commonly used shear strength parameters of deviator stress at failure, stress ratio at failure, cohesion, and angle of internal friction can be established from triaxial test data. A computer-interfaced MTS hydraulic load apparatus was used in all Phase 2 testing (Figure 7). Air was used as the confining pressure, and the tests were conducted with the sample vented to the atmosphere (open or drained condition). The specimen was rapidly loaded (1.5 in./sec) to failure. The 1.5 in./sec load rate corresponded to a failure strain of 5 percent occurring in 400 msec. A load duration of 400 msec is considered a realistic simulation of a relatively slow-moving vehicle. Load magnitudes and total axial deformations were recorded by the computer.

Phase 2 triaxial test samples closely approximated the DCP samples tested in Phase 1. Stress-strain plots for three confining pressures (5, 15, and 30 psi) were used to establish a Mohr-Coulomb failure envelope. Duplicate tests were performed if inconsistencies in the data were evident.

TABLE 1 MATERIAL CHARACTERISTICS

MATERIAL	GRADATION (% PASSING) SIEVE SIZE															DENSITIES EVALUATED (PCF)	SPECIFIC GRAVITY	COMMENTS
	2 in	1 1/2"	1 in	3/4 in	1/2 in	3/8 in	#4	#8	#16	#30	#40	#50	#100	#200				
SAND	--	--	--	--	--	100	93	76	60	43	--	14	2	2	111,113, 116	2.65	--	
CA-10 SANDY- GRAVEL (ROKEY)	--	--	100	--	79	--	47	--	--	--	16	--	--	8	119,123, 127	2.55	OPTIMUM MOISTURE CONTENT = 8.3% AS TESTED = 9.6% LL = 18 PI = 2	
CRUSHED DOLO- MITIC BALLAST	100	96	40	6	--	2	0	--	--	--	--	--	--	--	89,95,99	2.63	AREA #4 GRADATION	
BALLAST WITH 7.5% FA-20	100	96.3	44.2	12.6	--	8.8	6.7	4.6	2.7	1.0	--	0.8	0.4	0.1	99,104,107	2.63	--	
BALLAST WITH 15% FA-20	100	96.5	47.8	18.3	--	14.8	13.0	8.6	5.1	3.0	--	1.6	0.6	0.3	102,107, 112	2.63	--	
BALLAST WITH 22.5% FA-20	100	96.7	51.0	23.3	--	20.0	17.6	12.1	7.2	4.2	--	2.2	0.9	0.4	110,113, 116	2.62	--	
FA-20	--	--	--	--	--	100	96	66	39	23	--	12	5	2		2.60	NON-PLASTIC DOLO- MITIC FINES	
NOTE: CA-10 AND FA-20 ARE ILLINOIS D.O.T. STANDARD GRADATIONS. THE FA-20 DOLOMITIC FINES AND THE BALLAST WERE OBTAINED FROM THE SAME SOURCE.																		

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TABLE 2 MATERIAL CHARACTERISTICS CONTINUED

MATERIAL	EFFECTIVE GRAIN SIZE D_{10} (INCHES)	COEFFICIENT OF UNIFORMITY C_u	COEFFICIENT OF CURVATURE C_z	MAXIMUM AGGREGATE SIZE (INCHES)	D_{30} (INCHES)	D_{60} (INCHES)
SAND	0.009	5.1	0.87	0.19	0.019	0.046
CA-10 SANDY- GRAVEL (ROKEY)	0.004	80.0	1.01	1.0	0.036	0.32
CRUSHED DOLO- MITIC BALLAST	0.71	1.7	0.99	1.5	0.91	1.18
BALLAST WITH 7.5% FA-20	0.39	3.0	1.67	1.5	0.87	1.16
BALLAST WITH 15% FA-20	0.12	9.2	5.22	1.5	0.83	1.10
BALLAST WITH 22.5% FA-20	0.07	15.1	8.41	1.5	0.79	1.06

TEST RESULTS

DCP Data

DCP test results are presented in Table 3. Typical PR-depth plots are shown in Figures 8 and 9 for sand and Rokey CA-10, respectively. The PR-depth plots are the result of from four to six tests conducted on duplicate samples at each target density. The effects of overburden (confinement) and density are evident.

The penetration rate selected to characterize a sample was obtained by averaging the results of all trials at middepth,

middepth + 2 in., and middepth - 2 in. The values for the various DCP tests are summarized in Table 3.

Triaxial Data

Typical stress-strain plots are shown in Figures 10 and 11 for sand and AREA No.4 ballast, respectively. The stress-strain plots are differentiated by confining pressure and sample density. Note the characteristic shape of the stress-strain plot (Figure 10). In cases where the breakover point in the plot was not well-defined, the maximum deviator stress was assessed

at a strain of 5 percent (Figure 11). The triaxial test data are summarized in Table 4.

DATA ANALYSES

The principal objective of this study was to establish generalized DCP penetration rate-shear strength relations. Single and multivariate statistical analyses were used to correlate various shear strength parameters (i.e., deviator stress at failure, stress ratio at failure, and the angle of internal friction)

with the following factors: DCP penetration rate, density, maximum aggregate size, void ratio, effective grain size, coefficient of uniformity, and the coefficient of curvature.

Methodologies

The data base generated may be divided into two subgroups relating to material properties and strength (DCP or triaxial test) results. Material properties such as density, void ratio, and grain size distribution, are not easily measured under field conditions. It is, therefore, desirable to relate the shear strength parameters directly to PR.

Initial work focused on material properties and the DCP or triaxial test data relations. A matrix was generated, which allowed convenient manipulation of the data. The pertinent material properties and strength test parameters are defined below:

Penetration rate (PR). The vertical movement of the DCP apparatus corresponding to one drop of the sliding weight (inches/blow).

σ_1 . Major principal stress in the triaxial tests (psi).

σ_3 . Minor principal stress, also referred to as the confining pressure (CP), in the triaxial tests (psi).

Deviator stress (DS). The difference between the major and minor principal stresses at failure ($\sigma_1 - \sigma_3$) in the triaxial test procedure (psi).

Stress ratio (SR). The ratio (at failure) of the total vertical stress imposed on a triaxial sample to the confining pressure (σ_1/σ_3).

Angle of internal friction (Φ). The angle of the Mohr-Coulomb failure envelope established by multiple triaxial tests at various CPs (degrees). The following equation (for cohesion equals zero condition) was used in calculating Φ :

$$\Phi = \sin^{-1} ([SR - 1]/[SR + 1])$$

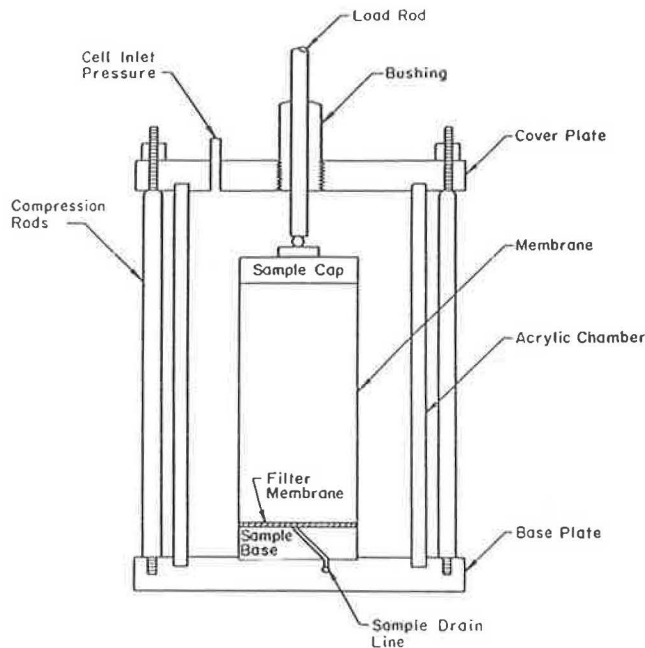


FIGURE 5 Triaxial cell schematic.

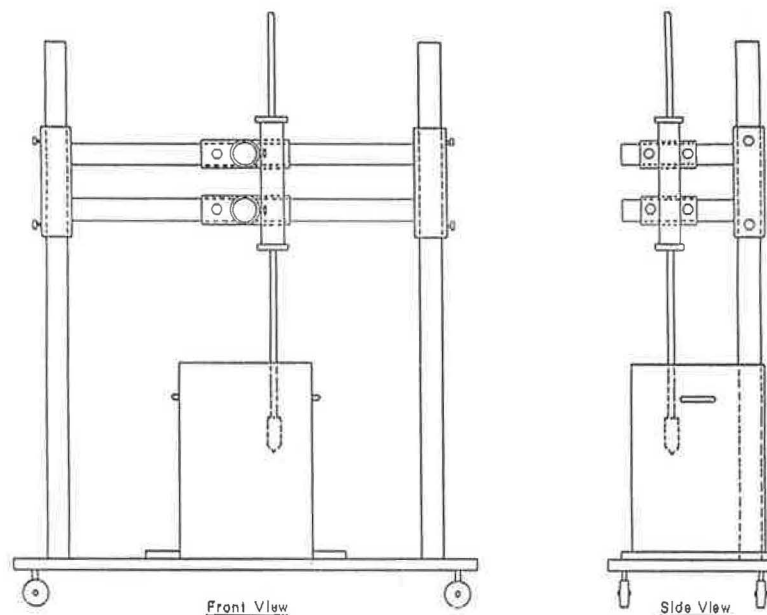


FIGURE 6 DCP test apparatus.

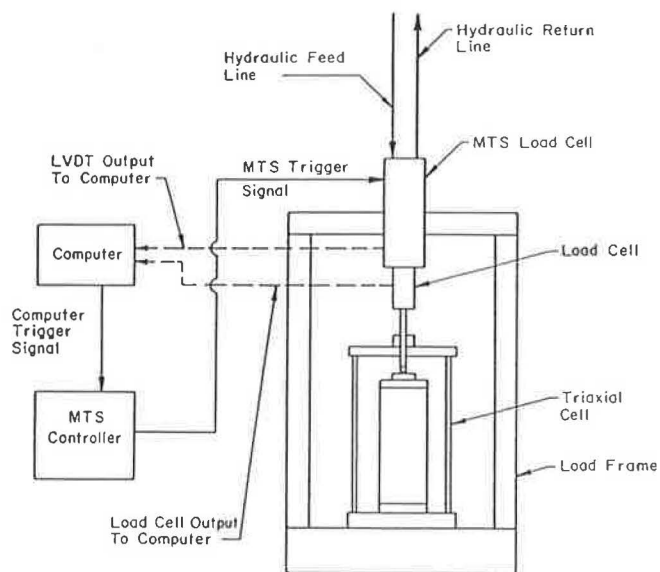


FIGURE 7 MTS test apparatus schematic.

TABLE 3 DCP TEST RESULTS

MATERIAL	DENSITY (PCF)	PENETRATION RATE (INCHES/BLOW)
SAND	111	1.20
	113	0.90
	116	0.50
CA-10 SANDY GRAVEL (ROKEY)	119	2.15
	123	1.15
	127	0.55
CRUSHED DOLOMITIC BALLAST (AREA #4)	89	1.80
	95	0.95
	99	0.70
BALLAST WITH 7.5% FA-20	99	0.65
	104	0.50
	107	0.40
BALLAST WITH 15% FA-20	102	0.55
	107	0.35
	112	0.25
BALLAST WITH 22.5% FA-20	110	0.60
	113	0.30
	116	0.20

NOTES:

FA-20 is a designation for the dolomitic fines used in this study. The ballast and FA-20 were obtained from the same source.

CA-10 and FA-20 are Illinois DOT standard gradations.

The penetration rates indicated are the average values of 4 to 6 tests taken at mid-depth, mid-depth +2 inches, and mid-depth -2 inches.

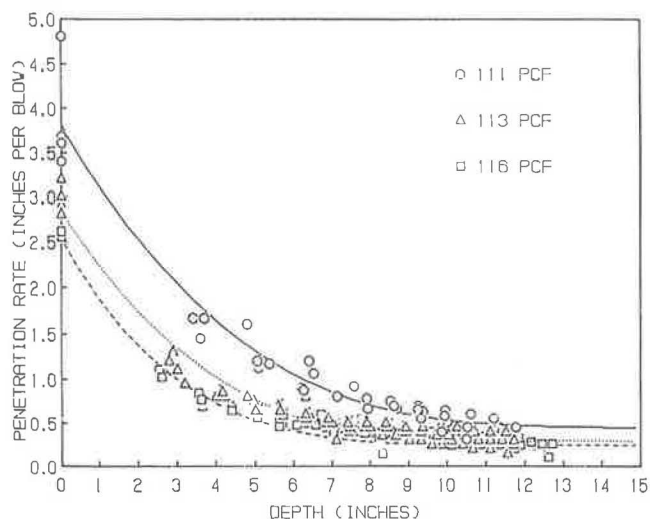


FIGURE 8 Typical DCP data for sand.

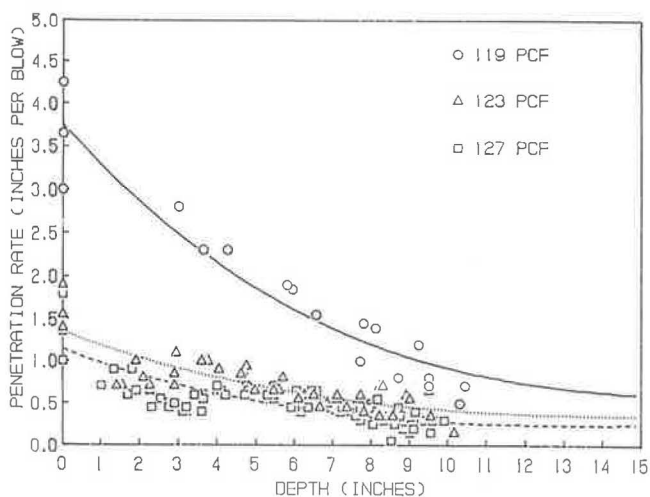


FIGURE 9 Typical DCP data for Rokey CA-10.

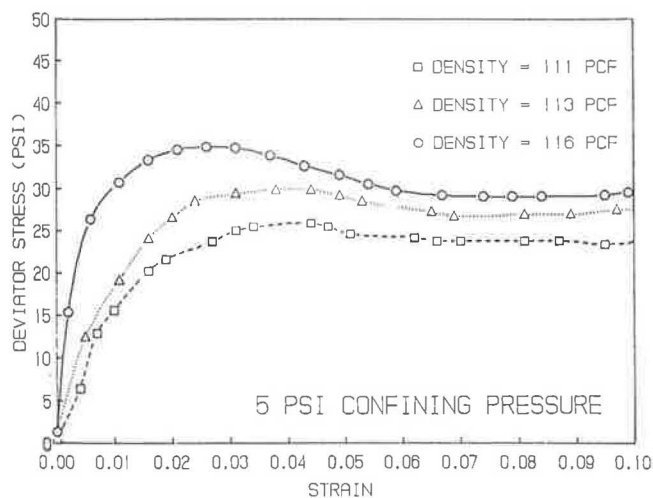


FIGURE 10 Typical stress-strain plots for sand.

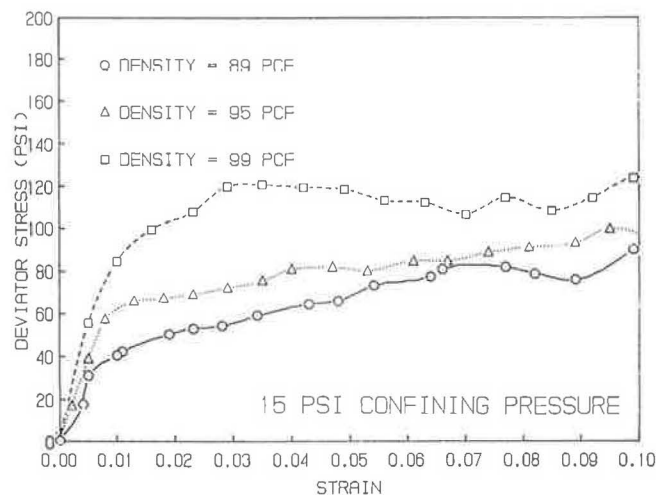


FIGURE 11 Typical stress-strain plots for area No. 4 ballast.

Density (γ). The mass per unit volume (pounds/cubic foot).

Void ratio (e). The ratio of the voids to the solids in a sample (calculated volumetrically).

Maximum aggregate size (MAS). The largest aggregate size found in a material based on sieve analysis (inches).

Effective grain size (D_{10}). The particle size corresponding to the point on the gradation curve where 10 percent of the particles are finer (inches).

D_{30} . The particle size corresponding to the point on the gradation curve where 30 percent of the particles are finer (inches).

D_{60} . The particle size corresponding to the point on the gradation curve where 60 percent of the particles are finer (inches).

Coefficient of uniformity (C_u). (D_{60}/D_{10}).

Coefficient of curvature (C_c). ($D_{30}^2/(D_{10} \times D_{60})$).

Preliminary linear regression, polynomial regression, and exponential and logarithmic correlations indicated (in all cases) that linear regression resulted in the highest correlation coefficients. Thus, the results presented in this paper include only single and multivariate linear regression analyses.

The triaxial and DCP tests were performed on samples of comparable density and material properties (gradation, moisture content, etc.). Confining pressure was selected as the basis for comparison among these procedures (i.e., the triaxial test data was differentiated by confining pressure for comparison to DCP test data).

One variable linear regression analysis was performed on the strength test parameter-material property matrix to determine the relative effect of the various material properties on the DCP and shear strength test results (Tables 5 and 6). The results of this analysis were used to select independent variables (other than PR) for the multivariate regression equations shown in Table 9.

A second series of single variable regression analyses was conducted to establish correlations between the DCP penetration rate and the shear strength test results (dependent variable) (Table 7). The results were used to establish the single variable regression equations shown in Table 8.

Multivariate regression analyses establish the effect of two or more independent variables on the dependent variable.

TABLE 6 TEST PARAMETERS VERSUS MATERIAL PROPERTIES

MATERIAL PROPERTIES	DENSITY (γ)			VOID RATIO (e)			EFFECTIVE GRAIN SIZE (D_{10})			COEFFICIENT OF UNIFORMITY (C_u)			COEFFICIENT OF CURVATURE (C_z)			MAXIMUM AGGREGATE SIZE (MAS)		
	CONFINING PRESSURES (psi)																	
TEST PARAMETERS	5	15	30	5	15	30	5	15	30	5	15	30	5	15	30	5	15	30
ALL BALLAST MATERIALS*																		
PR*	-.880	-.880	-.880	.907	.907	.907	.735	.735	.735	-.561	-.561	-.561	-.554	-.554	-.554	-	-	-
DS	.185	.634	.545	-.180	-.642	-.538	.138	-.210	-.147	-.226	.171	.067	-.231	.171	.066	-	-	-
SR	.185	.634	.545	-.181	-.623	-.538	.137	-.211	-.146	-.225	.170	.067	-.230	.169	.065	-	-	-
ϕ	.168	.661	.546	-.164	-.654	-.539	.174	-.225	-.138	-.248	.198	.069	-.252	.198	.068	-	-	-
ALL MATERIALS**																		
PR*	-.109	-.109	-.109	.097	.097	.097	.140	.140	.140	.390	.390	.390	-.527	-.527	-.527	-.329	-.329	-.329
DS	-.263	-.168	-.430	.265	.165	.440	.444	.230	.343	-.330	-.547	-.822	.192	.414	.364	.629	.492	.472
SR	-.261	-.167	-.430	.264	.164	.440	.443	.229	.343	-.329	-.546	-.822	.192	.413	.363	.627	.491	.471
ϕ	-.300	-.236	-.497	.310	.234	.511	.469	.256	.364	-.365	-.640	-.889	.236	.434	.359	.666	.494	.452

NOTE:

PR = PENETRATION RATE (inches/blow)
DS = DEVIATOR STRESS (psi)
SR = STRESS RATIO
 ϕ = FRICTION ANGLE

D_{10} , C_u , C_z AND MAS VALUES REPORTED ONLY FOR AGGREGATE MATERIAL TYPES. THE VALUES ARE IDENTICAL FOR INDIVIDUAL MATERIAL TYPES AND ARE NOT STATISTICALLY ANALYZED.

THE VALUES INDICATED FOR THE PR CORRELATIONS ARE IDENTICAL FOR EACH CONFINING PRESSURE BECAUSE OF THE DIFFERENTIATION BY CONFINING PRESSURE

SIGNIFICANT VALUE OF CORRELATION COEFFICIENT (R)	(α)	(R)
	.05	.997
*	.05	.576
**	.05	.468
	.10	.988
*	.10	.497
**	.10	.400

TABLE 7 ONE-VARIABLE LINEAR REGRESSION CORRELATION COEFFICIENTS: DCP PENETRATION RATE—SHEAR STRENGTH PARAMETERS

MATERIAL	SHEAR STRENGTH PARAMETERS								
	DEVIATOR STRESS			STRESS RATIO			FRICTION ANGLE		
	CONFINING PRESSURES (PSI)								
	5	15	30	5	15	30	5	15	30
SAND	-.999	-.999	-.989	-.999	-.999	-.992	-.995	-.999	-.990
CA-10 SANDY-GRAVEL (ROKEY)	-.992	-.997	-.975	-.992	-.997	-.976	-.981	-.995	-.974
CRUSHED DOLOMITIC BALLAST	-.991	-.867	-.934	-.993	-.867	-.934	-.998	-.905	-.928
BALLAST WITH 7.5% FA-20	-.881	-.958	-.994	-.881	-.958	-.994	-.902	-.979	-.999
BALLAST WITH 15% FA-20	-.902	-.943	-.922	-.896	-.942	-.922	-.930	-.974	-.939
BALLAST WITH 22.5% FA-20	-.991	-.976	-.971	-.991	-.976	-.972	-.990	-.982	-.977
ALL BALLAST MATERIALS*	-.281	-.617	-.517	-.280	-.617	-.517	-.275	-.649	-.517
ALL MATERIALS**	-.580	-.668	-.626	-.579	-.668	-.625	-.654	-.706	-.619

NOTE

SIGNIFICANT VALUE OF CORRELATION COEFFICIENT (R)	(α)	(R)
	.05	.997
*	.05	.576
**	.05	.468
	.10	.988
*	.10	.497
**	.10	.400

TABLE 8 ONE-VARIABLE LINEAR REGRESSION EQUATIONS

MATERIAL	CONFINING PRESSURE (PSI)	EQUATION	CORRELATION COEFFICIENT (R)	STANDARD ERROR OF ESTIMATE	DATA BASE PR RANGE
SAND	5	DS = 41.3-12.8 PR	-.999	.3	.5 - 1.2
	15	DS = 100.4-23.4 PR	-.999	.5	.5 - 1.2
	30	DS = 149.6-12.7 PR	-.989	.9	.5 - 1.2
CA-10 SANDY-GRAVEL (ROKEY)	5	DS = 51.3-13.6 PR	-.992	1.9	.55-2.15
	15	DS = 62.9- 3.6 PR	-.997	.3	.55-2.15
	30	DS = 90.7- 5.8 PR	-.975	1.5	.55-2.15
CRUSHED DOLOMITIC BALLAST	5	DS = 64.1-13.3 PR	-.991	1.4	.7 - 1.8
	15	DS = 139.0-40.6 PR	-.867	18.9	.7 - 1.8
	30	DS = 166.3-16.2 PR	-.934	5.0	.7 - 1.8
BALLAST WITH 7.5% FA-20	5	DS = 87.2-78.7 PR	-.881	7.5	.4 - .65
	15	DS = 216.1-213.9 PR	-.958	11.3	.4 - .65
	30	DS = 282.1-233.2 PR	-.994	4.4	.4 - .65
BALLAST WITH 15% FA-20	5	DS = 47.5- .45 PR	-.902	12.4	.25 - .55
	15	DS = 184.2-215.5 PR	-.943	16.3	.25 - .55
	30	DS = 206.4-135.7 PR	-.922	12.3	.25 - .55
BALLAST WITH 22.5% FA-20	5	DS = 49.7-23.1 PR	-.991	.9	.2 - .6
	15	DS = 133.1-68.6 PR	-.976	4.5	.2 - .6
	30	DS = 192.1-95.8 PR	-.971	6.9	.2 - .6
ALL BALLAST MATERIALS*	5	DS = 50.8- 6.3 PR	-.281	9.7	.2 - 1.8
	15	DS = 122.5-34.2 PR	-.617	19.8	.2 - 1.8
	30	DS = 169.1-23.1 PR	-.517	17.3	.2 - 1.8
ALL MATERIALS**	5	DS = 51.5-12.5 PR	-.580	9.6	.2 - 2.2
	15	DS = 115.9-32.8 PR	-.668	19.9	.2 - 2.2
	30	DS = 168.6-36.9 PR	-.626	25.1	.2 - 2.2

NOTE: DS = DEVIATOR STRESS (PSI) AT FAILURE

PR = PENETRATION RATE (INCHES/BLOW)

SIGNIFICANT VALUE OF CORRELATION COEFFICIENT (R)

(α)	(R)
.05	.997
*.05	.576
**.05	.468
.10	.988
*.10	.497
**.10	.400

dent variable. When considering materials of a similar nature (i.e., sand, sandy gravel, and ballast with a uniform fines content), the addition of terms other than the DCP penetration rate did not improve the accuracy [increased R , decreased standard error of estimate (SEE)] of the estimated deviator stress. For a broad range of granular materials (i.e., ballast materials with unknown or highly variable fines content, or unknown material type), the inclusion of additional terms in the deviator stress at failure prediction equations increases R and decreases SEE (Table 9).

The use of the multivariate equations requires determination of various material properties (C_u , MAS, e , and γ). The PR value is assumed to be middepth of the layer and should be the average of several trials.

The linear regression equations presented in Tables 8 and 9 are characterized by a range of R and SEE values. Thirteen of the 24 single-variable regression equations (Table 8) are significant at a level of significance (α) equal to 0.10. For the multivariate linear regression equations (Table 9), 25 of the 27 equations are significant at α equals 0.10. In general, better estimates (higher R , lower SEE) of the deviator stress at failure are obtained if the material type (ballast, sand, sandy

gravel) is known. The broader the data base range considered (specific material—all ballast materials—all materials), the less precise (lower R , higher SEE) the estimate.

The equations reported in Tables 8 and 9 are valid only for the specified conditions. Extrapolation beyond the limits of the data base developed in this study should be done with caution.

COMMENTS

Several important facts were noted during the DCP and triaxial testing programs and data analyses. The DCP device is well-suited for granular materials with a MAS ranging from sand size particles to 1½ in. It appears that there is an upper bound maximum aggregate size where the DCP is no longer a viable test method. Deflection of the penetration shaft and the inability to penetrate or displace large aggregates are the primary limiting factors. The upper MAS limit was not addressed in this study.

The MAS has a notable effect on DCP test variability. Generally, an increased MAS results in larger voids that con-

TABLE 9 MULTIVARIATE LINEAR REGRESSION EQUATIONS

MATERIAL	CONFINING PRESSURE (PSI)	EQUATION	CORRELATION COEFFICIENT	STANDARD ERROR OF ESTIMATE
ALL BALLAST MATERIALS	5	DS = 50.8-6.3 PR	.281**	9.7
		DS = 62.0-13.3 PR-.97 Cu	.542**	9.0
		DS = -137.8+8.1 PR+1.9 Cu-2.2 Y	.690*	8.2
		DS = -607.8-1.7 PR+5.1 Cu+236.6 Y -2.2e	.731*	8.2
	15	DS = 122.5-34.2 PR	.618	19.8
		DS = 135.3-42.1 PR-1.1 Cu	.653*	20.1
		DS = -597.6+36.3 PR+6.9 Cu-5.7 Y	.907	11.8
		DS = -1488+17.8 PR+13.0 Cu+448.3 Y -5.7e	.926	11.3
	30	DS = 169.1-23.1 PR	.517*	17.3
		DS = 182.2-31.2 PR - 1.1 Cu	.583*	17.3
		DS = -482.2+39.9 PR+6.2 Cu-5.3 Y	.918	9.0
		DS = -883.9+31.6 PR+9.0 Cu+202.3 Y -5.3e	.924	9.3
ALL MATERIALS	5	DS = 51.5-12.5 PR	.580	9.6
		DS = 37.0-9.0 PR+7.8 MAS	.743	8.2
		DS = 35.3-9.6 PR+6.4 MAS+7.0e	.746	8.4
		DS = -242.7-8.2 PR+1.9 MAS+126.9e+8.8 Y	.759	8.5
		DS = -209.4-11.1 PR+1.7 MAS+125.6e+7.2 Y +.08Cu	.763	8.8
	15	DS = 115.9-32.8 PR	.669	19.9
		DS = 116.7-26.4 PR-.28 Cu	.738	18.7
		DS = 100.0-23.4 PR+8.9 Cu-.24 MAS	.772	18.2
		DS = 158.0+4.9 PR-175.2 Cu+25.2 MAS-.95e	.850	15.6
		DS = -5.2+3.2 PR+1.1 Cu-96.6 MAS+25.2e-.91 Y	.852	16.2
	30	DS = 168.6-36.9 PR	.626	25.1
		DS = 170.5-21.3 PR -.69 Cu	.886	15.4
		DS = 156.8-18.8 PR+7.3 Cu-.66 MAS	.900	15.0
		DS = -168.5+9.8 PR+2.6 Cu+25.0 MAS-1.3 Y	.939	12.2
		DS = -341.3+10.6 PR+3.9 Cu+75.4 MAS+26.0 Y-1.3e	.940	12.7

NOTE:

- DS - DEVIATOR STRESS AT FAILURE
 PR - PENETRATION RATE
 Cu - COEFFICIENT OF UNIFORMITY (D_{60}/D_{10})
 Y - DENSITY
 e - VOID RATIO
 MAS - MAXIMUM AGGREGATE SIZE
 * - CORRELATION COEFFICIENT (R) NOT SIGNIFICANT FOR $\alpha = .05$
 ** - CORRELATION COEFFICIENT (R) NOT SIGNIFICANT FOR $\alpha = .10$

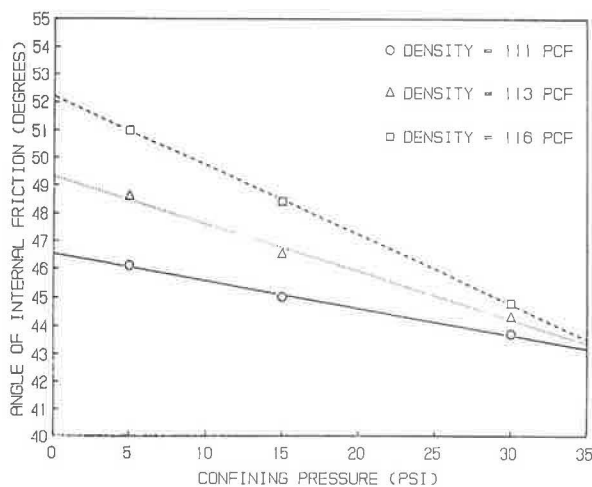


FIGURE 12 Angle of internal friction-confining pressure relations for sand.

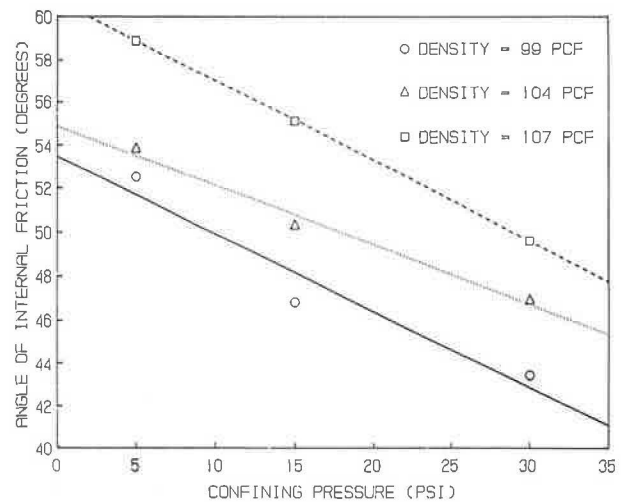


FIGURE 13 Angle of internal friction-confining pressure relations for Area No. 4 ballast with 7.5 percent FA-20.

tribute significantly to increased variability in the PR values. The inclusion of FA-20 fines in the AREA No. 4 ballast tended to reduce this effect.

The triaxial test phase evaluated samples comparable to those tested in the DCP phase. The confining pressure was not evaluated directly by the DCP test. The confining pressure influence (Figures 8 and 9) is related to the overburden effects evident in the DCP tests. The overburden effect (confining pressure due to the weight of the overlying material) was not evaluated beyond a depth of 15 in. in this study. Typically, the PR did not display large variations beyond middepth of the DCP mold.

The relationship between the shear strength parameters and the triaxial test conditions (i.e., density and confining pressure) exhibit several noteworthy trends. The angle of internal friction (calculated from the stress ratio at failure) increases with increasing density at a particular confining pressure and decreases with increasing confining pressure at a particular density. Figures 12 and 13 illustrate this effect. The second point is particularly important because, as the confinement due to overburden effects and loading increases, the friction angle decreases indicating a relative loss in strength. This behavior is common to many materials and is evident in a typical Mohr-Coulomb diagram with a curved failure envelope (9,10).

The strong impact of confining pressure on shear strength is evident in the regression equations presented in Tables 8 and 9. Notice in particular the increase in the intercept values (constants in the equations) with a confining pressure increase. The accuracy associated with predicting in situ shear strength is obviously dependent on the ability to estimate the in situ confining stress conditions reasonably.

SUMMARY

The conclusions and general findings of this study are as follows:

1. The DCP test may be used to estimate the shear strength of a variety of cohesionless granular materials (including sand, sandy gravel, and ballast) using the prediction equations developed.
2. Detailed material characteristics (such as gradation, maximum aggregate size, density, void ratio) are not required to predict shear strength from DCP data. However, as noted in Table 9, additional material characteristic inputs increase the accuracy of the prediction for ill-defined materials.
3. To select the appropriate prediction equation requires an estimate of the confining pressure under field loading conditions. The estimation of confining pressure under realistic field loading conditions is an area requiring further investigation.
4. The DCP device is a viable alternative and/or supplement to detailed in situ test pit type investigations. DCP tests are rapidly conducted and inexpensive. In most cases, numerous less sophisticated and detailed tests (such as the DCP) will provide more useful and valid information than a limited number of detailed tests.

5. The DCP can be used effectively to gather input information rapidly and economically for use in the USA-CERL RAILER system for performing simplified structural evaluations.

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TABLE 4 TRIAXIAL TEST RESULTS

MATERIAL	DENSITY (PCF)	CONFINING PRESSURE (PSI)	DEVIATOR STRESS (PSI)	STRESS RATIO	FRICTION ANGLE (DEGREES)
SAND	111	5	25.8	6.16	46.1
	111	15	72.6	5.84	45.0
	111	30	134.0	5.47	43.7
	113	5	30.0	7.00	48.6
	113	15	79.0	6.27	46.5
	113	30	139.0	5.63	44.3
	116	5	34.8	7.96	51.0
	116	15	88.9	6.93	48.4
	116	30	143.0	5.77	44.8
CA-10 SANDY GRAVEL (ROKEY)	119	5	21.5	5.30	43.0
	119	15	54.9	4.66	40.3
	119	30	77.9	3.60	34.4
	123	5	37.2	8.44	52.0
	123	15	58.9	4.93	41.5
	123	30	85.3	3.84	35.9
	127	5	42.9	9.58	54.2
	127	15	60.7	5.05	42.0
	127	30	86.8	3.89	36.2
CRUSHED DOLO- MITIC BALLAST	89	5	40.5	9.10	53.3
	89	15	69.3	5.62	44.3
	89	30	138.0	5.60	44.2
	95	5	50.4	11.1	56.6
	95	15	85.7	6.71	47.8
	95	30	147.0	5.90	45.2
	99	5	55.7	12.1	57.9
	99	15	122.0	9.13	53.4
	99	30	158.0	6.27	46.5
BALLAST WITH 7.5% FA-20	99	5	38.5	8.70	52.5
	99	15	80.7	6.38	46.8
	99	30	132.0	5.40	43.4
	104	5	41.8	9.36	53.8
	104	15	100.0	7.67	50.3
	104	30	162.0	6.40	46.9
	107	5	59.4	12.9	58.9
	107	15	136.0	10.1	55.1
	107	30	191.0	7.37	49.6
BALLAST WITH 15% FA-20	102	5	38.9	8.78	52.7
	102	15	70.0	5.67	44.4
	102	30	135.0	5.50	43.8
	107	5	46.8	10.3	55.4
	107	15	95.7	7.38	49.6
	107	30	149.0	5.97	45.5
	112	5	67.8	14.6	60.7
	112	15	139.0	10.3	55.5
	112	30	179.0	6.97	48.5
BALLAST WITH 22.5% FA-20	110	5	35.7	8.14	51.4
	110	15	92.8	7.19	49.1
	110	30	136.0	5.53	44.0
	113	5	43.5	9.70	54.4
	113	15	109.0	8.27	51.6
	113	30	158.0	6.27	46.4
	116	5	44.6	9.92	54.8
	116	15	122.0	9.13	53.4
	116	30	177.0	6.90	48.3
FA-20	113	15	113.0	8.53	52.2
	121	15	150.0	11.0	56.4

TABLE 5 ONE-VARIABLE LINEAR REGRESSION CORRELATION COEFFICIENTS: TEST PARAMETERS VERSUS MATERIAL PROPERTIES

TEST PARAMETERS	MATERIAL PROPERTIES					
	DENSITY (γ)			VOID RATIO (e)		
	CONFINING PRESSURES			CONFINING PRESSURES		
	5 psi	15 psi	30 psi	5 psi	15 psi	30 psi
SAND						
PR	-.999	-.999	-.999	.994	.994	.994
DS	.997	.999	.983	-.988	-.997	-.967
SR	.997	.999	.988	-.988	-.997	-.974
ϕ	.991	.999	.985	-.979	-.992	-.970
CA-10 SANDY GRAVEL (ROKEY)						
PR	-.989	-.989	-.989	.959	.959	.959
DS	.965	.976	.933	-.918	-.936	-.873
SR	.965	.976	.935	-.918	-.935	-.875
ϕ	.943	.972	.933	-.886	-.929	-.872
CRUSHED DOLOMITIC BALLAST						
PR	-.981	-.981	-.981	.998	.998	.998
DS	.998	.946	.985	-.996	-.952	-.893
SR	.997	.945	.984	-.998	-.951	-.893
ϕ	.991	.969	.981	-.999	-.947	-.927
BALLAST WITH 7.5% FA-20						
PR	-.999	-.999	-.999	.982	.982	.982
DS	.868	.950	.991	-.779	-.889	-.957
SR	.867	.949	.990	-.778	-.888	-.957
ϕ	.889	.972	.997	-.807	-.924	-.974
BALLAST WITH 15% FA-20						
PR	-.981	-.981	-.981	.981	.981	.981
DS	.967	.989	.978	-.967	-.989	-.978
SR	.963	.988	.979	-.964	-.988	-.978
ϕ	.982	.999	.987	-.982	-.999	-.987
BALLAST WITH 22.5% FA-20						
PR	-.960	-.960	-.960	.846	.846	.846
DS	.917	.998	.999	-.770	-.941	-.948
SR	.917	.997	.998	-.770	-.940	-.946
ϕ	.914	.995	.997	-.766	-.930	-.939

Generally, the use of multiple independent variables (PR and additional variables) had only a slight beneficial effect on the correlation coefficient (R). Multivariate regression equations are presented in Table 9 for all ballast materials regardless of fines content and all granular material types.

Discussion of Data Analyses

The inputs for the regression equations presented in Tables 7 and 8 are the in situ confining pressure (under field loading conditions) and the DCP penetration rate.

It is difficult to quantify the wheel loading-induced confining pressure stress states generated in typical granular layer-subgrade soil systems. Linear elastic layer analysis procedures (without failure criteria) frequently indicate tensile stresses in the bottom region of the granular layer. Stress-dependent moduli finite element models with Mohr-Coulomb failure criteria have been developed for railroad track systems (ILLI-TRACK) (6,7) and highway and airfield pavements (ILLI-PAVE) (5). In the ILLI-TRACK and ILLI-PAVE models, tensile stresses are not calculated in the granular material

layer. Although the finite element models provide an improved estimate of the stress state in the granular layer, the estimate should be considered as only approximate.

The DCP penetration rate should be the average of the PRs obtained at middepth, middepth + 2 in., and middepth - 2 in. within each layer. The PR value input into the equations should be the average value from a number of DCP tests conducted at each site (the results from each layer are averaged and a separate shear strength calculated).

Determination of in situ density, void ratio, gradation, etc. is time-consuming, costly, and generally impractical (if not impossible). An objective of this study is to predict strength parameters that are based on a rapid and inexpensive test method. Therefore, the single-variable equations reported in Table 8 are based solely on DCP test results and do not require the determination of additional in situ material properties. Factors such as moisture and density are implicitly accounted for in the single variable equations, because a direct relationship exists between the DCP PR and shear strength.

A step-wise multivariate linear regression analysis was performed, in which the deviator stress at failure was the depen-