Appendix B
Methods of Relating Field Density Data to Desired or Specified Values

B-1. General

Compaction control of soils requires the comparison of fill water content and/or dry density values obtained in field density tests with optimum water content and/or maximum dry density or determination of relative density if the fill materials are cohesionless. For fine-grained soils or coarse-grained with appreciable fines, field results are compared with results of laboratory standard effort (or in special cases 15-blow or modified effort) compaction tests performed in accordance with procedures given in EM 1110-2-1906 (Appendices VI and VIA). For free-draining cohesionless soils, relative density of the fill material is determined using test procedures described in EM 1110-2-1906 (Appendices XII and XIIA). However, see Control Using Relative Density under paragraph B-4*a* below.

B-2. Fine-Grained Soils

a. Standard compaction test. The performance of a standard laboratory compaction test on material from each field density test would give the most accurate relation of the in-place material to optimum water content and maximum density, but it is not generally feasible to do this because testing could not keep pace with the rate of fill placement. However, standard compaction tests should be performed during construction when an insufficient number of the compaction curves were developed during the design phase, when borrow material is obtained from a new source, and when material similar to that being placed has not been tested previously. In any event, laboratory compaction tests should be performed periodically on each type of fill material (preferably one for every ten field density tests) to check the optimum water content and maximum dry density values being used for correlation with field density test results.

b. One-point compaction method.

(1) In the one-point compaction method, material from the field density test is allowed to dry to a water content on the dry side of estimated optimum and is then compacted using the same equipment and procedures used in the five-point standard compaction test. (It must be mentioned that during drying, the material must be thoroughly and continuously mixed to obtain uniform drying; otherwise, erroneous results may be obtained). The water content and dry density of the compacted sample are then used to estimate its optimum water content and maximum dry density as illustrated in Figure B-1.

(2) In Figure B-1, the line of optimums is well-defined and the compaction curves are approximately parallel to each other; consequently, the one-point compaction method could be used with a relatively high degree of confidence. In Figure B-2, however, the optimums define not a line but a broad band. Also, the compaction curves are not parallel to each other and in several instances cross on the dry side. To illustrate an error that could result from using the

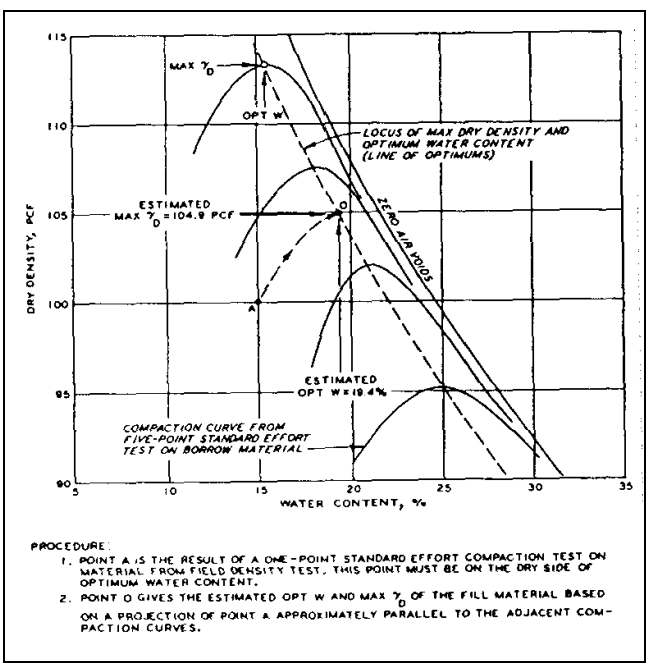

Figure B-1. Illustration of one-point compaction method

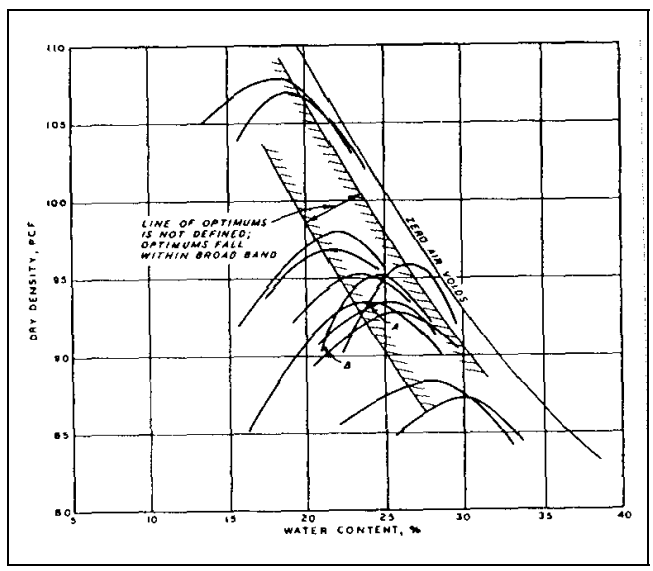

Figure B-2. Illustration of possible error using one- and two-point compaction methods

one-point method, consider the field density and water content shown by point B in Figure B-2. Point B is close to three compaction curves. Consequently, the correct curve cannot be determined from the one point. The estimated maximum dry density and optimum water content could vary from about 92.8 pcf and 26 percent, respectively, to 95.0 pcf and 24 percent, respectively, depending on which curve was used. Therefore, the one-point method should be used only when the data define a relatively good line of optimums.

c. Two-point compaction test results.

(1) In the two-point test, using the same equipment and procedures used in the five-point compaction test, one sample of material from the location of the field density test is compacted at the fill water content, if thought to be at or on the dry side of optimum water content (otherwise, reduce the water content by drying to this condition). A second sample of material is allowed to dry back about 2 to 3 percentage points dry of the water content of the first sample and then compacted in the same manner. After compaction, the water contents of the two samples are determined by oven drying or other more rapid means, and the dry densities are computed. The results are used to identify the appropriate compaction curve for the material tested as shown in Figure B-3.

(2) The data shown in Figure B-3 warrant the use of the two-point compaction test since the five-point compaction

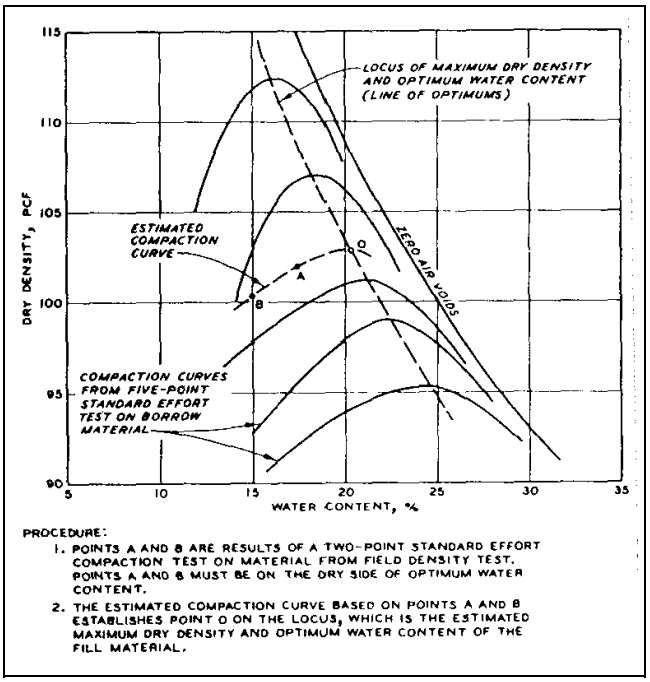

Figure B-3. Illustration of two-point compaction method

curves are not parallel. Using point A only, as in the one-point test method, would result in appreciable error as the shape of the curve would not be defined. The established compaction curve can be more accurately defined by two compaction points as shown. Although the two-point method is more accurate than the one-point method, neither method would have acceptable accuracy when applied to the set of compaction curves shown in Figure B-2. There are materials and instances when the two-point compaction test fails to identify the proper compaction curve. Experienced embankment construction engineers suggest that when this occurs, a third compaction point is necessary, and is performed for proper definition of the soil compaction curve.

d. Visual comparison. In the visual comparison method, selection of an appropriate compaction curve is based on visual identification of the type of material from the field density test with material (usually jar samples) on which five-point compaction tests have been run. Unfortunately, materials that appear similar can have widely varying compaction characteristics, and this method is not considered reliable.

e. Atterberg limits correlations. To develop Atterberg limits correlations, liquid limit, and plastic limit determinations and five-point compaction tests are made and plots are prepared of optimum water content versus liquid limit, versus plastic limit, and versus plasticity index. Similar plots are made of the limits values versus maximum densities. The plots are then analyzed to determine if adequate correlations exist (exhibited by plotted points falling in a narrow band across the plot). Figures B-4 and B-5 are examples of such plots. If a good correlation exists, appropriate limits tests are performed on the field density test material and the plots used to estimate optimum water contents and maximum densities of the in-place material. This method is applicable to fine-grained cohesive soils classified as CL and CH. Statistical analyses of the data shown in Figures B-4 and B-5 indicate relatively good correlations. Least square linear regressions were performed on the data shown in Figures B-4 and B-5 to determine the "best fit" linear equations to correlate optimum water content and maximum dry density with liquid limit and plasticity index. Using properties of statistical parameters, it can be shown that about 68 percent of the data points (of true optimum water content) on Figure B-4a will lie within plus or minus 1.4 percentage points of the indicated line of best fit; similarly, about 65 percent of the maximum dry density data points will lie within plus or minus 2.7 pcf of the indicated line. (Conversely, 32 percent of the data points will fall outside of these limits around the respective lines). Optimum water content and maximum dry density did not correlate as well with plasticity index. Approximately 68 percent of the actual optimum water contents and

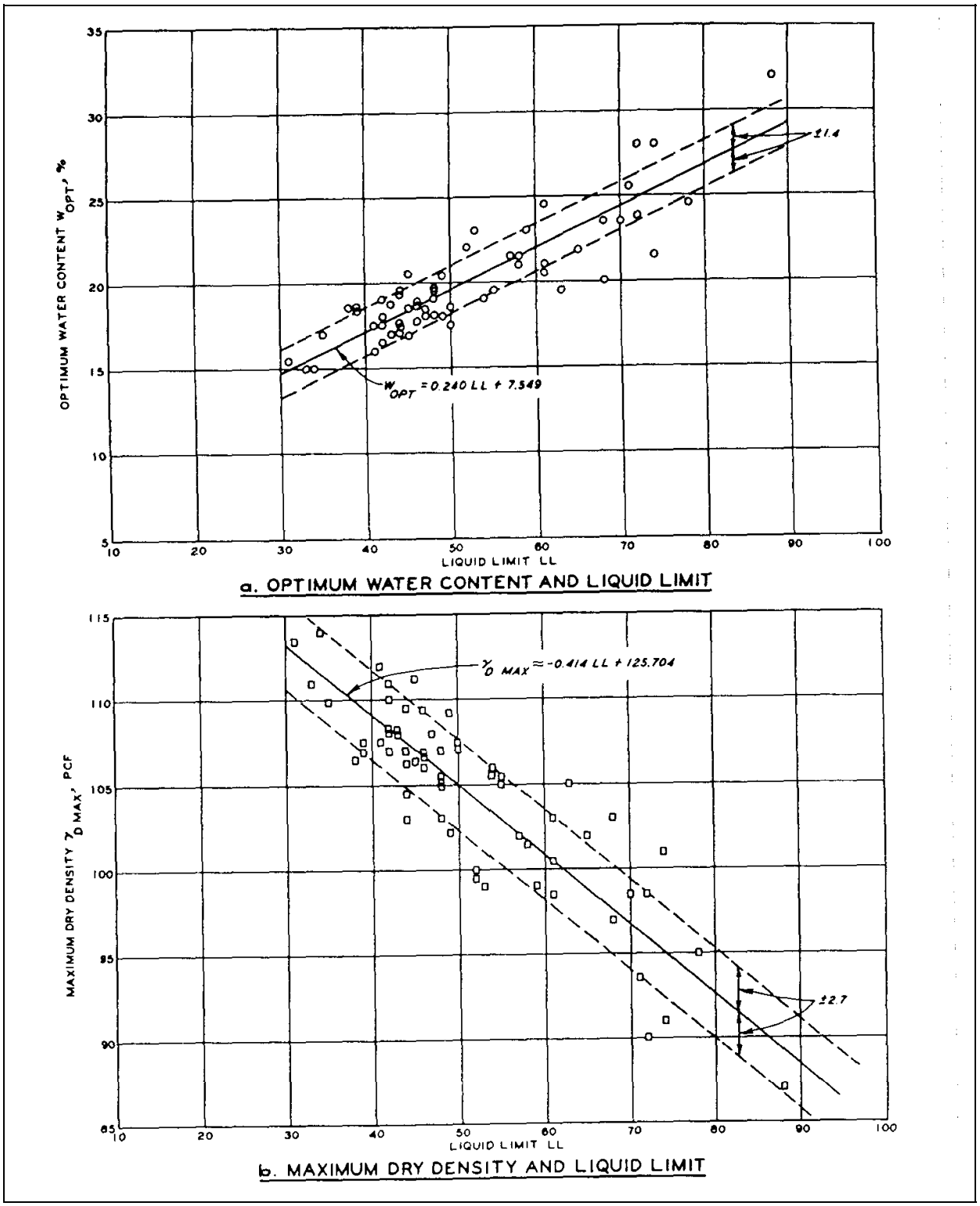

Figure B-4. Examples of plots of optimum water content and maximum dry density versus liquid limit

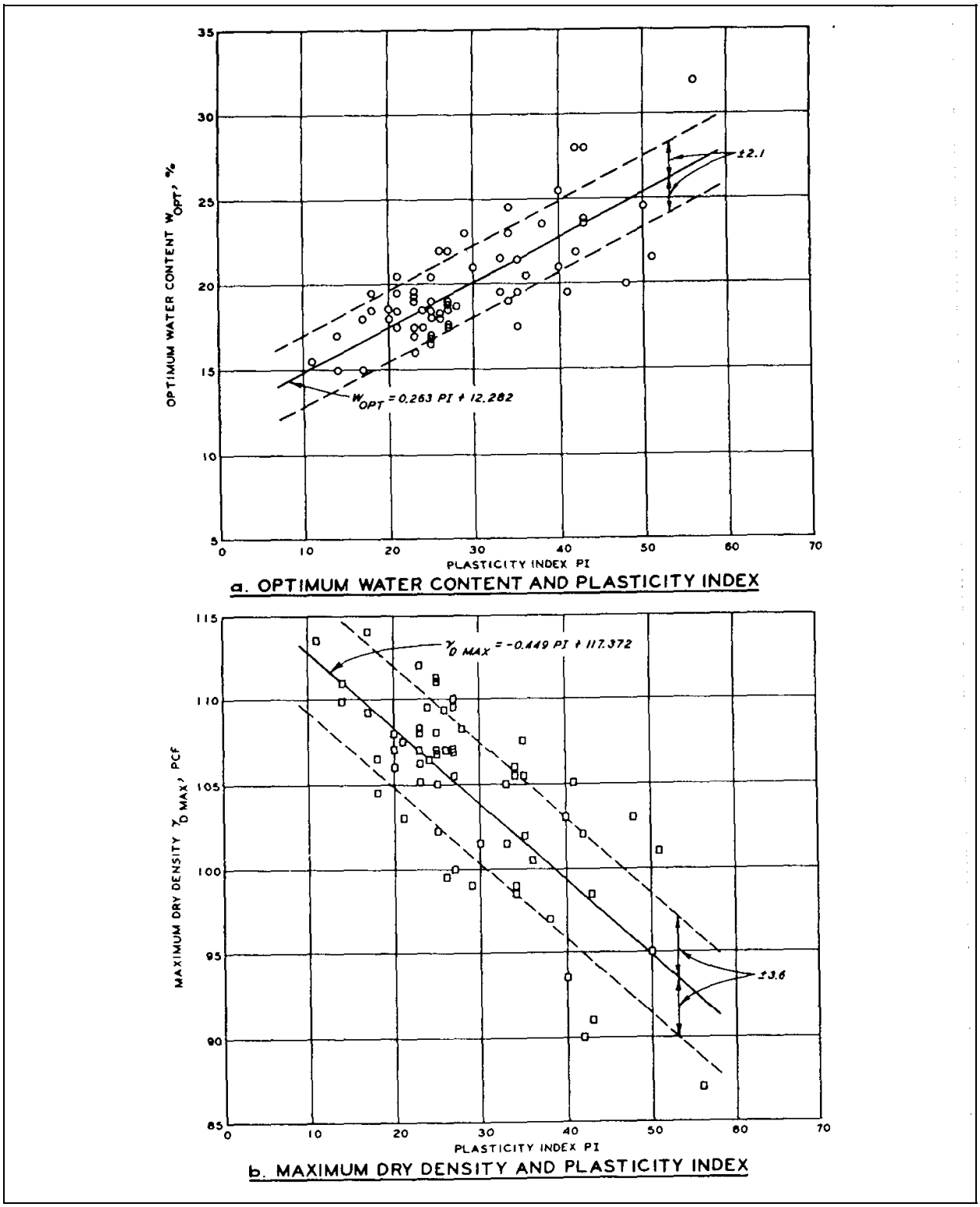

Figure B-5. Examples of plots of optimum water content and maximum dry density versus plasticity index

dry densities will be within ± 2.1 percent and 3.6 pcf, respectively, of those indicated by the lines of best fit. Therefore, when this method is used, it is very important that additional five-point compaction tests and Atterberg limits tests be performed to check the correlation and to extend the correlation for new borrow material for mixtures not previously tested. The Atterberg limits correlation method includes more variables than the two-point method and thus can be less accurate, depending on how carefully the particular method is used. However, the limits correlation method has the advantage of providing the exact classification of the soil, and of providing data that can be correlated with design strength studies.

f. Analysis of Atterberg limits correlations. A discussion of Atterberg limits correlations and comparison of results with the one-point method are given in by Torrey (1970). However, additional discussion of the method is deemed appropriate here to point out mathematical weaknesses in the procedure. In order to determine a mathematical relationship between the variables of interest (that is liquid limit, plastic limit, optimum water content, maximum dry density) using the methods of statistics, it is necessary to assume a frequency distribution between the variables. It was assumed that there is a normal or Gaussian distribution between the variables. A normal distribution has a very specific mathematical definition and, although the assumption of normal distribution is reasonable, it must be pointed out that there is no insurance that the assumption is valid. Additionally, it was assumed that the relationship between the variables of interest is linear; again, there is no evidence to support such an assumption; in fact, it is very likely that there is a curvilinear relationship between the variables of interest. Analysis of the data presented in Figures B-4 and B-5. showed that the linear correlations between optimum water content and liquid limit (shown in Figure B-4a) and maximum density and liquid limit (shown in Figure B-4b) explain only 77.6 percent and 76.3 percent, respectively, of variation between the regression line and the data points. This means that unidentified mechanisms explain about one quarter of the variation between the regression line and the points. Similarly, the linear correlations between optimum water content and plasticity index (shown in Figure B-5a) and maximum dry density and plasticity index (shown in Figure B-5b) explain only 57.8 percent and 55.7 percent of the variation, respectively; about 43 percent of the observed variation is unexplained by the mathematical model chosen. In this light, the correlation between the variables appears less sound, especially considering that there is no mathematical assurance that a relationship exists between these variables; the mathematical curve-fit procedure used in the analysis ensures only that the mathematical expressions given are the best possible linear fits. The numbers defining the error bands of the regression lines of Figures B-4 and B-5 are called the standard error of the estimate. Again, if the data are normally distributed about this line, theory predicts that about 68 percent of the points lie between the (error band) lines. However, this also indicates that 32 percent (about one-third) of the points will statistically lie outside the band. For example, since the standard error between maximum dry density and liquid limit is 2.7 pcf, if maximum dry density were estimated based on a determination of liquid limit of a soil sample taken from the area, chances are about one in three that the error in maximum density would be greater than 2.7 pcf. In this light, the use of this procedure to estimate either maximum dry density or optimum water content appears to be unsound and inappropriate. The use of one- and two-point compaction test results appears to be much more sound, especially considering that the results of a one-point compaction test may be obtained in about 40 min using microwave drying techniques outlined in paragraph 5-10*d* (1)(c). Conversely, the time required to obtain the results of a liquid and/or plastic limit test may be prohibitive in a construction environment where large volume rates of earth are being placed.

g. USBR rapid compaction control method. Details of this method are described in the U.S. Bureau of Reclamation Earth Manual (1963). The test is applicable to fine-grained (100 percent minus No. 4 sieve) cohesive soils with liquid limits less than 50. The method, however, is applicable to soils containing oversize particles providing the proper corrections, as stated in Torrey (1970) or in the Earth Manual (1963), are applied. It is a faster method than the standard compaction test, and is often more accurate than other methods. The method usually requires adding water to or drying back sampled fill material, and thorough mixing is required to obtain uniform drying or distribution of added water. Otherwise, the results may be erroneous, especially for highly plastic clays. In highly plastic (and probably difficult) clays, it is likely to be inaccurate because of the lack of sufficient curing time of the specimens.

B-3. Cohesive Soils

a. Oversize particles. The term “oversize particles” as used in this work refers to those particles larger than the maximum size allowed when using a given mold (i.e., No. 4 for a 4-in. mold, 3/4-in. for a 6-in. mold, 2-in. for a 12-in. mold). The term “fine fraction” refers to that part of the soil composed of particles equal to and smaller than the maximum size allowed for a given mold. Results of field density tests made in fill material containing oversize particles must sometimes be related to results of compaction tests made on materials from which oversize particles have been scalped, if the USBR rapid compaction control method is used, or if it has not been possible to perform compaction

tests using molds of sufficient size to accommodate the large particles.

b. Correction of field density test results. When the proportion of oversize material is not greater than about 35 percent, the dry density of the fine fraction can be calculated with reasonable accuracy from the following equation which associates all voids with the fine fraction:

$$\gamma_f = \frac{f\gamma_t\gamma_w G_m}{\gamma_w G_m - c\gamma_t} \tag{B-1}$$

where

γ_f = dry density of fine fraction, pcf
f = proportion of fine fraction by weight expressed as a decimal fraction
γ_t = dry density of total field sample, pcf
γ_w = unit weight of water, 62.4 pcf
G_m = bulk specific gravity of oversize particles (dry method), dimensionless
c = proportion of oversize particles by weight expressed as a decimal fraction

The water content of the fine fraction can be calculated from the following equation:

$$w_f = \frac{w_t - cw_c}{f} \times 100 \tag{B-2}$$

where

w_f = water content of fine fraction, percent
w_t = water content of the total field density sample, expressed as a decimal fraction
w_c = water content of oversize fraction, expressed as a decimal fraction

At the beginning of construction, charts can be prepared for materials having oversize particles relating dry densities and water contents of total samples to dry densities and water contents of fine fractions (Figures B-6a and B-6b) if it is desired to use the original Ziegler equation. Different charts are required for materials having oversize particles with significantly different bulk specific gravity and/or absorption values. In field density testing, the appropriate chart is entered using the percent oversize particles and the water content or dry density determined on the total sample to obtain the water content, dry density, and wet density of the fine fraction. Corrections for oversize particles will be subject to large errors if the percent of oversize particles is greater than about 35; in such cases, compaction control should be based on laboratory compaction tests performed in molds of appropriate sizes.

c. Modified Ziegler equation to estimate maximum density. A procedure to compute dry density of earth-rock mixtures has been determined as an extension of the Ziegler procedure and is discussed by Torrey and Donaghe (1991); the procedure is a modification of the development which resulted in Equation B-1. The modified equation accounts for the actual percent compaction of the gravel fraction when the total material (gravel and fines) is at its maximum density. This is done by incorporating the effect of a factor called the density interference coefficient, which is defined as

$$I_c = \frac{R_c}{P_g G_m} \tag{B-3}$$

where

R_c = decimal fraction of the percent compaction of the minus No. 4 or -3/4-in. fraction
P_g = decimal fraction of percent gravel in the total material
G_m = bulk specific gravity of the gravel

To determine the maximum dry density corresponding to the gradation of the total fill sample, use the equation

$$\gamma_{tmax} = \frac{P_g I_c \gamma_{fmax}\gamma_w G_m}{f\gamma_w + P_g c I_c \gamma_{fmax}} \tag{B-4}$$

where

γ_{tmax} = maximum dry density of the gradation of the total fill
γ_{fmax} = maximum dry density of the finer fraction determined at its optimum water content, W_{fopt}, by the one- or two-point compaction method

It should be noted that γ_{fmax} may be determined based on gravel content defined as either the -3/4-in. or the minus No. 4 sieve fraction of the total material to be placed in the fill. However, it is more efficient to use the minus No. 4 fraction because percent oversize particles (c) and percent gravel in the total material (P_g) are the same number. This will eliminate an extra sieving operation which would be required if γ_{fmax} and W_{fopt} are used for the -3/4-in. fraction, since both the percent oversize (+3/4-in. material) and the percent gravel in the total material would have to be determined. To facilitate its numerical evaluation, Equation B-4 may be rewritten in the form

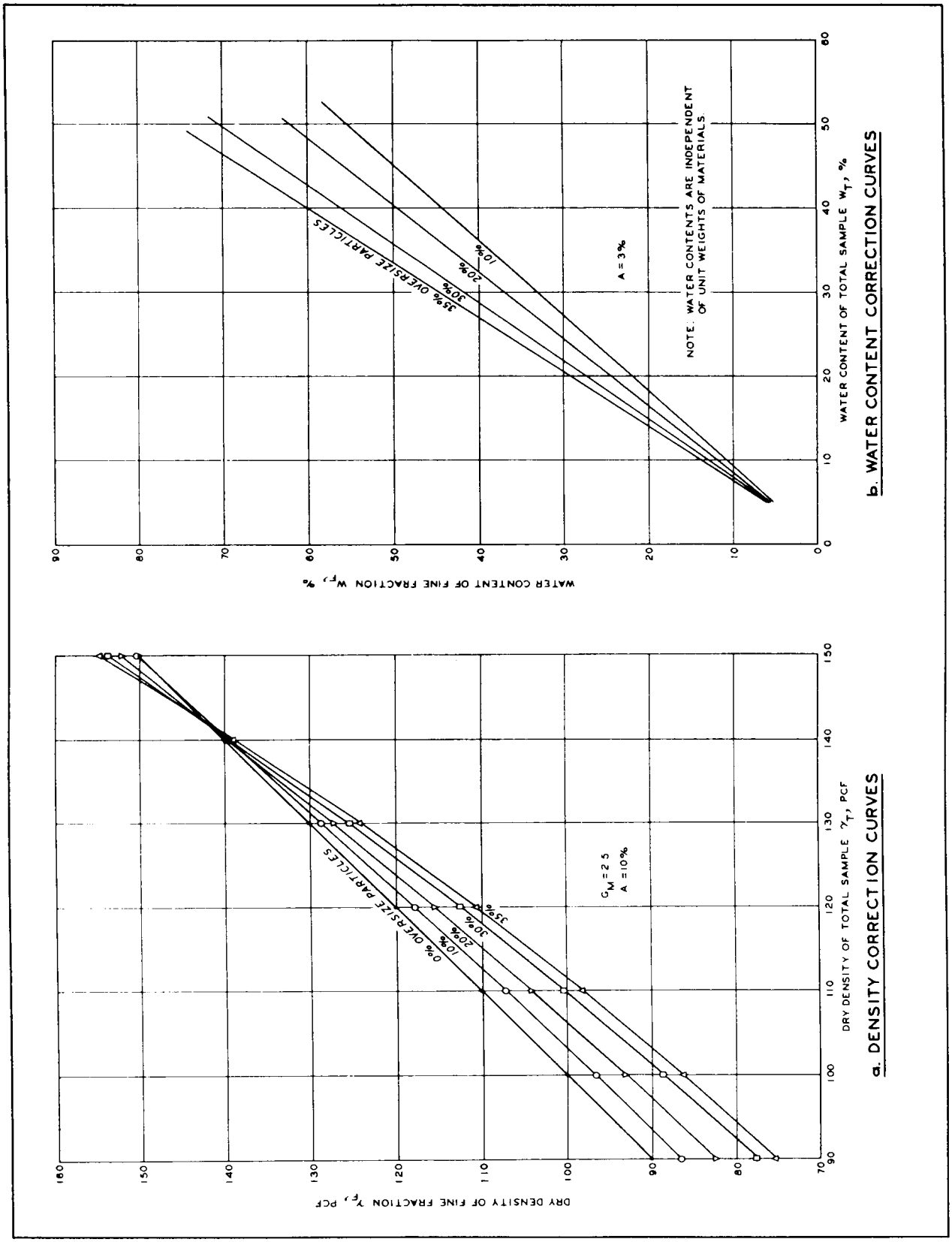

Figure B-6. Density and water content correction curves

$$\gamma_{tmax} = \frac{P_g I_c \gamma_w G_m}{f\frac{\gamma_w}{\gamma_{fmax}} + P_g^2 I_c} \tag{B-5}$$

which consists of three groups of terms. Figures B-7 and B-8 were prepared from data presented by Torrey and Donaghe (1991) and allow numerical evaluation of the groups of terms $P_g I_c \gamma_w G_m$ and $P_g^2 I_c$, respectively, in terms of the percent gravel in the total material. It should be noted that the term c in Equation B-4 is the decimal value of percent oversize particles by weight, and is equal to P_g if I_c is based on the minus No. 4 fraction. The value of bulk specific gravity used to determine the relationship presented in Figure B-7 is 2.5. The remaining group of terms in Equation B-5 is $f\gamma_w/\gamma_{fmax}$, and is easily evaluated. Accordingly, the maximum dry density of the fill containing up to 70 percent gravel may be determined from Equation B-5.

As an extension of Equation B-2, the optimum water content of the total material is given as

$$w_{topt} \approx f w_{fopt} + c w_c \tag{B-6}$$

where

w_{fopt} = optimum water content of the fine fraction

The optimum water content of the fine fraction, w_{fopt}, can be directly related to that of the total material, w_{topt}, and the gravel content of the total material, P_g, by an optimum water content factor, F_{opt}, defined as

$$F_{opt} = \frac{\frac{w_{fopt}}{w_{topt}}}{P_g} \tag{B-7}$$

When the optimum water content factor, F_{opt}, versus gravel content in the total material is plotted in log-log coordinates, the relationship is linear over a significant range of gravel content, up to more than 60 percent gravel content for some gravels. However, it appears necessary to demonstrate linearity above gravel contents of 50 percent, since some data examined deviated from linearity above about 50 percent gravel content. Linearity of the water content factor, F_{opt}, versus gravel content in the total material in log-log coordinates may be used to establish the total material curve without testing the total material, which would require large-scale compaction equipment. This may be achieved if the -3/4-in. fraction of the total material contains a sufficient range in gravel content to base the water content factor, F_{opt}, on the minus No. 4 fraction, while treating the -3/4-in. fraction as a total material.

B-4. Cohesionless Soils

Gradation tests are performed on sands and gravels used in pervious zones to determine compliance with specifications, and field density tests are performed and compared with laboratory relative density tests to ensure that in-place densities are adequate. Gradation tests are required on compacted filter layer samples to ensure specification compliance after compaction.

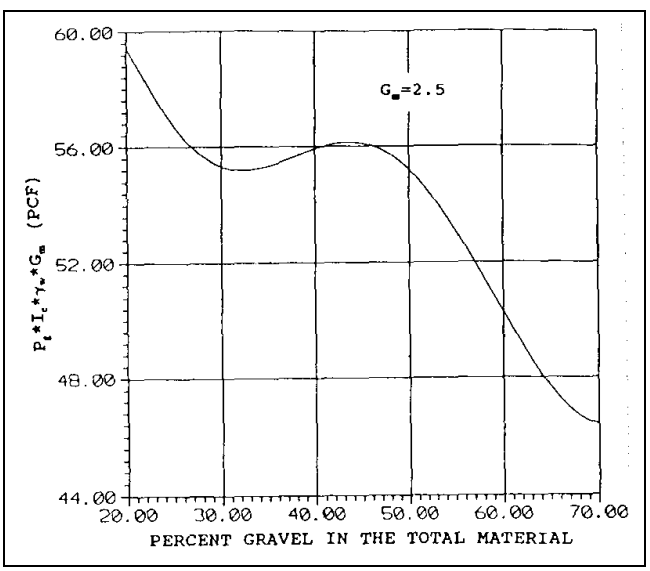

Figure B-7. Relationship between gravel content and parameters in the numerator of Equation B-5

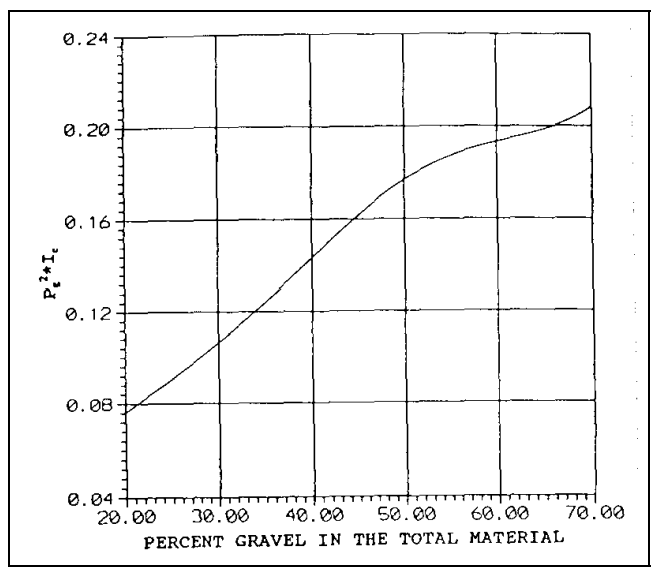

Figure B-8. Relationship between gravel content and parameters in the denominator of Equation B-5

a. Control using relative density. Where materials available for cohesionless fill vary significantly in gradation, maximum-minimum density tests should be performed on material from each field density test at least in the initial construction stages. Where cohesionless materials can be grouped into categories with relatively constant gradations, relative density tests and gradation tests can be performed on each different material. Gradation tests on material from field density tests can then make it possible to match field densities with appropriate relative density test results. However, it is necessary to point out that relative density is computed from maximum and minimum densities determined on the material in question, using the procedure outlined in EM 1110-2-1906. It was concluded by ASTM (1973) that the maximum density of cohesionless materials as determined on the "vibratory table" (as described in EM 1110-2-1906) is subject to considerable uncertainty. Further, the conclusions are that vibratory tables cannot, in general, be successfully calibrated for repeatable energy application to the soil specimen, large local density variations exist throughout the vibrated soil specimen, and density results obtained with the vibratory table are generally not repeatable from laboratory to laboratory. Therefore, control of the gradation and density of cohesionless fill using the method of relative density may be unacceptable, especially if the procedure involves coordinated effort and testing between two laboratories. An example is given by ASTM (1973) in which the standard deviation in maximum density of one sand tested by 14 laboratories is greater than 6 pcf. It is specified in EM 1110-2-1906 that minimum density tests be repeated until densities from two successive runs agree within ±1 percent. Maximum density is then obtained by placing a minimum density specimen on the vibratory table; only one maximum density test is required. Variation and uncertainty in laboratory-measured values of maximum density can cause serious problems in the construction of cohesionless fill and graded filters. Basic laboratory research is needed to resolve difficulties with the shaking table test for maximum density. Until research is performed and the source of uncertainty identified and resolved, particular care and caution should be used in determining maximum density. One method of minimizing uncertainty is to perform several maximum density tests to determine and ensure that large variations in maximum density are not being observed. A control criterion for maximum density specimens similar to that for minimum density specimens may be used—that is, agreement between two successive specimens within ±1 percent.

b. Alternative maximum density procedure. In light of the difficulty of obtaining duplicate results of maximum density on the vibratory table, consideration must be given to eliminating the test. A possible alternative procedure for maximum density determination is the Modified Providence Vibrated Density Test as described in EM 1110-2-1906. In this test, a sample of oven-dried soil is placed in a heavy steel mold, compressed under a surcharge, and vibrated to a maximum density by repeatedly striking the side of the mold with a hammer. Research presented by Tokue (1976) suggests that the level of shear strain, not acceleration, is directly related to densification of cohesionless soil. Many of the unknown uncertainties associated with the vibratory table may be avoided by use of this relatively simple procedure.

c. Materials with +3-in. particles. Relative density tests described in EM 1110-2-1906 are performed on cohesionless soils with particle sizes not greater than 3 in. If cohesionless soils contain a large amount of +3-in. material, large-scale field density tests would be needed for comparison with results of field density tests performed during construction of test fills to develop adequate compaction procedures. When no field density test results are available, control is achieved by careful inspection to ensure that the specified gradation is being met and that the specified compaction procedures are followed. Visual inspection of the sides of a test pit dug in the compacted fill can provide qualitative indications of the denseness of the material and of the existence of any significant voids.