Compaction Prestress

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The compressibility and shear strength characteristics of compacted soils, for both short- and long-term periods, are dependent on, among other factors, the as-compacted prestress and saturated prestress induced in the soil. Their presence is manifested in the consolidation and undrained shear test results available in the literature. Consequently, for an accurate interpretation of these test results, a knowledge of the induced compaction prestresses is essential. A procedure for the prediction of as-compacted prestress based on the precompaction soil conditions and the relevant compaction independent variables is presented. The procedure is based on general soil behavior using results from simple laboratory tests. The calculated values of the as-compacted prestress were compared with experimentally determined as-compacted prestresses, and a good correspondence was obtained. Using statistical regression techniques, prediction equations were derived for the experimentally determined as-compacted prestress, volumetric strain due to saturation, and saturated prestress. The volumetric strain and saturated prestress show a strong dependence on the values of as-compacted prestress. Thus, with a better understanding of the compaction prestresses, which can be controlled through compaction specifications, fills and embankments can be constructed with more predictable compressibility and shear strength behavior.

Excavation, transportation, dumping, and spreading in the field (or degradation in the laboratory) before compaction substantially obscure the geologic preconsolidation stress. Compaction causes densification by reduction of air voids caused by a change in the relative positions of the soil aggregates or grains, or both. This induces a compactive prestress in the soil, which, though analogous to preconsolidation stress, represents the fraction of the compaction energy/pressure that is effectively transmitted to the soil matrix by plastic deformation. The ensuing amount of plastic deformation depends on the duration of application of the compaction energy/pressure and the constraint posed by the induced pore fluid (water and air) pressures.

For an engineer to quantitatively predict and control the compressibility and shear strength characteristics of a compacted fill for both short- and long-term periods, an explicit knowledge of the magnitude of the as-compacted and saturated prestresses is essential.

The as-compacted prestress in a fill is influenced by compaction water content, compaction energy/pressure, and mode of compaction. Its value decreases with water content for a given compaction energy/pressure. Also, for a given water content, particularly on the dry side of optimum moisture content, the as-compacted prestress increases with compaction energy/pressure. Load levels greater than the as-compacted prestress are accompanied by relatively large deformations (just as is the case for preconsolidation stress in saturated soils) due to the ensuing soil aggregate and particle reorientation.

Unavoidable changes in environmental conditions during the long-term period will result in a probable saturation of a compacted fill under existing fill pressures. A reduction in the value of the as-compacted prestress accompanies the saturation, and the magnitude of the resultant saturated prestress is dependent on the magnitude of fill confining pressure.

The presence of saturated prestress is also manifested in many test results including

1. Compressibility tests by DiBernardo and Lovell *(1)* and Lin and Lovell *(2)* that demonstrated distinct changes in slope for *e* versus log *P* curves for samples saturated under various confining pressure levels.
2. Consolidated undrained shear tests by Johnson and Lovell *(3)* and Liang and Lovell *(4)*, for which the induced pore pressures during shear decreased with strain and the effective stress paths curved up and to the right.

In addition, the prediction models for volume changes associated with the saturation of compacted soil samples, subjected to various confining pressures, and the resultant saturated prestress show strong dependency on the as-compacted prestress.

Consequently, in this paper a theoretical procedure is proposed for the determination of as-compacted prestress from simple laboratory compaction tests. The values obtained from the equations are compared with experimentally determined as-compacted prestress. The effects of the various compaction variables (compaction water content, compaction energy/pressure), equivalent fill pressure, and subsequent saturation on the as-compacted prestress are examined.

Prediction equations are developed for the as-compacted prestress, volume changes due to saturation, and saturated prestress generated in a clay soil, compacted to various energy and water content levels and saturated under various levels of confining pressure.

EXPERIMENTAL APPARATUS AND PROCEDURE

The soil used for this study was a plastic fine-grained lacustrine clay deposit from New Haven in northeastern Indiana. The classification test results are given in Table 1.

The soil was sieved through a No. 4 sieve, mixed with a desired amount of water, and then cured for 5 days. Three compaction energy levels (15-blow low energy, standard AASHTO, and modified AASHTO) were subsequently applied at the various water content levels of interest. The relationships

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TABLE 1 PROPERTIES AND CLASSIFICATION OF NEW HAVEN CLAY

Category	Property and Classification
Liquid limit (%)	47
Plastic limit (%)	20
Plastic index (%)	27
Specific gravity	2.75
Clay fraction <2 μm (%)	33.0
Skempton's activity	0.82
Unified soil classification	CL
AASHTO soil classification	A-7-6

among dry density (γ_d), water content (w), and degree of saturation (S_r) are shown in Figure 1.

After compaction at a desired moisture content, the soil sample was transferred to an adjustable Proctor mold in which test sampling, using an oedometer ring, was accomplished.

Testing of the soil was conducted in Karol-Warner fixed ring oedometers. The oedometer ring was 63.5 mm (2.5 in.) in inside diameter, 101.6 mm (4.0 in.) in outside diameter, and 25.4 mm (1.0 in.) high. Loading was accomplished by a lever arm weight system. A seating pressure of 10 kPa was used after which the total applied pressure was increased, using a load increment ratio (LIR) of 0.5, to 14.86, 22.3, 33.44, 50.16, 25.24, 112.86 kPa and so forth until the as-compacted prestress was well defined. The duration of each load increment was 16 min. This time was adequate to define all presecondary effects.

During the service life of a fill, environmental changes can lead to a near saturation condition, with attendant changes in volume and in the as-compacted prestress in the soil mass. This was approximated by compressing the soil, using an LIR of 0.5 and load duration of 16 min, until vertical consolidation pressures of 10.0, 69.4, 137.5, and 276.2 kPa were achieved. These consolidation pressures, at standard AASHTO optimum dry density, correspond to fill heights of 0.61, 4.2, 8.4, and 16.9 m (2.0, 13.9, 27.5, and 55.3 ft), respectively. The soil samples were subsequently saturated by a back pressure process, then unloaded and reloaded at an LIR of 0.5 until the saturated prestress and compression indices were well defined. The end of 100 percent primary consolidation was determined by plotting dial reading versus the logarithm of time.

ANALYTICAL PROCEDURE FOR THE DETERMINATION OF AS-COMPACTED PRESTRESS

Using the results of impact compaction tests, a procedure is proposed for the computation of as-compacted prestress. The

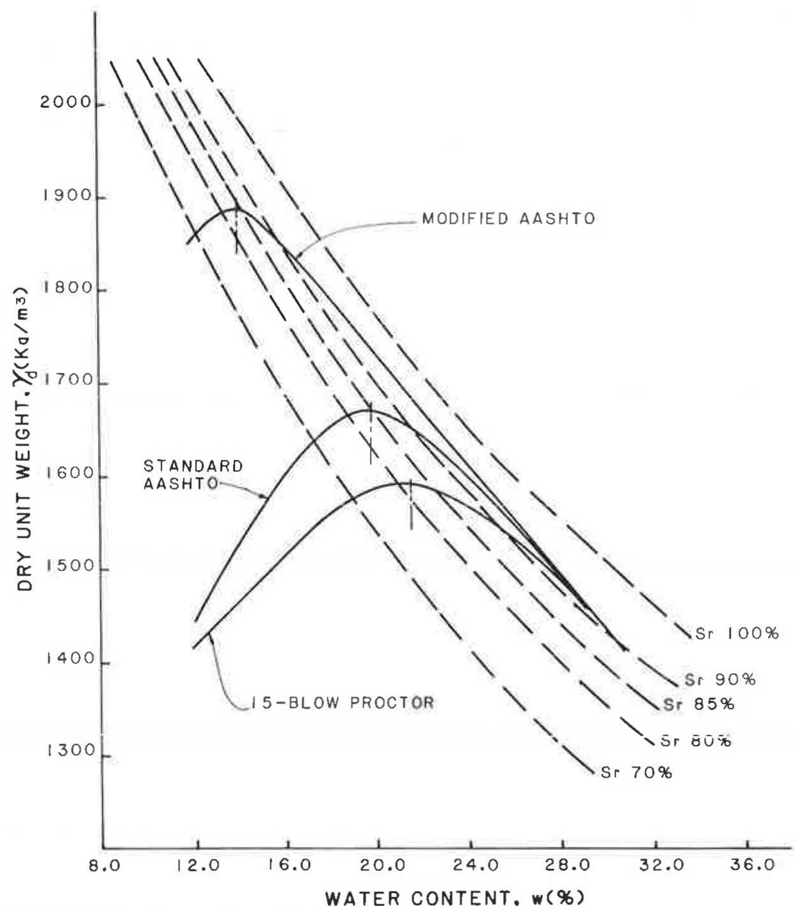

FIGURE 1 Dry unit weight versus moisture content curves for New Haven clay.

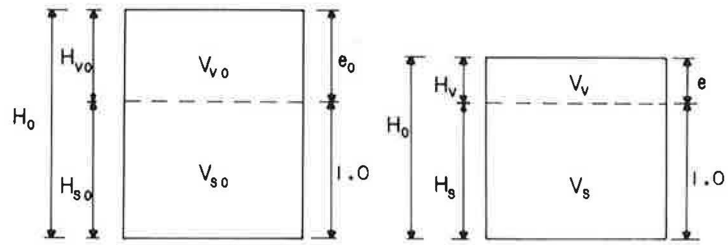

FIGURE 2 Phase diagram for a compacted soil.

following assumptions were made in the derivation of the relationship:

1. The void ratio of the compacted soil in the mold is uniform;
2. There is no energy loss in the drop of the hammer; and
3. The as-compacted prestress, which is the fraction of the compaction energy/pressure effectively transmitted to the soil matrix due to plastic deformation, is uniform throughout the sample.

The plastic deformation (δ_p) that occurs at any energy level for a soil at an initial void ratio (e_o) and water content (w) is derived as follows (Figure 2):

$$\frac{H_{so}}{H_o} = \frac{1}{1 + e_o} \tag{1}$$

$$\frac{H_s}{H} = \frac{1}{1 + e} \tag{2}$$

but

$$H_{so} = H_s$$

Hence

$$\frac{H_o}{H} = \frac{1 + e_o}{1 + e} \tag{3}$$

$$H_o - H = \delta_p = \frac{H(e_o - e)}{1 + e} \tag{4}$$

where

e_o = initial void ratio corresponding to a loosely filled mold,
H_o = height of soil corresponding to a void ratio (e_o) required to produce a compacted height (H),
e = void ratio at the end of compaction, and
H = height of mold.

The nominal compaction energy for the Proctor-type compaction test is given by

$$E = W \times h \times N_B \times N_L \tag{5}$$

where

E = nominal compaction energy,
W = weight of hammer,
h = height of drop of hammer,
N_B = number of blows per layer, and
N_L = number of layers.

For the Proctor-type test, which produces one-dimensional deformation, the strain energy per unit volume (U) stored within the soil is

$$U = \frac{1}{2}\sigma_s \varepsilon_{zp} \tag{6}$$

Equating the strain energy per unit volume (U) stored in the soil to the external work done per unit volume,

$$\frac{1}{2}\sigma_s \varepsilon_{zp} = \frac{E}{V_o} \tag{7}$$

$$\frac{1}{2}\sigma_s \frac{\delta_p}{H_o} = \frac{E}{AH_o} \tag{8}$$

$$\frac{1}{2}\sigma_s \delta_p A = E \tag{9}$$

where

σ_s = stress generated in the soil as a result of plastic deformation,
ε_{zp} = plastic strain in the soil at a given water content,
δ_p = plastic deformation of the soil at a given water content,
H_o = sample height corresponding to an initial (loose) void ratio (e_o), and
A = cross-sectional area of mold.

From the results of the laboratory compaction tests (Figure 3) the relationship between E and δ_p is seen to be nonlinear. Thus, multiplying both sides of Equation 9 by δ_p yields

$$\frac{1}{2}\sigma_s \delta_p^2 A = E\delta_p \tag{10}$$

$E\delta_p$ in this expression represents the area under the E versus δ_p curve. Observe (Figure 3, Curves 3 and 4) that for water contents wet of optimum there are specific energies required for the mobilization of the maximum plastic deformation.

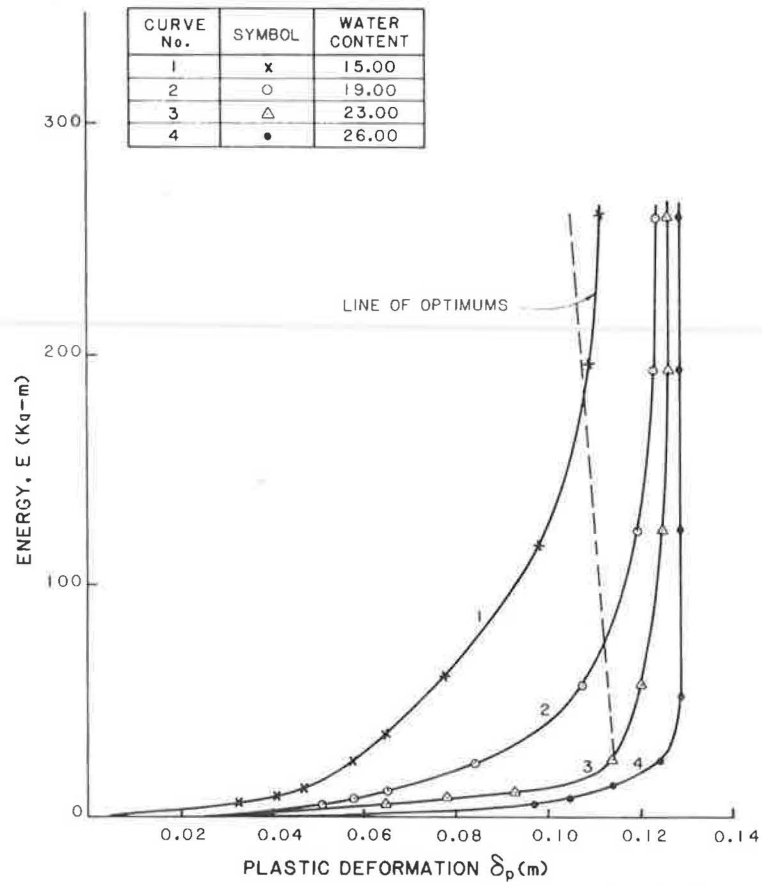

FIGURE 3 Compaction energy versus plastic deformation for New Haven clay.

Determination of the area under an E versus δ_p curve can be effected by two procedures:

1. Application of a numerical technique for the evaluation of the area (A_{EP}). Then

$$\frac{1}{2}\sigma_s A \delta_p^2 = A_{EP} \tag{11}$$

$$\sigma_s = \frac{2A_{EP}}{A\delta_p^2} = \frac{2A_{EP}(1 + e)^2}{AH^2(e_o - e)^2} \tag{12}$$

2. The plot of energy versus plastic deformation for the New Haven clay, as typified by the curves in Figure 3, can be represented by a hyperbolic function of the form

$$\delta_p = \frac{E}{a + bE} \tag{13}$$

If the E versus δ_p data are plotted on transformed axes as shown in Figure 4, Equation 13 can be rewritten as

$$\frac{E}{\delta_p} = a + bE \tag{14}$$

where a and b are the intercept and slope of the resulting straight line, respectively. The area under the curve (Figure 5) is then given by

$$\int_0^{RCE} E d(\delta_p)$$

$$= \int_0^{RCE} E d\left(\frac{E}{a + bE}\right)$$

$$= \int_0^{RCE} \frac{E a dE}{(a + bE)^2}$$

$$= \left\{\left[\ln(a + bRCE) + \frac{a}{a + bRCE}\right] - [\ln(a) + 1]\right\}\frac{a}{b^2} \tag{15}$$

Hence

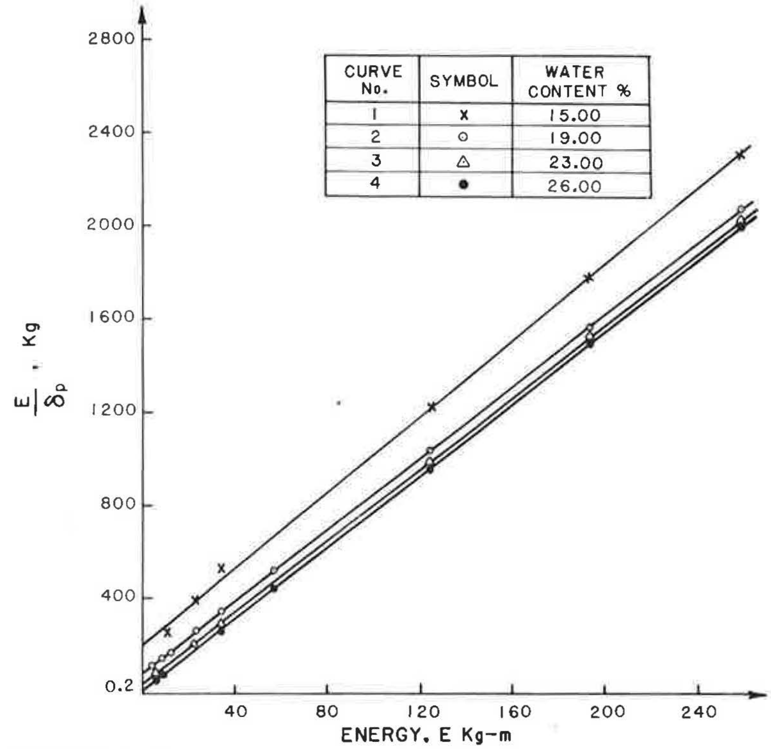

FIGURE 4 Transformed hyperbolic compaction energy–plastic deformation curve.

$$\sigma_s = \frac{2a(1 + e)^2}{Ab^2H^2(e_o - e)^2} * \left\{ \left[\ln(a + bRCE) + \frac{a}{a + bRCE} \right] - [\ln(a) + 1] \right\} \quad (16)$$

where

a = intercept of the transformed E versus δ_p curve for a desired moisture content representing the initial force (kg) that can be sustained by the soil,

b = slope of the transformed E versus δ_p curve at a desired moisture content representing the reciprocal of the plastic deformation that will occur when a great deal of energy is applied, and

RCE = applied compaction energy for which the as-compacted prestress is desired.

where

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Observe from Figure 6 the variations of a and b parameters

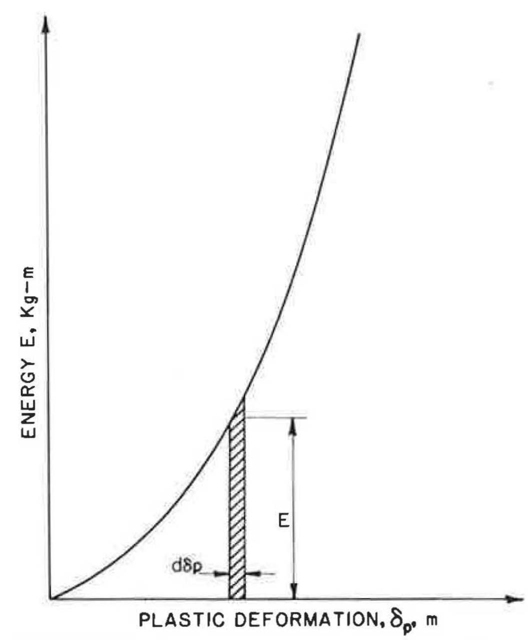


FIGURE 5 Integration scheme for the area under E versus δ_p curve.

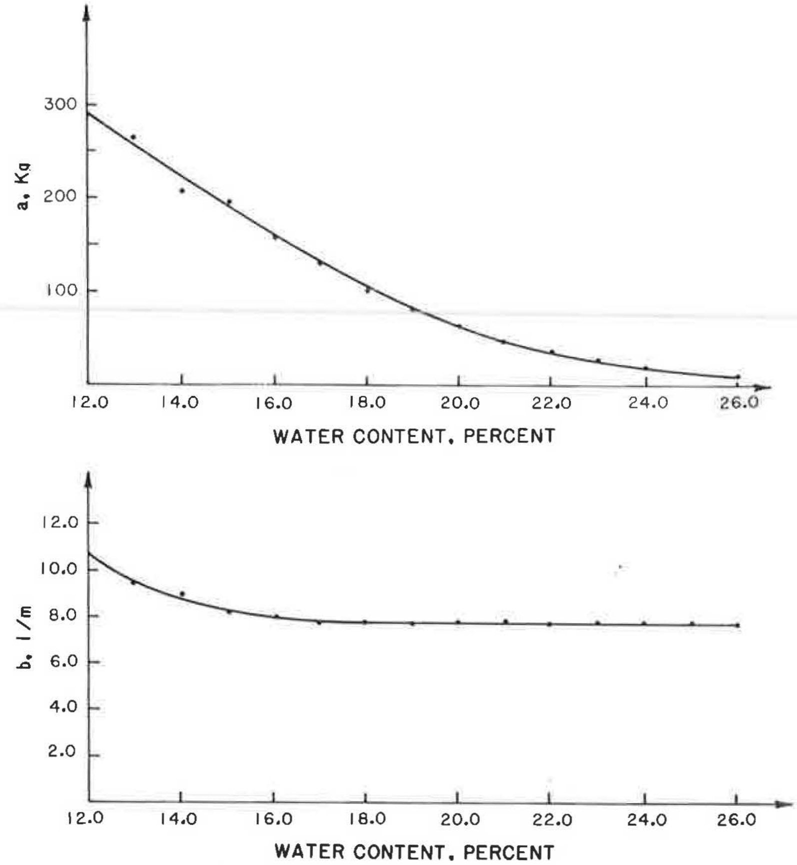


FIGURE 6 Variations of *a* and *b* with water content.

with water content. The *a* parameter shows a continuous decrease with water content whereas the *b* parameter decreases to a constant value at a water content of about 18 percent.

The calculated total stress generated in the soil as a result of the plastic deformation is the predicted prestress (σ_s). It was computed for various water contents and energy levels and shown in Figure 7.

RESULTS AND ANALYSIS

As-Compacted Prestress

Typical as-compacted compressibility curves are shown in Figure 8. The following codes were adopted for sample identification: L, S, and M refer to 15-blow (low-energy) Proctor-type compaction, standard AASHTO, and modified AASHTO efforts, respectively. The letters D, O, and W refer to moisture content conditions of dry of optimum, optimum, and wet of optimum. The numbers 1, 2, and 3 are used to differentiate among samples of identical moisture content dry of optimum, optimum, and wet of optimum.

The relative compressions (compression at any given time divided by compression at 16 min) for dry-of-optimum samples (e.g., LD1) were greater than those of wet-of-optimum (e.g., LW1'). The higher relative compression is attributable to the more readily achievable outflow of air through interconnected voids due to the higher air permeability. Observe in Figure 8 the effect of increasing water content and degree of saturation on the compressibility of the low-energy samples. At low consolidation pressure levels, less than the as-compacted prestress, the wet-of-optimum samples (e.g., LW1) are more compressible than the dry-side samples (LD1) whereas at high pressure ranges (pressures greater than their respective as-compacted prestress) the dry-side samples exhibit a more compressible behavior. Also note in Figure 8 that, for a given energy level, the as-compacted prestress decreases with increasing compaction water content. Consequently, for fill design, especially for the short-term period, the as-compacted prestress should be determined.

Laboratory as-compacted prestresses, which are the fractions of the compaction energy effectively transmitted to the soil skeleton due to plastic deformation and represent the stress level beyond which significant particle orientation occurs, were determined and plotted as points on the predicted curves (Figure 7).

By using a statistical regression procedure, a prediction equation for as-compacted prestress was also developed for the impact computed for New Haven clay:

$$\sigma_s = -\ 45.9398 + 131337.66\ \frac{\sqrt{E}}{w^2} - 18982.205\ \frac{\sqrt{E}}{w} + 1023.6757\ \sqrt{E} - 17.80117w\ \sqrt{E} - 0.12497 * 10^{-4} w^2 E^2 \qquad (17)$$

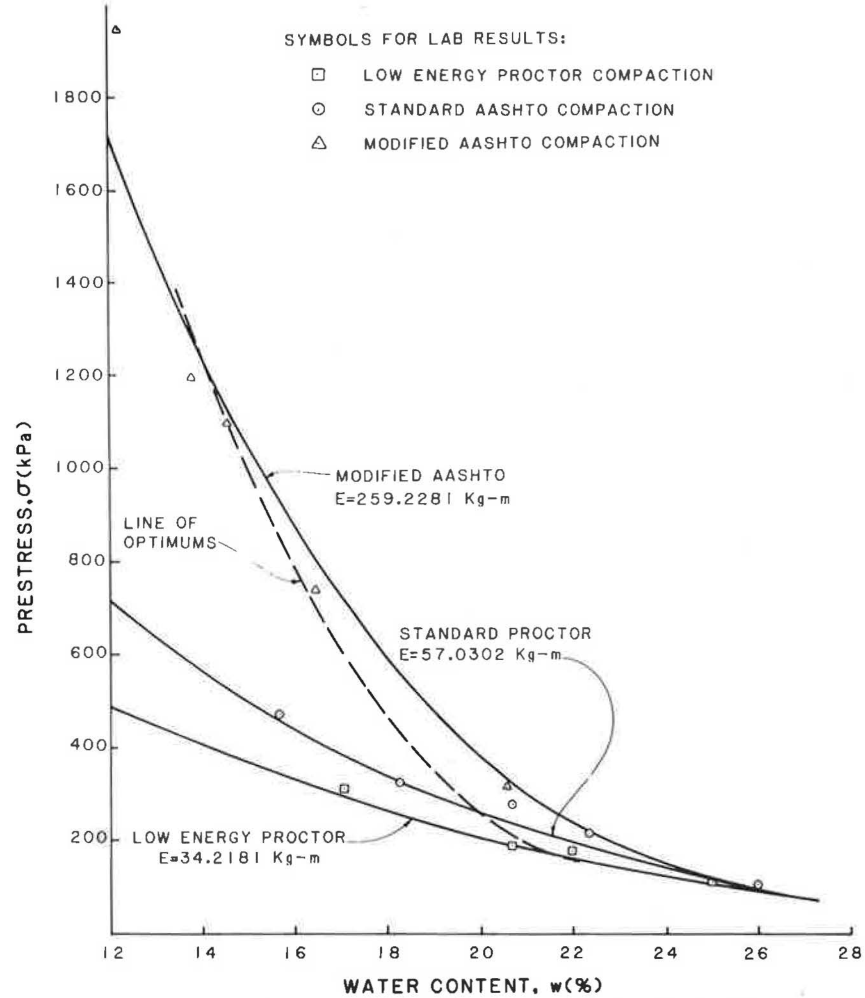
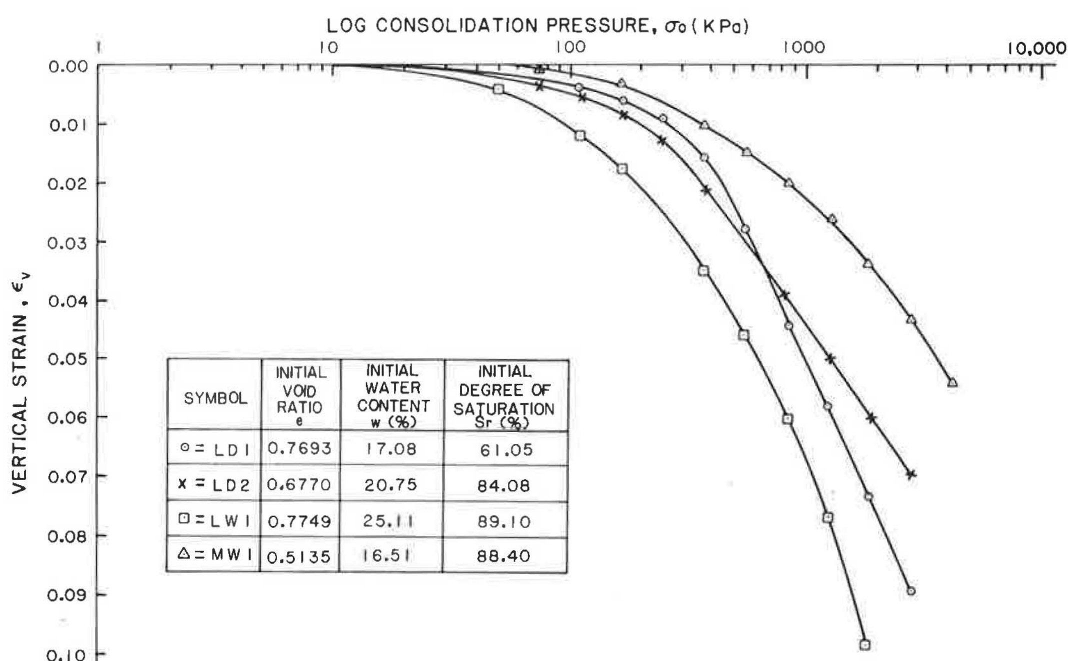


FIGURE 7 As-compacted prestress–water content relationship for New Haven clay.



SYMBOL	INITIAL VOID RATIO e	INITIAL WATER CONTENT w (%)	INITIAL DEGREE OF SATURATION Sr (%)
○ = LD1	0.7693	17.08	61.05
x = LD2	0.6770	20.75	84.08
□ = LW1	0.7749	25.11	89.10
△ = MW1	0.5135	16.51	88.40

FIGURE 8 Effect of water content on compressibility behavior of as-compacted New Haven clay.

where

σ_s = as-compacted prestress in kPa,
E = nominal compaction energy in kg-m, and
w = compaction water content.

The coefficient of determination (R^2), which represents the amount of variation explained by Equation 17 is 0.9974. The as-compacted prestress is a function of compaction energy and water content with the prestress value decreasing with water content at a given energy level. Also, the as-compacted prestress at a given water content increases with compaction energy. At very wet of optimum, beyond 26 percent for the New Haven clay, identical values of the as-compacted prestress were obtained for the compaction energies used.

Volume Change and Saturated Prestress

The effects of saturation due to changes in environmental conditions were approximated by loading compacted samples to different levels of confining pressures and then saturating them in an oedometer by a back-pressure process. The one-dimensional volume changes $\left(\frac{\Delta V}{V_o}\right)$ were measured.

The samples were subsequently unloaded and reloaded at LIR = 0.5 until the saturated prestress and compressibility indices were well defined. Load increments were applied at the end of 100 percent primary consolidation, which was determined by the Casagrande dial reading–log time procedure. The saturated prestress values were determined by the Casagrande construction procedure. Typical results are shown in Figure 9.

By using statistical regression techniques, a prediction equation was developed for one-dimensional percent volume change, $\left(\frac{\Delta V}{V_o}\right)$ percent. The percent volume change is described in terms of as-compacted void ratio (e), compaction water content (w), confining pressure (σ_o) and as-compacted prestress (σ_s).

$$\frac{\Delta V}{V_o}(\%) = -0.7595 + 0.3094 * 10^{-3} w^2 \sqrt{\sigma_o} - 0.2242 * 10^{-2} e\sigma_s - 0.7839 * 10^{-6} w \sigma_o^2 - 0.1221 * 10^{-2} \frac{\sigma_o^2}{w^2} + 1.8653 \frac{\sigma_o}{w^2} \quad (18)$$

The coefficient of determination (R^2) of this prediction model is 0.8437. For this model, a positive value of percent volumetric strain $\left(\frac{\Delta V}{V_o}\right)$ percent indicates compression, and a negative value represents swelling.

The percent volumetric strain at zero confining pressure is a function of the interaction term ($e\sigma_s$) only. Observe that, for constant values of water content and confining pressure, the compacted samples exhibit increased swelling tendencies with the interaction term ($e\sigma_s$). Thus, soil compacted at dry of optimum with a very high void ratio and as-compacted prestress will swell the most. Samples compacted on the dry side of optimum moisture content possess high negative pore pressures. Introduction of water to the compacted clay samples

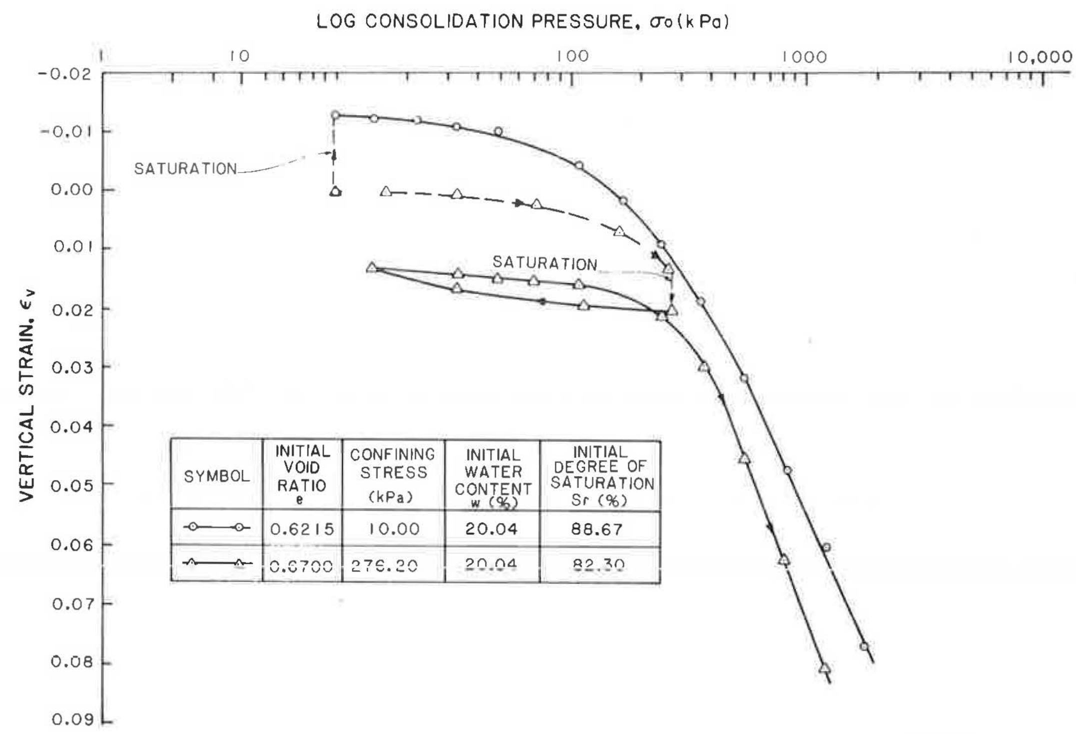


FIGURE 9 Effect of confining pressure on compressibility behavior of standard AASHTO-compacted New Haven clay.

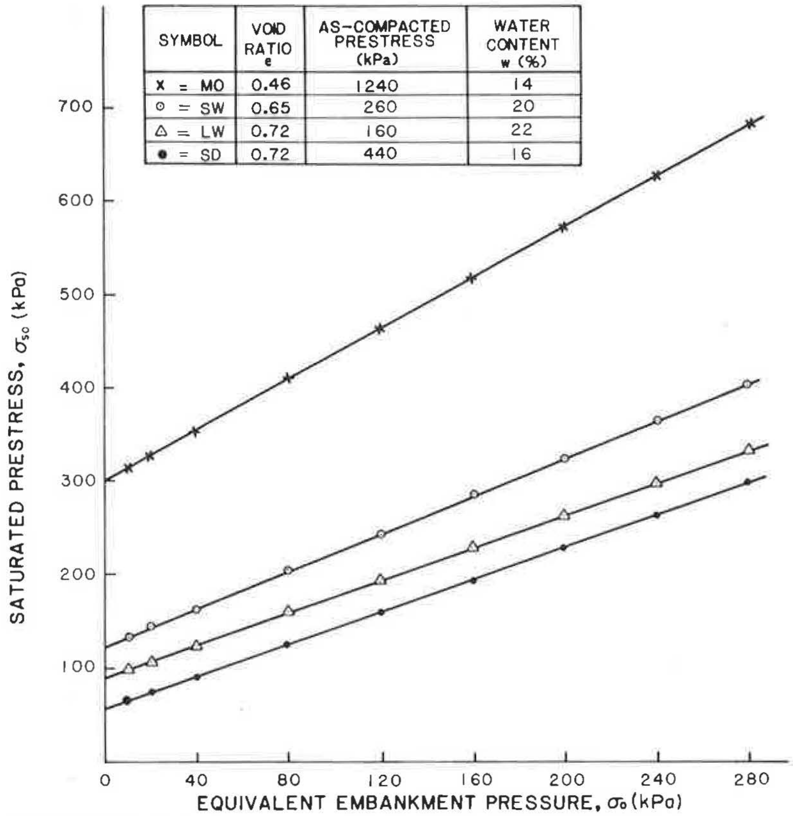


FIGURE 10 Relationship between saturated prestress and equivalent embankment pressure for various void ratios, water contents, and prestresses.

results in a decrease in their negative pore pressures and consequently a decrease in their effective stresses, giving rise to the swelling tendencies and the observed reduction in the as-compacted prestress.

The amount of swell also depends on the type of clay minerals present in the soil, initial compaction moisture content, and confining pressure. The amount of water adsorbed by dry-of-optimum samples is required to satisfy the clay micelles. The resultant expanded clay lattice, together with the adsorbed water, softens the clay aggregates, which under the influence of the confining pressure are compressed. Wet-of-optimum samples consist of more plastic and swollen aggregates. When compacted at various energy levels, the clay particles within the aggregates have a more parallel orientation, and the collection of particles and aggregates has a minimum volume of large voids, a maximum volume of small voids *(5)*, a decreased negative pore pressure, and a decreased as-compacted prestress. A reduced amount of water is required to satisfy the micelles and hence the soils show reduced swelling tendencies.

The independent variables used for the predictions of saturated prestress (σ'_{so}) are confining pressure (σ_o), compacted void ratio (e), compaction water content (w), and as-compacted prestress (σ_s). The prediction equation is

$$\sigma'_{so} = 1559.6762 + 2.24866\sigma_o(1 - 0.85007e) - 4707.3684e(1 - 0.63896e) - 5.9509\sigma_s\left(1 - 0.12317w + 0.003621w^2\right) + 0.83127w^2 \qquad (19)$$

The coefficient of determination $\left(R^2\right)$ of this prediction equation is 0.937. It should be noted that the prediction equations given are valid for the ranges of the independent variables for which they were derived.

Figure 10 shows the relationship between saturated prestress and confining pressure for various as-compacted void ratios, compactive prestresses, and water contents. Observe that, depending on the nature of the volumetric strain and the magnitude of the confining pressure, the saturated prestress equals or exceeds the as-compacted prestress and confining pressure during saturation. For the soil samples in which compression occurred, during saturation and under relatively large confining pressure, the obtained saturated prestresses are a result of plastic deformations (primary and secondary compressions) that have oriented and arranged the clay particles into a more stable configuration. Consequently, for a compacted fill, the soil at various depths will be at different overconsolidation ratios ($OCR = \sigma'_{so}/\sigma'_o \geq 1$) after saturation.

CONCLUSIONS

A procedure for the determination of as-compacted prestress based on precompaction soil conditions, relevant independent compaction variables, and test results from simple laboratory compaction tests has been presented. The curve representing the relationship between energy and plastic deformation has been approximated by a hyperbolic function. Transformation of axes has helped in the determination of parameters essential to the prediction of as-compacted prestress. These parameters are essentially functions of compaction water content only. A good agreement was obtained for predicted and experimentally determined as-compacted prestress. The analytical procedure could be extended, with appropriate modifications, for the prediction of field as-compacted prestress using data from test pads.

As-compacted prestress has been shown to be dependent on compaction water content and compaction energy/pressure. The as-compacted prestress decreases with water content for a given compaction energy level. Also, at a constant water content, particularly for dry-of-optimum soils, the as-compacted prestress increases with compaction energy.

From the prediction models developed, using linear regression procedures, the volume changes associated with saturation and the resultant saturated prestress showed strong relationships with as-compacted prestress. The soil samples exhibit an increased swelling tendency with increase in as-compacted prestress. The volumetric strain due to saturation is also a function of the compaction water content, confining pressure, and compacted void ratio. The saturated prestress was also shown to increase with confining pressure. Its magnitude is also dependent on compacted void rate (e), compaction water content (w), and as-compacted prestress (σ_s).

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Publication of this paper sponsored by Committee on Quality Assurance and Acceptance Procedures.