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Compressibility of Field-Compacted Clay

P.S. LIN AND C.W. LOVELL

This study investigates the compressibility of a plastic Indiana clay (St. Croix) compacted in the field. Correlation among compaction variables and compacted properties was a prime objective. The clay was compacted to three levels of effort and five levels of water content by two kinds of rollers. As-compacted compressibilities were assessed in the laboratory oedometer, and compaction prestress values were interpreted from the e-log p curves. These values were always less than the nominal roller pressures previously applied to the soil. A regression model was written in terms of the compaction pressure and an interaction between pressure and compaction water content. Other compacted samples were saturated under three levels of confinement, with the aid of vacuum and backpressure. The subsequent volume changes depended on the compaction variables as well as on the confinement during saturation. A correlation was developed among the volumetric strain, the initial void ratio, the compaction water content, and the confinement during saturation. Soaked compressibilities were also measured and compared with the as-compacted values. The variability of the field samples is large. Comparable studies with samples of laboratory-compacted clay had been previously made and reported. Coupling of the relations for field compaction with those previously established for laboratory compaction is also reported here.

Compacted soils are used in large quantities in the construction of roadway embankments and other fills. The stability of these structures against a slope failure is always of major concern, and in most cases it is the only criterion taken into consideration in the design. However, as the construction of higher embankments becomes more common, specification of compaction procedures so that embankment settlement can be predicted and controlled for both the short- and long-term conditions is increasingly more important.

During an embankment design, the geotechnical engineer quantitatively predicts and controls the overall performance of field-compacted soil. One method is to construct a special fill section by using a range of compaction processes and then testing samples from the soil mass after each process. Such a test pad with the associated costs of field sampling, laboratory testing, and analysis is not economically feasible for most projects. Therefore, the design engineer must infer the compressibility behavior of field-compacted soils from relations developed in the laboratory. Because this inference process may not be the most desirable, this paper presents a rational method of predicting the field-compaction response from laboratory tests.

This study investigates the compressibility behavior of a field-compacted soil in the as-compacted and soaked conditions. The soil used was plastic residual clay, and field compaction was achieved by using a Caterpillar model 825 tamping roller and a RayGo Rascal model 420C vibratory roller. Three energy levels and five molding water contents were used for each roller type to study their effects on compressibility behavior. To examine the as-compacted compressibility characteristics, the compacted samples were trimmed to appropriate size and loaded incrementally in the oedometer. Of particular interest was the value of compactive prestress. During the service life of an earthen embankment, environmental changes may affect an increase or decrease in the volume of the mass.

In order to simulate the changes in the mass that may occur in service, compacted samples were saturated by a back-pressure technique in the oedometer under an equivalent embankment load. Of major interest was the percentage of volume change on wetting under loading. Saturated compressibility was also measured.

A similar study of the compressibility characteristics of laboratory-compacted samples from the same area soil was made by DiBernardo (1). Combined, the results of both studies will allow the engineer to predict the field response from laboratory-compacted samples.

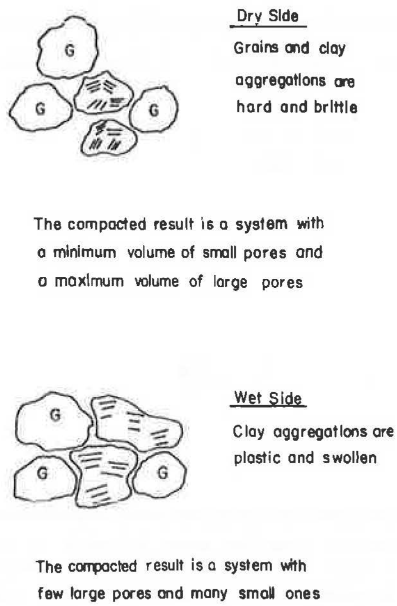
BACKGROUND

The concept of compactive prestress is generally defined as analogous to the preconsolidation pressure, where the pressure effect is caused by the compaction process (2). Lambe (3) agreed with this definition, but added that the value of the compactive prestress was sensitive to chemical and physical changes in the soil with time.

The process of compaction of a soil involves transmittal of the external compaction energy to the soil skeleton and pore fluids. On completion of the process, an induced prestress in the soil that may or may not be equal to the compaction pressure is produced. Abeyesekera (4) observed that this value of compactive prestress is important with respect to compacted shale behavior.

In order to determine the compactive prestress, Woodsum (2) statically compacted soil directly in oedometer rings, allowed the soil to come to equilibrium with water under an applied load, and performed the consolidation test. He found that, as the confining pressure remained constant and as the compaction pressure (P_{cp}) increased or void ratio decreased, the value of prestress (P_s) increased. Moreover, he found that, although the value of prestress increased with increasing compaction pressure, the prestress ratio (P_s/P_{cp}), which was similar to the overconsolidation ratio for saturated soils, varied but slightly. This prestress ratio reflects the effective transmittal of external compaction energy to the soil skeleton. On completion of the compaction process, the induced prestress in the soil may or may not be equal to the compaction

Figure 1. Effect of water content on compaction of a clayey soil.



pressure. In practical applications, this may suggest that, for a given compaction process and type of soil, the efficiency of the process does not increase with increasing effort.

The compressibility characteristics of compacted soils were reviewed by Wahls, Fisher, and Langfelder (5) in great detail. A compacted soil was considered to be a three-phase system composed of solids, air, and water. The volume decrease, which is caused by an applied load, is generally the result of (a) compression of the solids, (b) compression of the water, (c) compression of the air, and (d) escape of water or air from the pores. From a practical standpoint the change in volume is principally the result of c and d. They also concluded that the factors that primarily influence compacted compressibility were soil type, degree of saturation, molding water content, and method of compaction.

DiBernardo and Lovell (1) examined the effect of laboratory kneading compaction on the as-compacted and soaked compressibility behavior of St. Croix clay. They found that a large percentage of as-compacted compression occurred within the first minute of loading. The compression versus time relations indicated similar fluid continuity conditions (i.e., continuous air voids for dry and optimum conditions). They also summarized soaked compressibility behavior as follows:

1. For a given initial compaction condition, the soaked compressibility is greater than the as-compacted compressibility for the corresponding pressure ranges;
2. For a given compaction pressure and level of confinement on soaking, as the water content increases, the virgin compressibility (C_c) decreases; and
3. For a given degree of saturation and confinement level on soaking, as the compaction pressure increases, C_c decreases.

Hodek (6) explained the behavior of kaolinite compacted in the laboratory by static pressures under conditions of no lateral strain in terms of a deformable aggregate model. According to Garcia-Bengochea (7), pore-size distribution measurements for compacted clays have also provided strong evidence for a deformable aggregate model. Hodek and Lovell (8,9) developed a model or mechanism to explain the achievement of the compacted unit weight. The mechanism took into account the precompaction soil preparation and conditioning as well as the soil interactions that occur during compaction.

Figure 1 (8) illustrates the effect of moisture content on compaction of a clayey soil. The aggregation is a fabric unit within which individual clay particles of various sizes interact. On the dry side, the clay aggregates are shrunken, hard, and brittle. The compaction forces move these pieces around and perhaps even break some of them, but the result is a system that has a minimum volume of small pores and a maximum volume of large pores. In contrast, on the wet side, the clay aggregates are swollen and plastic. The compaction forces are able to not only move the pieces closer together but also to deform them to minimize the interaggregate space. The system now has few large pores and many small ones.

EXPERIMENTAL APPARATUS AND PROCEDURE

The soils used for both the field and laboratory compaction were obtained from the IN-37 realignment project in Perry County. The soil was St. Croix. The difference between the soils used for the field and laboratory compaction is given in the table below. It is apparently caused because the soil used for field compaction was taken from shallower depths (0-5.5 ft); the samples taken for laboratory compaction were from deeper depths (5.5-13.0 ft). Laboratory variability is low due to the soil being taken from several locations and thoroughly mixed before compaction and testing.

	Field			
Item	Mean	Low	High	Laboratory
Atterberg Limits				
Liquid limit, w_l (%)	40.0	30.0	53.2	53.0
Plastic limit, w_p (%)	18.4	16.7	21.3	21.0
Plasticity index, I_p (%)	21.9	16.4	29.0	32.0
Specific gravity (G_s)	2.78			2.80
Soil classification				
Unified	CL			CH
American Association of State Highway and Transportation Officials	A-6			A-7-6

Ten test pads were constructed of the test soils in the area of the relocation project of IN-37 in June 1978. The test pads were constructed in order to create field-compacted soil for subsequent investigation of mechanical properties and fabric descriptors. Each pad was 4.3-m (14-ft) wide and 35.4-m (116-ft) long.

Five test pads were rolled by a Caterpiller model 825 segmented pad tamping roller (C) and five pads were rolled with a RayGo Rascal model 420C segmented pad vibratory roller (R). Five different water contents were tested for each method of compaction. They had water contents on both the dry side and wet side of field optimum water contents. For identification these were designated 1-5, from the lowest to the highest moisture level. We hoped to maintain a uniform water content within each pad. Each test pad was sampled following the completion of 4, 8, and 16 passes of the compaction equipment over the pad. These samples were labeled A, B, and C, respectively, for identification of energy levels (10).

A Karol-Warner fixed ring consolidation cylinder was used in this investigation. The oedometer ring is 63.5 mm (2.50 in) in inside diameter, 101.6 mm (4.0 in) in outside diameter, and 25.4 mm (1.0 in) in height. The loading system used to compress the sample is a lever armweight type.

The first step in the trimming process for the field samples was to remove the wax and cheesecloth covering. This was accomplished by using a sharp knife to cut through the covering, and care was taken to prevent damage of the soil sample inside. The next step was to put the soil sample directly into the oedometer ring. The upper and lower faces of the sample were trimmed with a steel straightedge by using the top and bottom of the ring as guides.

Following the seating load adjustment period (typically 10 min), the applied pressure was increased, by using a load increment ratio (LIR) of 0.5 to 14.9, 22.3, 34.7, 49.5, and 76.8 kPa before the prestress value for the particular sample was reached. The applied pressure was decreased and then increased again until the prestress value for the particular sample could be well defined. The duration of each load and unload was 10 min, during which dial readings were typically recorded at 0, 0.1, 0.5, 1, 2, 4, 8, and 10 min.

During the service life of an earthen embankment, environmental changes may cause an increase or decrease in the volume of the mass. In order to simulate the changes in the mass that may occur in service, the field-compacted sample was compressed by using LIR = 0.5 and load duration of 10 min in the as-compacted condition until a vertical pressure of either 160, 320, or 480 kPa was applied. The samples were then saturated by a deairing and back-pressure procedure. The consolidating loads--either 160, 320, or 480 kPa--represent the pressure exerted by an equivalent embankment height of 7.8, 15.6, or 23.5 m (25, 50, or 75 ft), respectively.

DISCUSSION OF RESULTS

As-Compacted Compressibility

An as-compacted compressibility sample designated by R5B2 would indicate that the sample was compacted by the Rascal equipment (R) at the fifth water content level (5) and was the second sample (2) collected after the equipment made eight passes (B).

The relative compression (compression at time = t divided by the total compression at time = 10 min) versus time curves for dry, wet, and at optimum samples are shown in Figure 2. For the dry-side and optimum samples (C1A2, C2A3), the magnitudes of relative compression are virtually the same at each successive time plotted. The compression of both samples was dominated by the outflow of pore air; specifically, the air voids were interconnected (Yoshimi, 11). The magnitude of relative compression with time for an initially wet-of-optimum sample (C4A3) is also shown in Figure 2. In comparison the wet-side sample exhibits the least amount of relative compression within the 10-min period.

The effects of increasing water content and degree of saturation on compressibility behavior of samples compacted to energy level A (4 passes) are shown in Figure 3. This figure shows a marked difference in the compressibility behavior for dry- and wet-side samples, depending on the range of consolidation pressure considered. That is, in the low-pressure range (20-300 kPa), the wet-side sample is more compressible than the dry-side sample. However, in the high-pressure range (> 300 kPa), the dry-side sample is more compressible than the wet-side sample.

The effect of increasing the compactive effort on the compressibility behavior of initially dry of optimum samples is shown in Figure 4. This figure shows that the slope of the curves within the respective high-pressure ranges becomes steeper (i.e., increasingly more negative) with decreasing compactive effort.

The value of compactive prestress can be useful in design, because the compressibility behavior of the mass will be different at embankment-confining pressures above and below this value. Prestress ratio versus degree of saturation is plotted in Figure 5. This figure shows that the prestress ratio decreases with increasing saturation. For the partial range of saturation considered in this study, the prestress ratio is always less than one, which may indicate that not all of the energy delivered achieves densification. Figure 5 also shows that the prestress ratio of the Rascal vibratory roller is higher than that of the Caterpillar tamping roller at the same degree of saturation. The compactive efforts reported here are only nominal pressures [i.e., they are the pressures applied by the compactor during the compaction process (12)]. Therefore, the actual prestress ratios (i.e., compactive prestress-nominal compactive pressure) are more than likely greater than the values shown on Figure 5.

Soaked Compressibility

A soaked compressibility sample designated by C2A2a would indicate that the sample was compacted by the Caterpillar equipment (C) at the second water content level (2) was the second sample (2) collected after the equipment made four passes (A), and was incrementally loaded and soaked at an applied pressure that corresponds to an embankment height of 7.8 m (a).

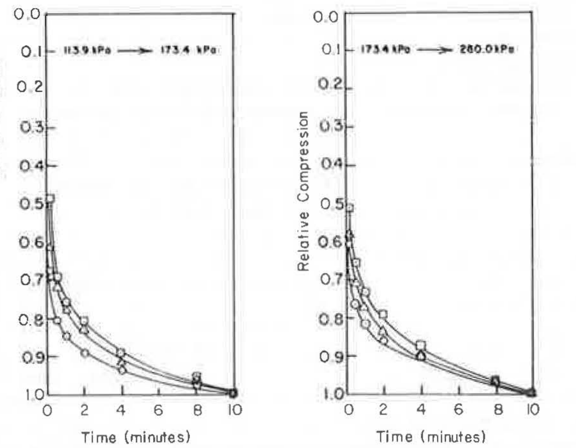
DiBernardo and Lovell (1) showed typical soaked compression versus log time curves as in Figure 6. Each curve has a characteristics type 1 shape, as proposed by Leonards and Girault (13). The division of consolidation into primary and secondary components was illustrated by two techniques--the usual Casagrande approximation and pore water pressure measurements. As shown, the amount of compression at the end of primary consolidation (R_{100}), as determined by the two methods, is nearly identical. In addition, the time for full dissipation of pore pressure to occur (t_{100} value at Δu = 0) corresponds well with the Casagrande t_{100} value; however, typically the former time was 20 percent less. Because the Casagrande construction provides a very good approximation for the end of primary consolidation, doubly drained oedometer tests were performed without measuring pore water pressure for routine testing. Such a procedure will reduce the duration of each test considerably; however, a certain amount of time is still needed before each R_{100} can be determined by the Casagrande construction.

Testing of the compacted material in the as-compacted condition gives an indication of the expected compressibility behavior of that soil prior to modification by the environment. In order to get some measure of the effects of a change in the service environment, as-compacted samples were loaded to simulate different levels of embankment confining stresses and saturated by first soaking the samples and then applying back-pressure saturation. The one-dimensional percentage of volume changes ($\Delta V/V_o$) that occurred on incremental loading and wetting will be examined,

$$\Delta V/V_o = \Delta e/(1 + e_o) \quad (1)$$

where Δe is the change in void ratio on satura-

Figure 2. Comparison of relative compression for dry, wet, and at-optimum samples.



tion, and e_o is the initial void ratio.

The relation among percentage of volume change on wetting ($\Delta V/V_o$), initial void ratio (e_o), and the sustained load on saturation (P_o) is shown in Figure 7. This figure shows that, for a given sustained load, the percentage of increase in volume increases as initial void ratio decreases, and the percentage decrease in volume increases as the initial void ratio increases. Abeyesekera (4) and DiBernardo and Lovell (1) obtained similar results for a compacted shale and a compacted highly plastic clay, respectively.

The percentage of volume change on saturation versus confining stress is shown in Figure 8. This figure shows that most samples increase in volume when saturated under a confining stress of 161 kPa. This stress is approximately equivalent to a depth of cover of 7.6 m in a compacted earthen embankment. The higher confining stresses of 322 and 483 kPa corresponded to depths of cover 15.2 and 22.9 m, respectively. At these stresses most samples displayed a tendency for slight volume reduction, except for the near-optimum samples compacted with

Figure 3. Effect of moisture content on compressibility for four passes.

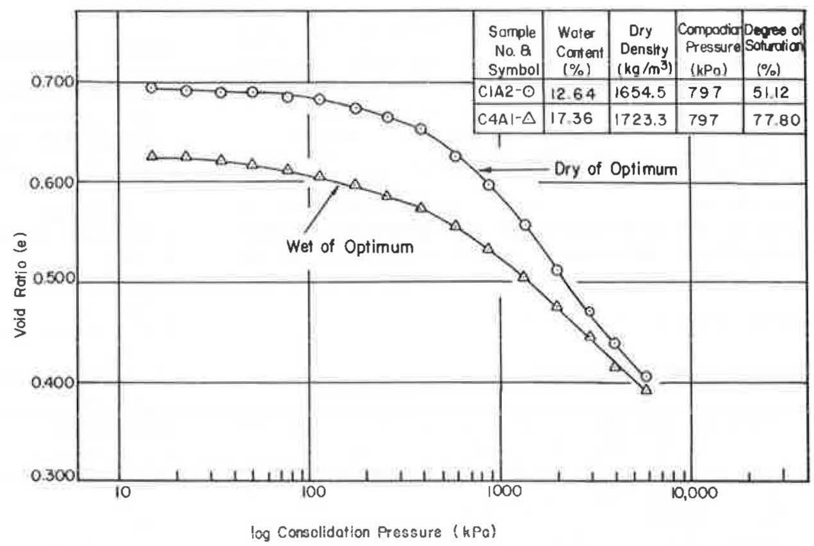
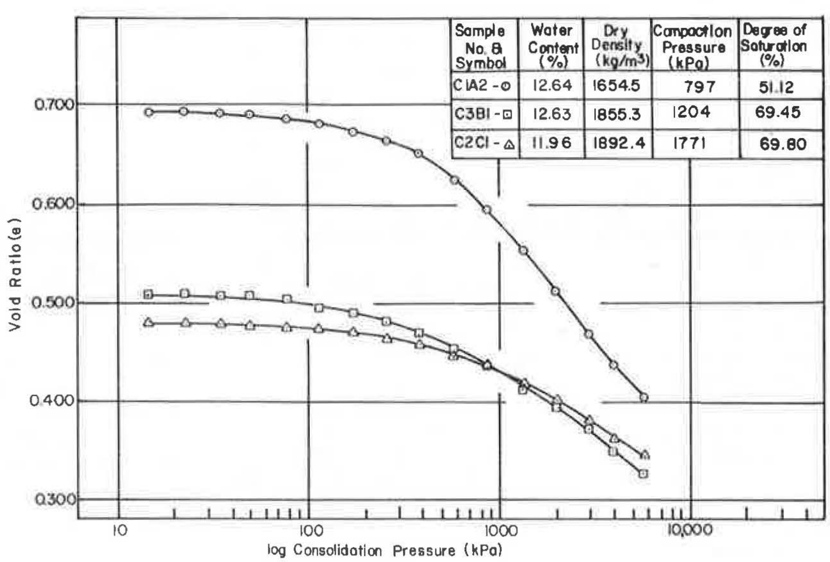


Figure 4. Effect of compactive effort on compressibility for dry of optimum.



energy level C (16 passes). These showed a significant decrease in volume, which might be termed a collapse. Such large decreases occurred quickly on exposure to water. The volume changes for all the samples were essentially completed while the samples were soaking. There was little additional volume change (0.05 to 0.10 percent) during back-pressure saturation.

The introduction of water to an as-compacted sample affects the clay on both the microscale and macroscale. On the microscale, water that comes into contact with the clay minerals can result in significant swelling of the clay. The amount of swell depends on the degree of hydration of the clay minerals present and the initial moisture condition of the clay. At the macroscale, the expanding clay minerals result in a softening of the intact clay aggregates, which may result in greater deformations and consequently an increased compressibility under load. The addition of water to a partly saturated clay will decrease the negative pore water pressure, and the subsequent decrease in effective stress should permit swelling. The change in volume that results from any addition of water to a compacted clay can be seen to be the combination of several processes. Whether or not the net volume increases or decreases depends on the initial moisture content, the dry density, and the applied confining stresses.

At the low confining pressure of 161 kPa most samples compacted near optimum or dry of optimum swelled when saturated (Figure 8). Apparently, the swelling pressure from the hydrating clay minerals, in conjunction with the reduced effective stress due to saturation, exceeded the confining pressure and resulted in an increase in volume. The confining pressures of 322 and 482 kPa were sufficient to overcome the swelling tendency for all samples.

The sample compacted with energy level C (16 passes) to near-optimum condition collapsed when saturated under a confining stress of 483 kPa. As previously discussed, near the optimum the compacted structure is open, with large pores between the intact clay aggregates. The introduction of water to the compacted samples reduces the effective stress and softens the clay aggregates. The shear resistance at an aggregate contact will be reduced as the aggregate softens. If the confining stress is low, the samples may swell, as was observed for most dry-of-optimum samples that have a confining stress of 161 kPa. The tendency for swell is counteracted as the confining stress is increased. A critical confining stress, at which no volume change occurs during saturation, exists for each initial sample condition. At confining stresses greater than the critical stress, volume reduction occurred on saturation.

The collapse behavior may be related to the compactive prestress induced in a sample. The induced prestress is the level of stress below which a sample compresses little when loaded. The introduction of water will soften aggregate contacts and reduce resistance. Consequently, clay aggregates tend to rearrange, which results in a reduction in volume. When the confining stress is near the prestress, the soil skeleton will not have compressed much. However, any additional stress will exceed the prestress level and result in a large volume reduction.

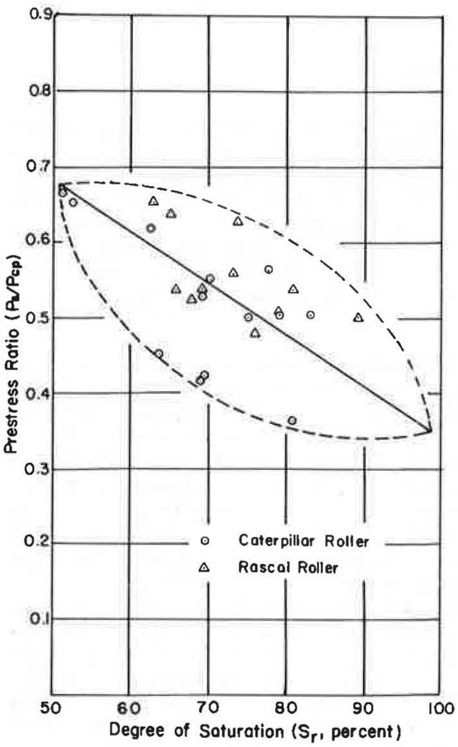


Figure 5. Prestress ratio versus degree of saturation.

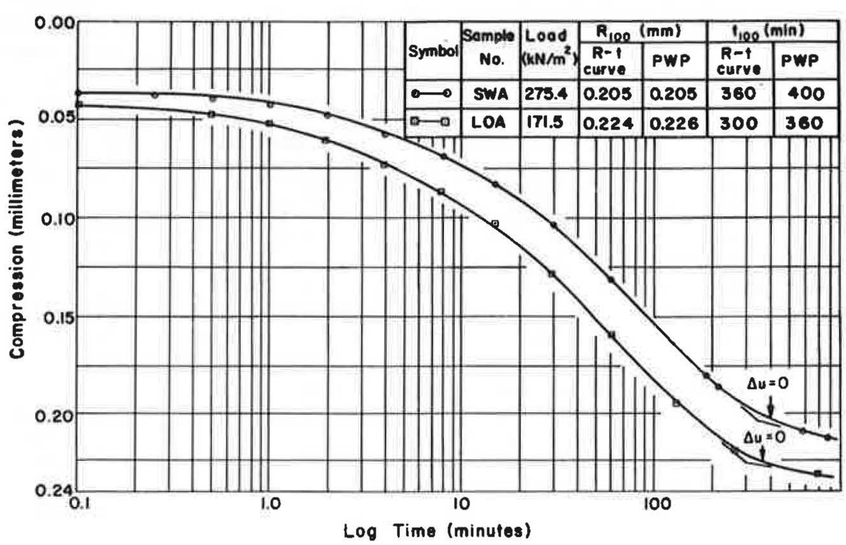


Figure 6. Comparison of methods for obtaining R_{100} and t_{100}.

Figure 7. Percentage of volume change on saturation versus initial void ratio.

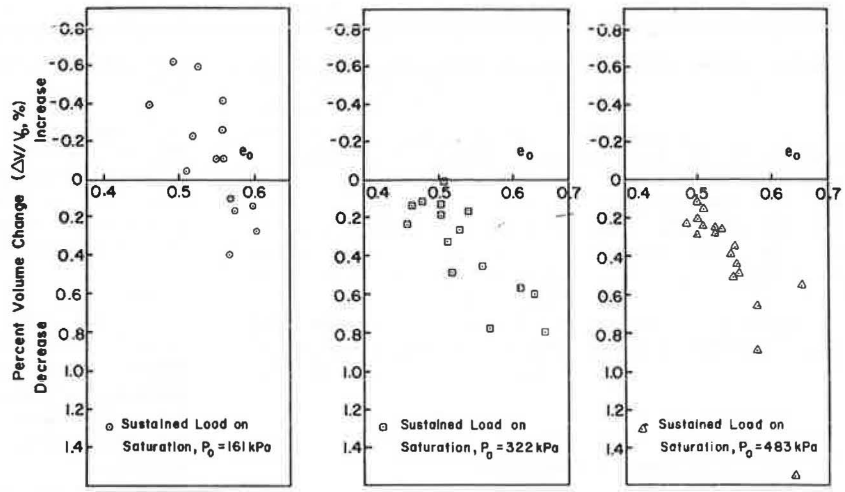
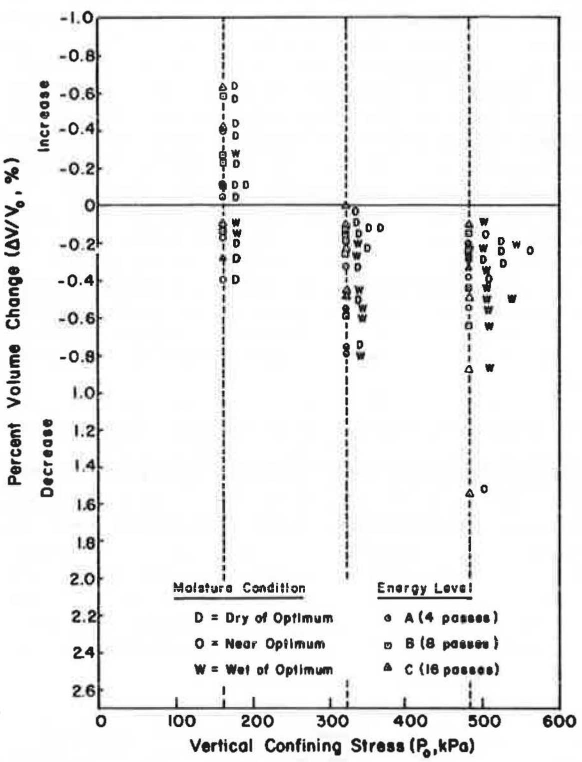


Figure 8. Percentage of volume change on saturation versus confining stress.



The effect of confinement on soaked compressibility behavior for dry-of-optimum samples is shown in Figure 9. At the low confining pressure of 161 kPa, sample R3C3a swelled on wetting. At the high confining pressures of 322 and 483, samples R4C3b and R2C6c compressed on wetting. This is consistent with the previous discussion (i.e., at low confinement the swell pressure from the hydrating clay minerals, in conjunction with the reduced effective stress due to saturation, exceeded the confinement and resulted in a volume increase). At high confinements the confining pressures were sufficient to overcome the swelling tendency and produced a volume decrease.

Statistical Correlations

Multiple regression is a useful technique for studying the relation between a dependent variable and a set of independent variables. It is used to develop a linear model of independent variables that can predict, control, or describe a dependent response. By using the data collected from the experimental tests, regression models were developed that could describe the response of either the as-compacted prestress or the percentage of volume change on saturation.

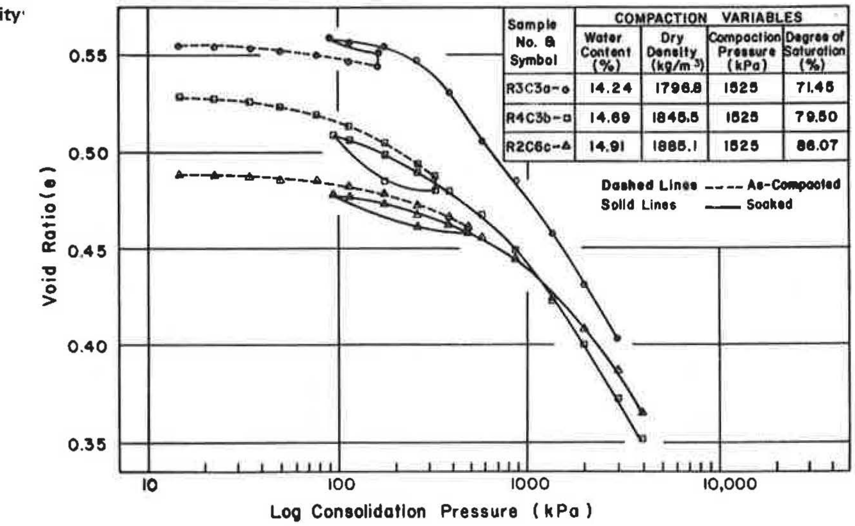
Each of the independent variables was first plotted against the appropriate dependent variable. This was done by using the Statistical Package for the Social Sciences (SPSS) procedure SCATTERGRAM. If the scatter plots showed a linear trend, the independent variable was considered to be correlated with the dependent variable and was selected for further investigation. Most of the computer procedures used for the regression analysis are included in SPSS procedural programs at Purdue University (14).

The next step was to isolate a subset of the independent variables that were found to be correlated with the dependent variable, so that an optimal expression that used as few variables as possible could be obtained. STEPWISE is an SPSS search procedure that progressively adds independent variables to the model and may delete variables already in the model after each step if they no longer add significantly to the model's descriptive capabilities. The program is also capable of testing for high correlation among the independent variables. Such correlated variables can then be prevented from entering the model. This option was suppressed during this analysis because the set of independent variables was derived from combinations of the initial sample conditions.

After the subset of variables had been isolated by the STEPWISE procedure a number of regression equations were obtained by using those variables singly and in combination. Criteria were set by which the models could be compared and the best model could be selected. Requirements for the overall multiple regression equation include the following:

1. A high coefficient of multiple determination (R^2), which indicates the amount of variation explained by the variables included in the model;
2. An increase in the adjusted coefficient of multiple determination (R_a^2) with each addi-

Figure 9. Effect of confinement on soaked compressibility behavior for dry of optimum.



tional independent variable entered into the model; and

3. The overall F-test at the α = 0.05 significance level must be met.

If all of the above criteria were suitably met by more than one model, the final selection was based on the value of R_a^2 and the simplicity of the regression equation.

Two dependent variables were used in regression analysis--compactive prestress (P_s) and one-dimensional percent volume change on saturation ($\Delta V/V_o$). All independent variables based on the initial sample conditions were considered in the selection procedure. A number of regression equations met the criteria previously discussed for the compactive prestress. Before selecting one of these regression equations, the variables chosen by DiBernardo and Lovell (1) to predict the prestress for the laboratory-compacted St. Croix clay were forced into a regression equation for the field-compacted St. Croix clay. The adjusted coefficient of multiple determination (R_a^2) was 0.86.

The variables used by DiBernardo and Lovell (1) for predicting percentage of volume change on saturation (water content and compaction pressure) were forced into a regression equation for the field-compacted St. Croix clay, with very poor results. The equivalent embankment pressure on wetting had to be included in any regression relation in order to obtain an acceptable value of R_a^2. This is also rational for the laboratory-compacted data, and this prediction equation was rewritten to include the effect of confinement. The final regression models selected for the field-compacted soil, as well as prediction models for laboratory-compacted soil based on the DiBernardo (1) data, are given below.

For compactive prestress, ($\hat{P}_s$), in the laboratory,

$$\hat{P}_s = -343.52 - 0.002\,00\, w^2 P_{cp} + 48.91\, P_{cp}^{1/2} \quad (2)$$

In the field,

$$\hat{P}_s = -160.99 - 0.000\,63\, w^2 P_{cp} + 27.04\, P_{cp}^{1/2} \quad (3)$$

where

$\hat{P}_s$ = estimated value of compactive prestress (kPa),
w = water content (%),
P_{cp} = compaction pressure (kPa),
w^2P_{cp} = interaction term between water content (%) squared and compaction pressure (kPa), and
$P_{cp}1/2$ = square root of compaction pressure (kPa)$^{1/2}$.

For 1-D percentage of volume change on saturation ($\Delta\hat{V}/V_o$), in the laboratory,

$$\Delta\hat{V}/V_o = -6.50 + 1.102\, e_oP_o^{1/2} - 0.001\,02\, wP_o \quad (4)$$

In the field,

$$\Delta\hat{V}/V_o = -2.26 + 0.400\, e_oP_o^{1/2} - 0.000\,26\, wP_o \quad (5)$$

where

$\Delta\hat{V}/V_o$ = estimated value of 1-D percentage of volume change on wetting (%),
$e_oP_o^{1/2}$ = interaction term between initial void ratio and the square root of equivalent embankment pressure on wetting (kPa), and
wP_o = interaction term between initial water content (%) and equivalent embankment pressure on wetting (kPa).

The prediction model to estimate the compactive prestress ($\hat{P}_s$) induced by the compaction process is described in terms of compaction water content and compaction pressure. Figure 10 shows the compactive prestress regression models of the laboratory as-compacted soil and the field as-compacted soil, superimposed. This figure shows that, for a given water content, the estimated compactive prestress increases as the compaction pressure increases. Similar results had been obtained by Woodsum (2), Abeyesekera (4), and DiBernardo and Lovell (1). If the compaction pressure is held constant, an increase in the water content will result in a lower value of compactive prestress.

The percentage of volume change on the wetting model is described in terms of the initial void ratio (e_o) and the water content (w), each in combination with the equivalent embankment pressure (P_o). In these models a positive value of percentage of volume change indicates settlement and a negative value indicates swell when water is introduced under load. Because of the negative value of the constant term, any sample would swell if there

Figure 10. Compactive prestress models.

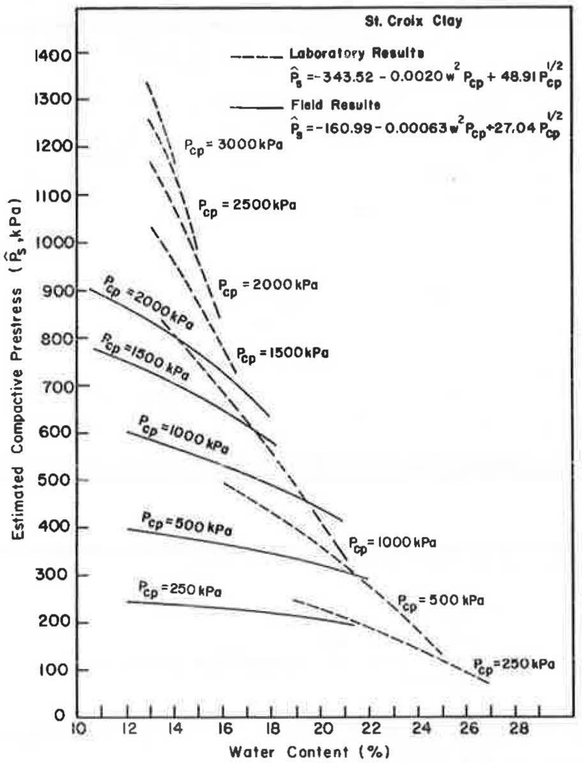


Figure 11. Effect of void ratio on percentage of volume change model for constant water content.

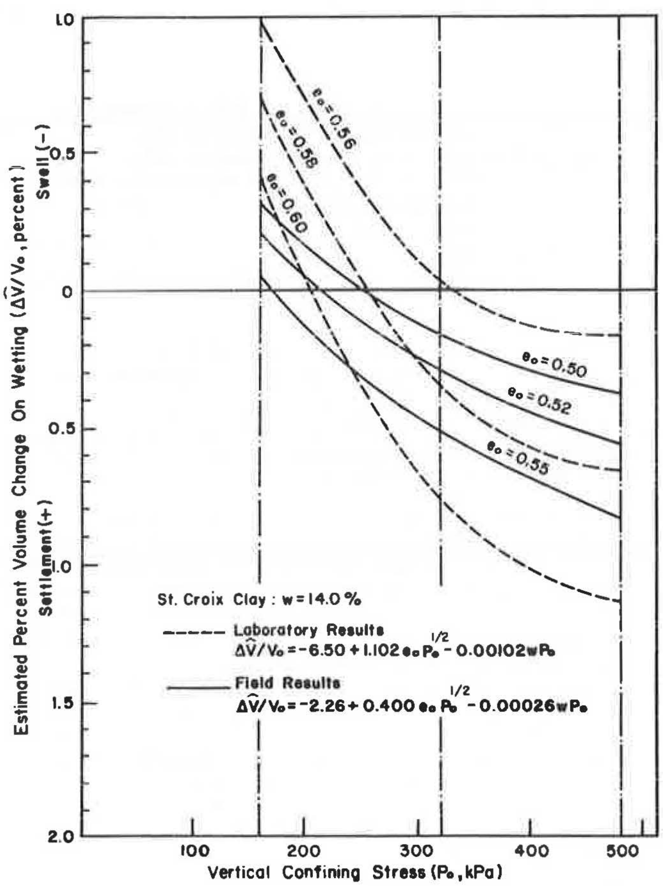
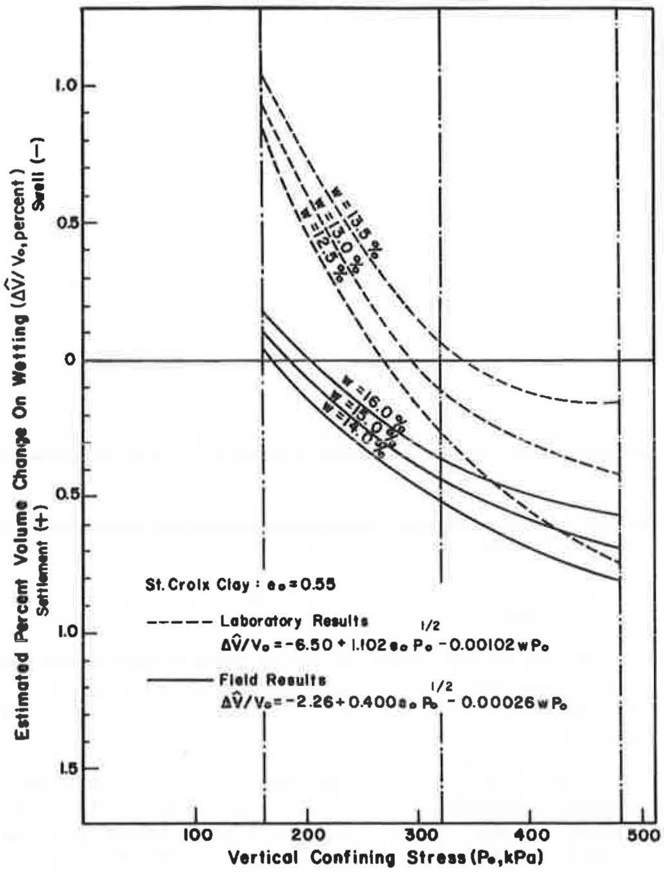


Figure 12. Effect of water content on percentage of volume change model for constant void ratio.



is no embankment pressure ($P_o = 0$). The reduction in effective stress on saturation and the volume increase of the clay minerals during hydration are the causes for the tendency to swell.

The effect of void ratio on the estimated percentage of volume change with constant water content is shown in Figure 11. The variable term in the model that involves the initial void ratio (e_o) and the square root of the equivalent embankment pressure ($P_o^{1/2}$) is preceded by a positive sign. This indicates that this term overcomes the tendency to swell. Figure 11 shows that an increase in the initial void ratio reduces the tendency to swell. As the equivalent embankment pressure increases, the percentage of volume change eventually becomes positive.

The variable term in the model that involves the water content (w) partly offsets the effect of the positive term. Figure 12 shows that an increase in water content reduces the expected volume decrease on saturation. The coefficients of the variables in the models are such that the negative term never exceeds the positive term within the range of values investigated. This ensures that under no conditions can sample swell exceed that of the free swell case.

Although the shapes of the field and laboratory compactive prestress and percentage volume change on wetting curves are similar, they are not identical. However, the simple procedure of superimposing equational models, as has been done in Figures 10-12, may prove to be a useful practical technique for predicting field response from laboratory tests.

An important objective of this study was to show how the laboratory-field correlation can be devel-

Figure 13. Prediction of field compactive prestress from laboratory-compacted samples.

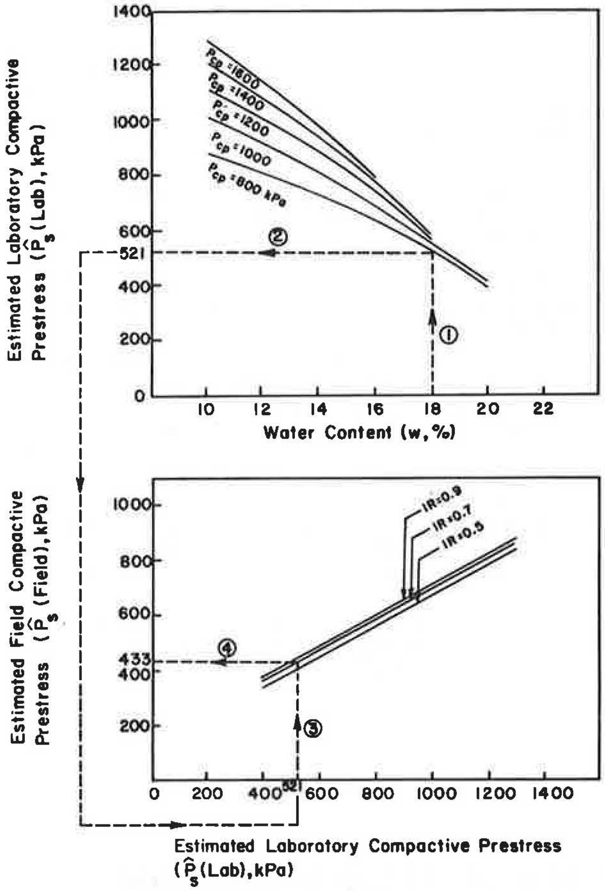
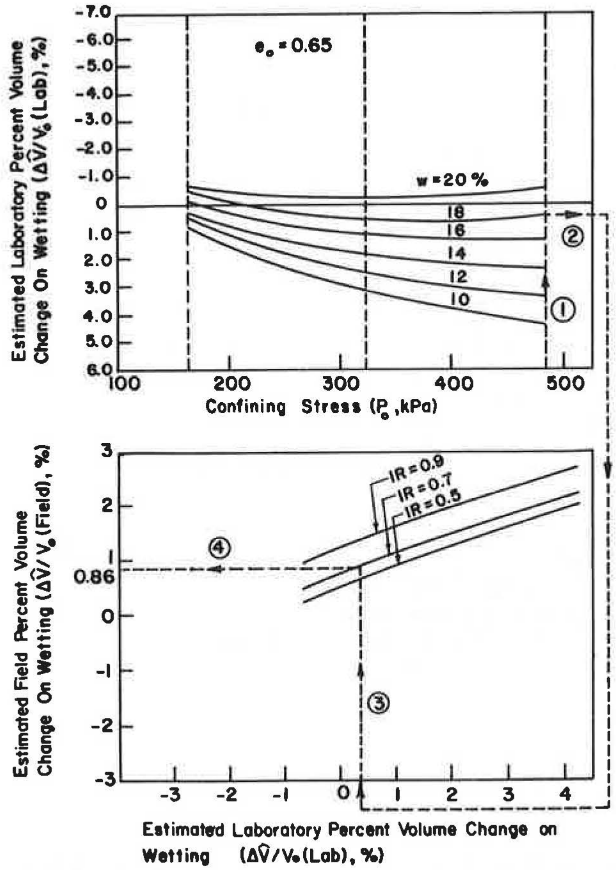


Figure 14. Prediction of field percentage of volume change on wetting from laboratory-compacted samples.



oped and used. These same procedures can be employed to cover additional typical soils and compaction rollers. Where the correlation between the laboratory- and field-compacted soils has been accomplished, the engineer can simply take bag samples from the excavation, run laboratory compaction and compressibility tests, and make good predictions of embankment compressibility. Thus, an alternate to the present procedures is (a) simply assume that the field-compacted values are the same as the laboratory-compacted ones or (b) generate the field-compacted parameters from test pad samples.

Behavior for soils similar to the St. Croix clay can be predicted by comparison of compaction curves and plasticity. A statistical prediction procedure was developed and is illustrated in Figures 13 and 14.

CONCLUSIONS

This paper has examined the effect of field compaction on the as-compacted compressibility, volume change on soaking, and soaked compressibility behavior of a plastic compacted clay (St. Croix).

The experimental and statistical results of the field-compaction study lead to the following conclusions:

1. The compression versus time relations show that a large percentage of the as-compacted compression occurs within the first minute of loading.
2. Samples compacted on the dry side of the line of moisture optimums for any compactive effort are less compressible than those compacted on the wet side of the line of optimums for loads less than the prestress level. However, the dry-side samples are more compressible than the wet-side samples when the applied load is greater than the prestress level.
3. The value of compactive prestress induced in a sample increases with increasing compaction pressure and decreases with increasing moisture content at a given compaction pressure.
4. For the saturated condition, at low confining stresses the swell pressure from the hydrating clay minerals, in conjunction with the reduced effective stress due to saturation, exceeded the effect of confinement and resulted in an increase in volume. At high confinements the confining pressures were sufficient to overcome the swelling tendency and resulted in a decrease in volume.
5. The field-compacted relations are similar to those developed by DiBernardo and Lovell (1), which involve the same variables, exponents, and signs. Regression constants are different.
6. The similarity of laboratoryand field-compacted relations allows the two predictions to be simply related in graphical form (Figures 10-12).
7. Predictions of field-compacted relations from laboratory tests can be accomplished for soils that are somewhat different by using IR = I_p (field)/I_p (laboratory). I_p is the Atterberg plasticity index.

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Compaction Practice for Dam Cores at Hydro-Quebec

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Glacial till is used mainly as an impervious material in earth and rockfill dams built in Quebec. It is, in general, a well-graded mixture of sand, silt, and gravel, with 25-80 percent passing the no. 200 sieve and a natural water content at or above optimum (Proctor standard). Its natural water content, together with its very high sensitivity to atmospheric humidity, strongly influence the choice of compaction equipment, compaction procedure, and time schedule. This paper presents Hydro-Quebec's experience with this type of material, including choice of the compaction equipment, establishment of the compaction procedure, pretreatment of the borrow pit material, as well as the results and performances obtained at various sites. In addition, the paper describes the particular compaction problems and results of a manufactured material (sand and sensitive clay mixture) used as core material in certain water-retaining dikes.

One of the main economical advantages of an earth or rockfill dam is the possibility of using relatively cheap local soil deposits as construction materials. In this context, glacial till deposits that cover large areas of the continental shelf of Canada are used extensively as material for the impervious zone of earth and rockfill dams. The use of natural clay deposits as impervious material is rather limited (a) because of its localized presence along the lowlands of the St. Lawrence valley and the eastern shore line of the James Bay, and (b) because its geotechnical characteristics (high sensitivity) require special placement and compaction procedures.

The till, an abrasion product of the glaciers, is frequently used in construction specifications as indicative of an unsorted unstratified heterogeneous mixture of clay, silt, sand, gravel, cobbles, and boulders. It also denotes a very dense and stiff material of low compressibility. These characteristics, when complimented with a proper amount of fine particles (<0.074 mm) and a well-graded grain size composition, represent those of an ideal material for dam cores.

However, the compaction characteristics of this material are substantially influenced by its water content. As a matter of fact, the soil is difficult to handle (compact) when the natural water content reaches 2 percent above optimum and becomes rapidly soupy when it reaches +3 percent or more. This is a severe limitation because it is often found in situ at a water content above optimum. The problem becomes more acute when one considers the adverse climatic conditions encountered in the northern regions of Quebec, where the construction season is short and rainy.

The importance of proper compaction should be emphasized in view of the close relation among density, shear strength, permeability, and compressibility. All these parameters are of particular importance in the safety and behavior of the dam.

This paper presents Hydro-Quebec's experience and practices in handling this type of material as illustrated by three case histories. The first project involved uses till that had a natural water content at or slightly above its optimum and hence presented no problem of placement or compaction. In the second project, the use of a till that had a natural water content substantially higher than