Prediction of Roller Compaction Efficiency

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The usual procedure for specification of roller equipment, lift thickness, and number of passes to compact a soil fill material of prescribed water content to an optimum density is one that heretofore has traditionally depended on empirical relations and similitude modeling—the use of laboratory-derived test data on soil compaction. In this study, soil compaction under a towed roller is predicted by using the finite-element method (FEM) of analysis. The format of the analysis encompasses the transient loading nature of the tire or roller. By expressing the compaction effort exercised by the rigid roller in terms of the amount of compaction energy required to produce a resultant unit deformation of a particular soil lift thickness, FEM analysis allows one to obtain an evaluation of the influence of soil type, lift thickness, water content, and number of passes on compaction efficiency. In addition, the format for analysis is structured to incorporate compaction of additional soil layers through a layered soil-analysis procedure. The analysis of soil compaction efficiency is supported with corresponding laboratory experiments that involve wheel tow-bin tests.

The general procedure for specification of size and capability of roller equipment for compaction of soil fill material is one that depends on prior experience and assessment of results obtained from laboratory compaction tests on the soil fill material. The questions that need to be answered in a compaction program can be stated simply as follows:

1. What type and size of roller? and
2. What is the lift thickness? Number of passes? Soil water content?

The answers to the above questions are not always sought through rigorous analytical means because of the lack of analytical models that deal specifically with the coupled surface interaction between roller and soil. By and large, available analytical techniques generally regard the problem of compaction as a simple boundary value problem and thus concern themselves with soil deformation under load.

The problem of interest, because of present concern for energy conservation, is one that is posed in terms of roller compaction efficiency. [i.e., "How efficient is a particular roller in compacting a specified (known) soil?"] The input energy (work done) required by a roller to produce a specific degree of compaction is a function of the following:

1. Roller type--rigid or pneumatic tire;
2. Roller loading--speed, slip, towed or self powered, and arrangement of rollers (tires);
3. Tire properties and characteristics--diameter, width, cross-sectional shape, aspect ratio, inflation pressure, carcass stiffness and shape, tire structure, and tire material properties (note that, for this particular study, although tests were also performed with pneumatic tires, because of the very extensive data and results available, only the rigid roller results will be discussed); and
4. Soil--stress-strain behavior in loading and unloading composition and type, density, moisture content, saturation, soil structure, and confining pressure.

Efficient soil compaction matches the soil response (load or rebound) characteristics with lift thickness, number of passes, and roller loading features to produce the maximum soil density for the desired fill thickness with the least amount of input work (roller passes and energy input).

Compaction of layers of soil is increased by increasing the magnitude of roller-imposed normal stresses established at the roller-soil interface; however, note that, if the roller-imposed normal stresses exceed the local bearing capacity of the soil, the soil will extrude or flow under the rollers instead of compacting. This is obviously not an efficient compaction process.

In this study an analytical model is established (a) to calculate the amount of work done in compaction per unit distance traveled by a moving roller for every pass and (b) to determine the total work required to produce a certain soil density or permanent deformation of the soil layer. Soil compaction under a moving roller is predicted by using the finite-element method (FEM) of analysis. The format of the analysis encompasses the transient loading nature of the roller (or tire). By expressing the compaction effort delivered by the rigid roller in terms of the amount of compaction energy required to produce a specific resultant dry density of a particular soil lift thickness, FEM analysis allows one to obtain an evaluation of the influence of soil type, lift thickness, water content, and number of passes on compaction efficiency. Roller compaction efficiency is evaluated by comparing the work spent by the roller to produce certain density with that obtained in a standard Proctor test. Note that expression of compaction efficiency with reference to the standard Proctor test technique is arbitrary (i.e., the standard Proctor density is taken as optimum for a convenient reference state).

The experimental program in this study uses a soil tow-bin and, for roller soil, compaction that covers the range of soil from loosely placed soil to fully compacted soil (i.e., no further change in the density of the compacted soil with increasing number of passes). Because of the phenomenon of local shear failure in the first pass, the analytical portion of the study directs its attention to compaction of the soil layers beyond the first pass loose soil compaction.

METHOD OF ANALYSIS

The performance of a roller that moves with constant speed on a soil surface is analyzed by applying the principle of energy conservation. The energy balance relation equates the roller input energy (powered roller) or pull energy (towed roller) to the sum of the following energy components (Figure 1):

1. Energy spent in compacting the soil,
2. Energy dissipated at roller-soil interface through slip between roller and soil surface,
3. Energy dissipated because of distortion of the roller under load (this form of energy dissipation is negligibly small in the case of rigid rollers), and
4. Output energy (powered roller); i.e., drawbar pull. (In the case of a towed roller system, drawbar pull is zero and sometimes even negative.)

For convenience in presentation of the analysis, it is assumed that at any stage of roller compaction, the soil continuum consists of two layers, as shown in Figure 2 (1). The underlying soil layer (i.e., the previously compacted layer) has reached optimum or close to optimum density and can be assumed to remain in the as compacted state. The top layer is the current soil layer to be compacted and is analyzed accordingly. If desired, a multilayered compaction analysis can be performed where the underlying layers are also analyzed and considered as undergoing further densification. However, by and large, the increases in densities in the underlying layers are small--if efficient compaction is achieved--and can be ignored as a first approximation in the analysis given here.

Figure 1. Roller-soil energy systems.

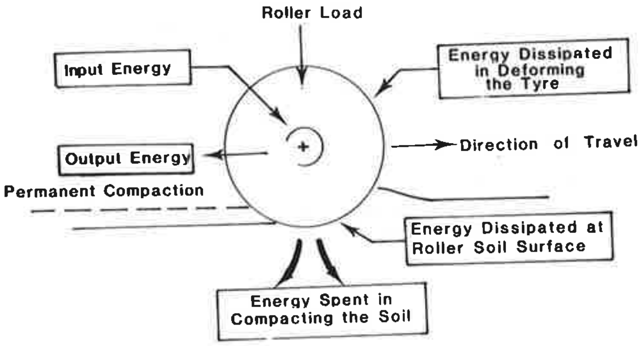
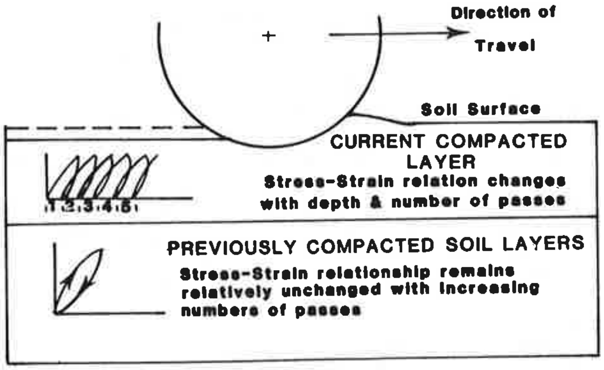


Figure 2. Idealized soil continuum showing a developed two-layer system.



ANALYTICAL RELATIONS

The governing equations used for the FEM analysis developed for rigid wheel motion by Yong and Fattah (2) and extended for pneumatic tire motion on soft soil (3) has been adapted for soil compaction analysis (4) and need not be repeated here. Since the rollers (tires) used for compaction are relatively wide, a plane-strain type of analysis can be adopted and all calculations are given in terms of a unit width of the roller. The boundary conditions that satisfy the actual physical roller-soil interaction behavior can be specified in terms of loads or displacements. For this study, the load boundary condition was used.

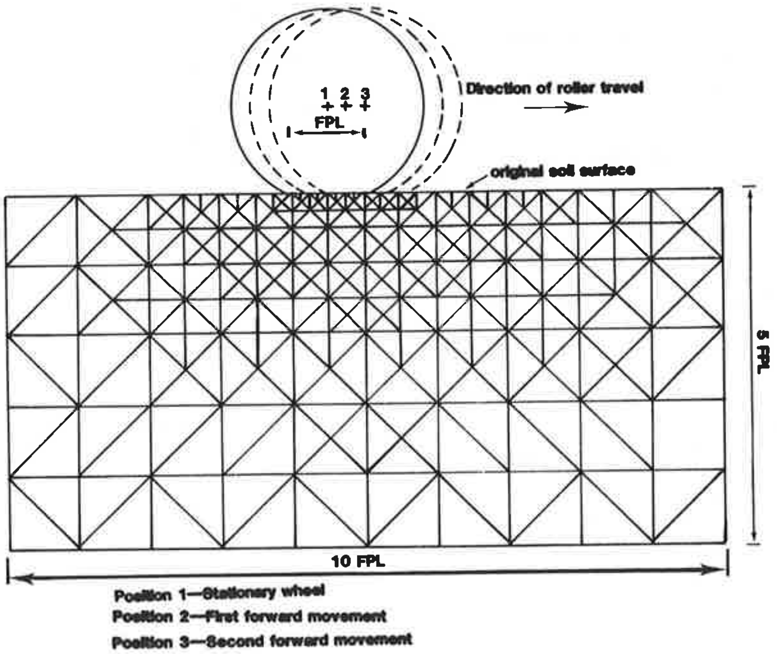
Load Boundary Conditions

To specify the load boundary at the roller-soil interface two items are required: (a) stress-distribution due to roller load and forward motion and (b) contact area. The roller-soil interfacial stresses can be determined from continuum mechanics; however, the problem solution can be complex because of (a) the transient type of soil loading, (b) the nonlinearity of the soil stress-strain relations, (c) roller distortion under load and in motion, and (d) relative movements at the roller-soil interface due to slip. To simplify the problem solution, the interfacial stress distribution can be specified in terms of known distributions based on previously available, or reported, measurements (5).

Constitutive Relations

Since the roller load imposed in compaction is a transient type of loading, any point in the soil continuum is subjected to a state of loading or unloading according to its position with respect to the roller (i.e., for each roller pass the soil is subjected to a complete stress-reversal cycle). The constitutive relation should, therefore, encompass a complete stress-reversal cycle. Because of the nonlinear stress-strain behavior of the soil, a nonlinear elastic response was used to represent the

Figure 3. Finite element idealization.



soil during loading and an elastic response was used for the unloading process. For loading and unloading of a soil element the following code was used in the analysis:

$$W = \sigma_{ij} de_{ij} \tag{1}$$

where

σ_{ij} = state of stress,
de_{ij} = incremental state of strain,
If $\Delta W < 0$ the element is unloading, and
$\Delta W > 0$ the element is loading.

ANALYTICAL SOLUTION

The finite element used in the problem solution is shown in Figure 3. For simplicity, the idealization, which is dimensionless, is essentially a function of the contact length of roller at the roller-soil interface. This is identified as the footprint length (FPL).

For this study the displacement and load boundary conditions were used and an incremental technique employed for problem solution. The complete solution, which covers roller motion from a stationary start to a constant travel speed, can be obtained by using the incremental displacement approach in two major steps.

The stationary roller position is considered first and the subsoil stresses, strains, displacements, and the roller-soil interfacial reactions are calculated accordingly. Displacement boundary conditions are applied in the form of vertical displacement increments and stresses calculated at the end of each increment by using the nonlinear stress-strain relations. These are then augmented to their previous values and the process continued until the augmented vertical reactions at the roller-soil interface reach the value of the roller load.

At the end of each vertical displacement increment the possibility of contact occurence of a new node with the roller is checked as follows:

$$\delta_0 - \delta_i > Z_i \tag{2}$$

where

δ_i = vertical displacement of the soil surface at node i,
Z_i = initial gap between the roller and soil surface at node i, and
δ_o = vertical displacement increment of the roller.

The second step in the solution is to assume that the roller is moving with a constant speed. For a steady-state roller loading and homogeneous soil, any tracer object will describe the same particle path as any other placed at the same initial depth. Hence, the displacements of any nodal point on the soil surface can be determined with knowledge of the particle path and the original position of the nodal point with respect to the intersection of the roller centerline with the original soil surface.

By using equal increments of time or roller distances, the nodal displacements at the roller-soil interface can be determined, provided the shape of the particle path is known. The boundary displacements are used as the loading boundary required for calculating roller-soil interfacial stresses, subsoil stresses, and strains. This process is continued and the results are added to previous values until the summation of the vertical reactions at roller-soil interface remain constant with any incremental roller travel distance.

The technique for using the load boundary condition at roller-soil interface is similar to the second step used--the displacement boundary approach. The implementation of the analysis calls for one to determine the stresses and displacements in the soil beneath the roller with the roller center in position 1 (Figure 3). This computational procedure is repeated by moving the roller center to position 2. Note, however, that in moving the roller from position 1 to 2, unloading at position 1 occurs as loading in position 2 occurs. The solution is essentially applied in the continuous roller travel on the soil surface by taking successive roller positions. This procedure accounts for the transient motion of the roller (i.e., the solution format is a pseudo-kinematic procedure). Since the state of stress in the soil at the end of the increment depends on the initial state of stress established at the beginning of the travel increment, the incremental roller travel computational procedure is terminated automatically when the state of stress at any point in the soil at fixed coordinates with respect to roller center does not change significantly with the imposition of the next increment.

EXPERIMENTAL PROGRAM

The experimental program was designed to provide information to serve as input and to verify the predicted results of the analytical model.

Soil Properties and Roller Characteristics

The soil used in the experiments was a mixture of English paper clay kaolinite and fine silica sand that passes sieve no. 30 in the ratio of 1 to 4, respectively. Figure 4 shows the results of standard Proctor compaction tests for different soil mixtures, from which the ratio of 1 to 4 was chosen. The liquid limit for the kaolinite was 54 percent, plastic limit was 37 percent, and specific gravity was 2.62.

To obtain the relevant soil mechanical properties, soil samples were prepared at different initial densities and tested in plane strain compression. Typical stress-strain curves for the soils are shown in Figure 5. These are used as input to the analytical model.

The model rigid roller used was 35 cm in diameter, with a width of 9.5 cm.

Tow-Bin Tests

The moving roller tests were performed in a soil bin that was 200-cm long, 30-cm deep, and 10-cm wide to permit plane strain test conditions. The following parameters were considered:

1. Roller load was 31.75 kg and 45.81 kg,
2. Translational speed was 17.3 cm/s, and
3. Number of roller passes was a maximum of 16.

The following measurements were made:

1. Surficial, such as drawbar pull, input torque, and rut depth and
2. Subsurface, such as soil deformations as a function of time by using an automatic motor drive camera.

The soil properties such as density, vane shear strength, water content, and unconfining compressive strength, were measured before and after roller-soil compaction.

Figure 4. Standard Proctor test.

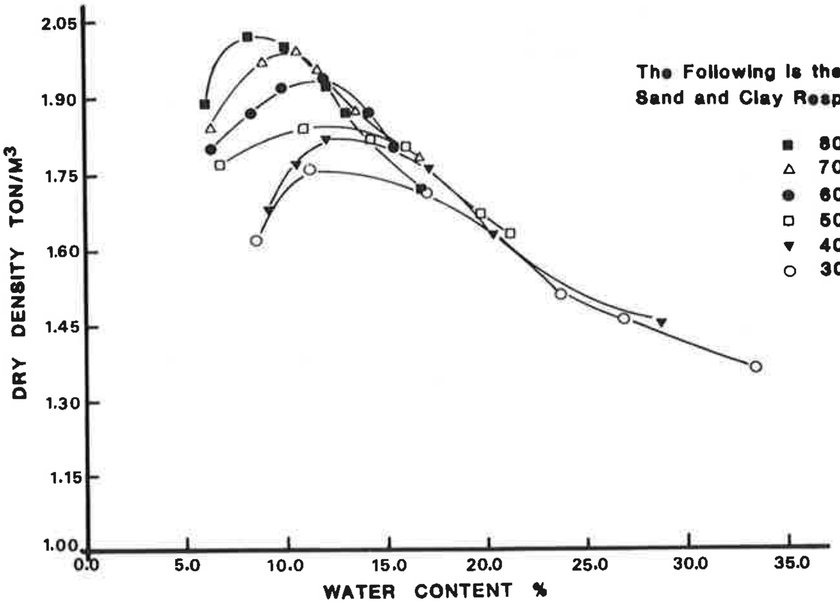


Figure 5. Stress-strain curve of clayey sand.

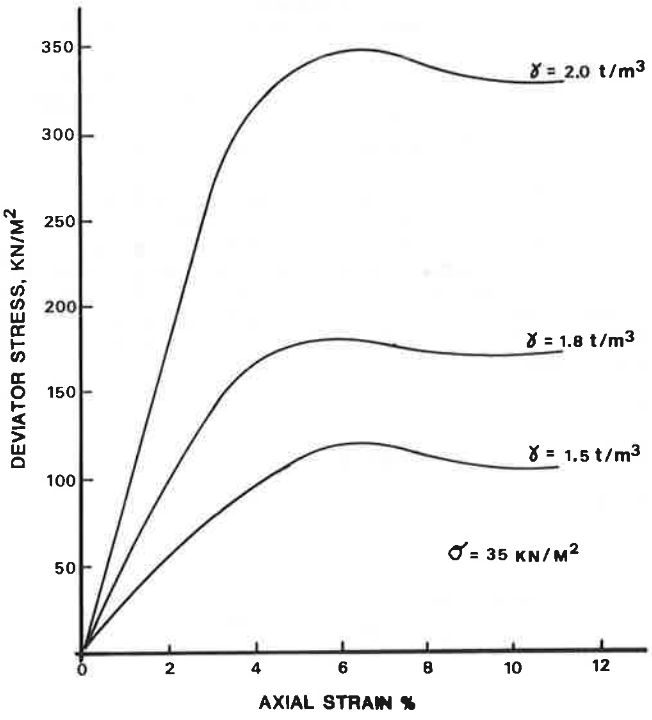
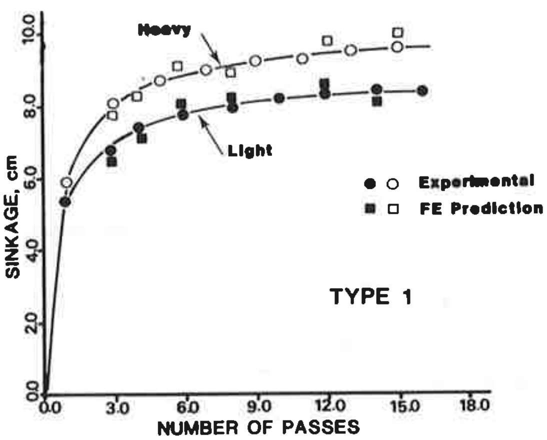


Figure 6. Effect of number of passes on soil surface deformation.



RESULTS AND DISCUSSION

Since the analytical model used in this study is basically a continuum mechanics approach for solving a boundary value problem, the FEM solution predicts the subsoil stresses, strains, deformations, and deformation energies that result from roller motion on the soil in the compaction process. The calculation procedures also allow for determination of surface deformations, roller motion resistance, changes in the roller-subsoil densities, and hence the work done.

Figure 6 shows the effects of the number of passes on soil surface permanent deformation for the case of smooth towed rigid roller. As expected, the initial sinkage is high and decreases as the number of passes increases, to the point where the sinkage becomes relatively constant after a certain number of passes, according to the type and initial condition of the tested soil. The results show good agreement between the finite-element prediction and the measured sinkage values. Note that the analytical model is used to predict the performance of the roller after the first pass.

Figure 7 shows the finite-element predicted and measured density profile after 16 passes. The change in density is determined by calculating the change in the area of every finite element after every pass. The predicted values agree with the measured values.

Figure 8 shows the predicted and measured roller rolling resistance (towed force) as a function of number of passes. The rapid decrease in the rolling resistance with increasing number of passes is expected because of the increase in density of the soil. The stiffness and strength of the soil layer will increase correspondingly, and surface deformations will decrease with the increasing number of passes.

Figure 7. Dry density versus depth after 16 passes.

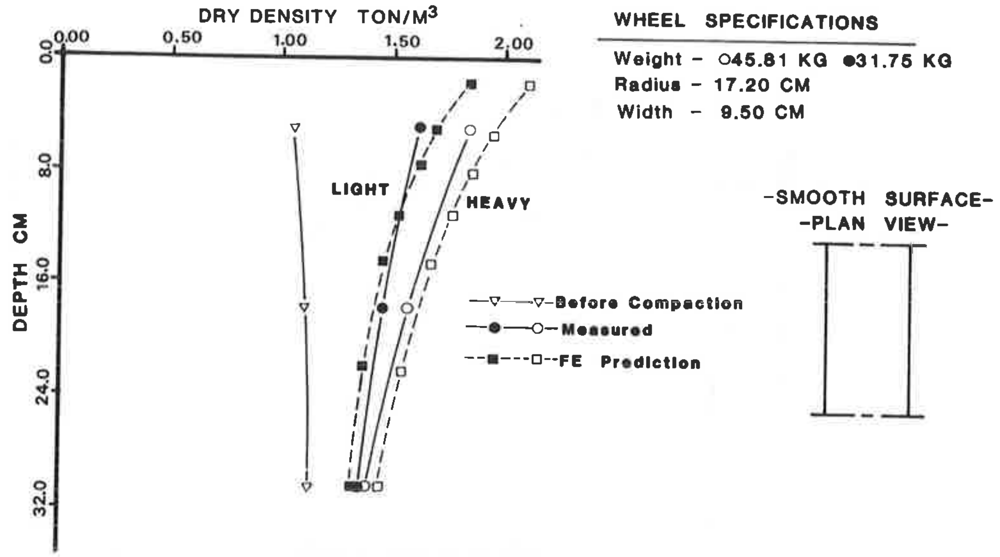


Figure 8. Effect of number of passes on towed roller motion resistance.

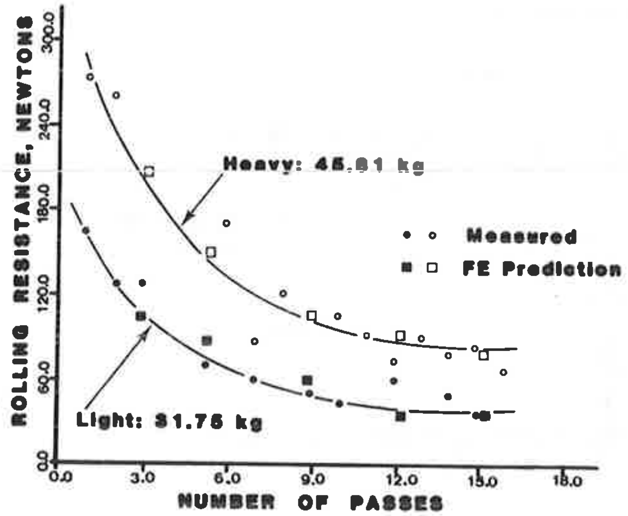


Figure 9 shows the relations for the energy spent in compacting the soil versus dry density. In this figure the finite-element-predicted results are compared with those calculated from the roller multipass tests and the Proctor mold and ram tests. Note that the increasing density is an average of several values obtained throughout the soil density profile.

In the FEM, the energy spent in compacting the soil is calculated at each incremental roller travel distance in each finite element by using the following formula.

For the constant strain triangular element,

$$W = (1/2\Delta X) [\sigma_{x_1} + \sigma_{x_2}) d\epsilon_x + (\sigma_{y_1} + \sigma_{y_2}) d\epsilon_y + (\tau_{xy_1} + \tau_{xy_2}) d\epsilon_{xy}] \, dA \quad (3)$$

The total compacting energy per unit of travel distance can be calculated by

$$D = \sum_{1}^{N} W \quad (4)$$

where

$\sigma_{x_1}, \sigma_{y_1}, \sigma_{xy_1}$ = states of stress at the start of the increment,
$\sigma_{x_2}, \sigma_{y_2}, \sigma_{xy_2}$ = states of stress at the end of the increment,
$d\epsilon_x, d\epsilon_y, d\epsilon_{xy}$ = incremental states of strains,
ΔX = incremental roller travel distance, and
N = number of finite elements.

The energy spent in compacting the soil is calculated by using the surficial measurements of the two bin tests as follows: It is assumed that the towed roller input energy is equal to the energy spent in compacting the soil; therefore, the energies dissipated at roller-soil interface and in deforming the roller are vanishingly small. The soil compacting energy can be calculated as

$$P * L = D \quad (5)$$

Work per unit travel distance

$$P = D/L \quad (6)$$

where

P = drawbar pull (N),
D = compaction energy (N-m), and
L = travel distance (m).

Thus, in the case of a towed rigid roller, the energy spent in compacting the soil per unit of travel distance is numerically equal to the drawbar pull. If one assumes that the energy is spent uniformly over the depth of the soil layer, the energy spent per unit volume of the soil at a certain pass is equal to:

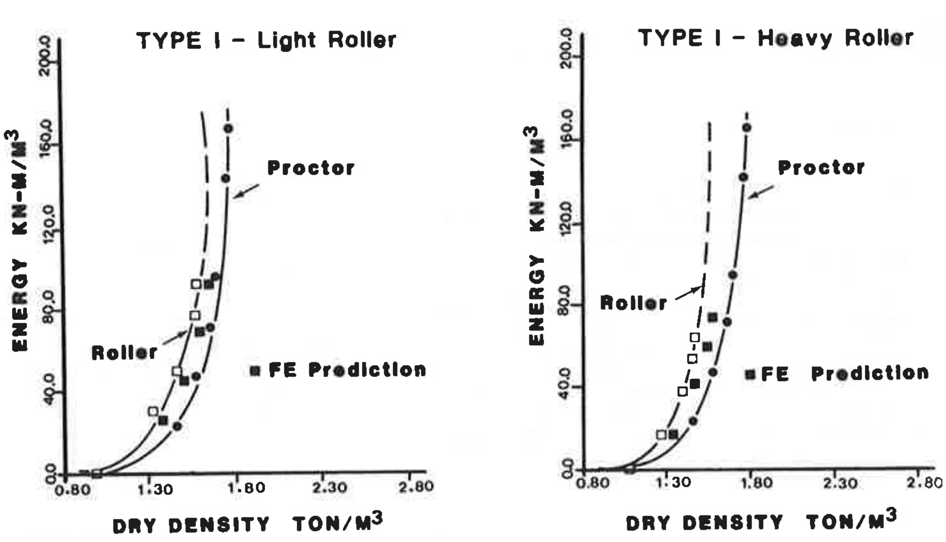
$$P/d = D/L * d \quad (7)$$

where d is the depth of soil layer.

The compacted energy per unit volume of the soil after a certain number of roller passes is calculated as,

$$E = \sum_{i=1}^{N} P_i/V_i \quad (8)$$

Figure 9. Compacting energy-dry density relation.



where

E = input energy per unit volume,
V_i = cross-sectional area of the compacted soil at pass i,
P_i = roller towed force at pass i, and
N = number of passes.

In calculating the input energy as a function of the dry density in the case of the Proctor test, different samples were subjected to a varying number of blows, so that the varying applied input energy could be related to the different obtained dry densities. The initial density with respect to state of zero energy was obtained by filling the Proctor mold loosely. The testing procedure used was the same as that used in the standard Proctor test. The input energy per unit of volume for the Proctor test can be calculated as

$$E = W * L * N_B * N_L / V \qquad (9)$$

where

E = input energy per unit of volume,
W = weight of hammer,
L = height of hammer drop,
N_B = number of blows per layer,
N_L = number of layers = 3.0, and
V = volume of the mold.

Figure 9 shows that the finite-element prediction for the compaction energy-soil density relation compares well with that calculated from the results of the tow bin tests but differs slightly from that obtained from the Proctor tests.

Theoretically, the change in soil density should be a function of the compacting energy and its rate of application to the soil. Thus, the difference in the energy relations shown in Figure 9 may be due to the difference in the rate of application of the soil-compacting energy or the method of averaging the soil dry density and not to the method of compaction. The results also show that the soil density does not change after a certain level of compacting energy. The magnitude of this energy is a function of its rate of application, the initial physical and mechanical properties of the soil, and the roller parameters. This energy value may be called the compaction energy limit.

The efficiency of the roller can be evaluated as the ratio between the density predicted by using FEM and that of the Proctor test at the roller-limiting compacting energy.

CONCLUSION

The comparison between predicted and experimentally computed values of compaction energy for the case of towed roller show that the analytical model presented can be used to evaluate the compactibility of the soil in terms of the minimum energy required to produce a certain permanent density. This model takes into account the effect of the successive roller passes and the changes in the soil properties with depth from pass to pass provided the soil stress-strain relations at different dry densities are used to generate the required constitutive relations for the model.

ACKNOWLEDGMENT

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