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Finite Element Analysis of Multipass Effects of Vehicles on Soil Compaction

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ABSTRACT

FINITE element procedure was used to simulate multiple wheel loading and to predict its effect on soil compaction. Results of nonlinear analysis, conducted using an incremental loading procedure, show effects of tire size, soil type, and number of passes on soil compaction. The results of the study also demonstrate the potential use of the procedure in compaction related studies. However, experimental verification of the model is necessary before the procedure can be recommended for wider use.

INTRODUCTION

Effects of soil compaction on soil structure, texture and strength, and on plant development and crop yields have received considerable attention from researchers in the past (Klingbiel and O'Neal, 1952; Ingles, 1974; Fountaine, 1958; Negi et al., 1980; Chancellor, 1971; Camp and Gill, 1969; Eavis and Payne, 1968; Rosenburg and Willits, 1962; Voorhees, 1977). In recent years, there has been a growing interest in machine-induced soil compaction, perhaps because of the steady increase in the size of field machines as well as increased use of conservation or no-tillage practices.

During most agricultural and forestry operations, a significant portion of the site will be exposed to single or, at times, multiple passes of vehicles. The compaction which can result from this single or multiple loading will depend on factors such as soil and vehicle type, soil moisture level, number of passes, vehicle weight, contact pressure, etc. Most studies dealing with vehicle loading and soil compaction have been experimental. One disadvantage with the experimental procedure is that it is laborious, time consuming, and expensive. An alternative is to develop a mathematical model capable of describing the soil-tractive device interaction. Combined use of such a model and experimental procedure should be helpful to better understand the effects of various soil and vehicle parameters on soil compaction as well as the machanics of soil compaction. Therefore, the overall objective of this study was to develop a numerical procedure to predict the soil compaction from multiple wheel loadings. The specific objectives of the study were:

1. To develop a finite-element model to predict the soil compaction from single and multiple wheel loading by a pneumatic tire.
2. To demonstrate the effect of soil type, tire size, and multiple wheel loadings on soil compaction through the use of the model.

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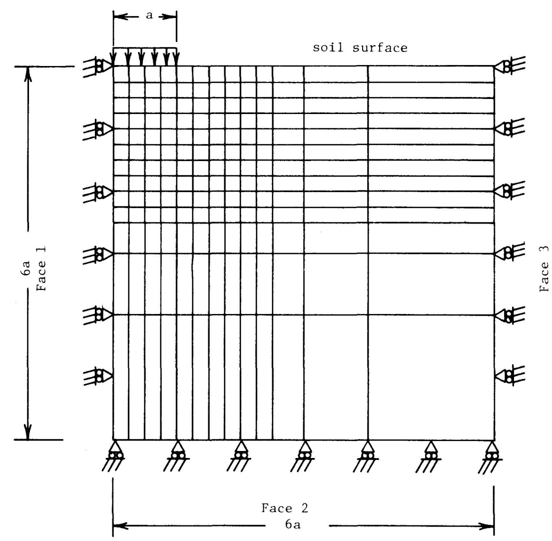

Fig. 1—Idealized system for analyzing soil compaction due to multiple wheel loading.

PROCEDURE

The finite element model developed for describing soil-wheel interaction was based on the assumptions that the elliptical wheel-soil contact area can be approximated by an equivalent circular area, and that the wheel contact pressure is uniformly distributed over the area. These assumptions helped to reduce the complexity of the problem by allowing it to be analyzed as an axisymmetric problem rather than as a three-dimensional problem. A typical idealized system for an axisymmetric problem is shown in Fig. 1. For such cases, because of the symmetry about the vertical axis, it is necessary to analyze only one-half the system. The procedure and basic steps involved in the finite element analysis are available in many published texts; therefore, they are not repeated here.

The finite element model and the program developed during this study have the capability to predict the effect of soil type and tire size on soil compaction (Pollock, 1983). The details of these analyses are included in this section.

Constitutive Relationships for Soils:

The hyperbolic model developed by Duncan and Chang (1970) to represent a typical stress-strain relationship (Fig. 2) was used in this study. This model

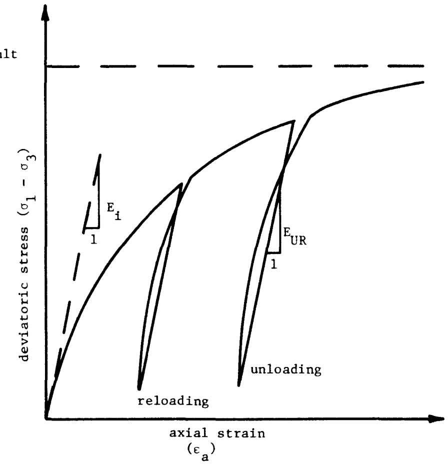

Fig. 2—A typical stress-strain relationship for soil during loading and unloading with constant confining pressure (σ_3).

was selected for its generality as well as for convenience involved in determining the model parameters through triaxial tests. The hyperbolic model is given by:

$$E_t = 1 - \left[\frac{R_f(1 - \sin\phi)(\sigma_1 - \sigma_3)}{2c\cos\phi + 2(\phi_3 + P_a)\sin\phi} \right]^2 \text{KPa} \left[\frac{\sigma_3 + P_a}{P_a} \right]^n \quad [1]$$

Where E_t = tangent modulus of elasticity
ϕ = angle of internal friction
c = cohesion
P_a = atmospheric pressure
σ_1 = major principal stress
σ_3 = minor principal stress (confining pressure)
R_f = failure ratio
K,n = dimensionless numbers determined from triaxial test results

Soil being nonlinear elastic material, an incremental loading procedure was used to perform the nonlinear analysis (Desai & Abel, 1972).

The procedure proposed by Duncan and Chang (1970) for loading and unloading of soil was used with minor changes to simulate repeated passes of a wheel on the soil surface. The soil response to unloading and reloading which occurs during successive wheel passes was modeled assuming a constant modulus of elasticity. The following equation was used to compute the modulus of elasticity during unloading and reloading.

$$E_{ur} = (K_{ur})P_a \quad [2]$$

where E_{ur} = unloading-reloading modulus of elasticity
K_{ur} = dimensionless number determined from triaxial test results

Soil compaction resulting from multiple wheel loading on clay and sand was considered during this study. Clay and sand were considered rather than an agricultural soil because: (a) hyperbolic model parameters for an actual agricultural soil were not available, and (b) the primary intent of the study was to evaluate the potential use of the finite element method for simulating multipass effects of wheel loading on soil compaction; it was decided that this goal could be met with published data for clay and sand. The hyperbolic model parameters used in the analysis are summarized in Table 1.

TABLE 1. SOIL PARAMETERS USED FOR THE FINITE ELEMENT ANALYSIS (DUNCAN AND CHANG, 1970).

Parameters	Soil Type: Clay	Soil Type: Sand
Poisson's ratio (ν)	0.48	0.34
soil density (ρ)	1770 kg/m^3 (0.064 lb/in.^{3})	1467 kg/m^3 (0.053 lb/in.^{3})
coefficient of earth pressure at rest (K_o)	0.95	0.50
angle of internal friction (ϕ)	0 deg	30.4 deg
cohesion (c)	48 kPa (6.9 psi)	0.0 kPa
K	47.0	295.0
K_{ur}	400.0	1090.0
n	0.001	0.65
failure ratio (R_f)	0.90	0.90

Tire Sizes and Contact Pressure:

Two tire sizes were considered during the study. The data on a 18.4-38, 6 ply tire provided by Deere and Company were used for one set of analyses. For a wheel load of 23,360 N (5250 lb), the contact area and contact pressure for this tire were estimated to be 1872 cm^2 (290.1 in.^{2}) and 125 kPa (18.1 psi), respectively. Using the area information, the radius of a circle with equivalent area was determined. This radius was rounded off and used for the finite element analysis, so that the contact area actually used in the analysis was slightly higher than the actual contact area. To demonstrate the effect of tire size on soil compaction, the analysis was conducted for a second contact area; this area was approximately 30% higher. The wheel load, however, was kept constant. The contact pressure over the larger contact area was 86.2 kPa (12.5 psi). This increased contact area, though not representing a specific tire, could demonstrate the effect of wide tires on soil compaction. The analysis was conducted for the larger contact area only in clay soil.

Soil Compaction Computation

Volumetric strain at various locations within the soil mass was considered as an indicator of the degree of soil compaction. The volumetric strain at the centroid of each element within the idealized system was computed using the following relationship (Poulos and Davis, 1974):

$$\epsilon_v = \epsilon_z + \epsilon_r + \epsilon_\theta \quad [3]$$

where ϵ_v = volumetric strain
ϵ_z, ϵ_r, and ϵ_θ, = volumetric strain in the vertical, radial, and tangential directions, respectively.

Because the computation of the three strain components is a normal step in the finite element analysis, volumetric strain information for each element was readily obtained.

Finite Element Idealization and Boundary Conditions

The soil mass considered in the analysis had radius and depth equal to six times the radii of the contact area. One-half the vertical cross section passing through the center of the cylindrical soil mass under consideration was idealized with rectangular elements of varying size, as shown in Fig. 1. The idealized system included 169 elements with 196 nodal points. The boundary conditions applied were as follows:

1. Face 1 of the idealized system is the axis of symmetry. Points on this face could not have movement in the radial direction. Hence, they were kept on rollers allowing movement only in the vertical direction.
2. Face 2 is located at a depth of six times the radius of the loaded area from the surface. Points on this face were assumed to have no movement in the vertical direction; they were kept on rollers allowing only radial displacement.
3. Face 3 is located at a distance of six times the radius of loaded area from the axis of symmetry. Points on this surface were assumed to have no radial movement; they were kept on rollers allowing only vertical movement.
4. Points on the soil surface were free to move in either direction.
5. The boundary pressures applied were 124 kPa (18 psi) or 86.2 kPa (12.5 psi), depending upon the contact area under consideration. For all cases considered, the boundary load was distributed over the first four elements (between the first and fifth nodal points).

Finite Element Analysis of Multiple Wheel Loading

A finite element analysis was conducted for three different cases to observe the compaction from multiple wheel loading. They are:

1. Multiple passes of 18.4-38 bias ply tire in clay.
2. Multiple passes of 18.4-38 bias ply tire in sand.
3. Multiple passes of a hypothetical tire with larger contact area in clay.

For the analysis, appropriate boundary-condition information and nodal and elemental data were input as required. Based on earth pressure at rest, the initial modulus of elasticity was computed for each element using the hyperbolic model (equation [1]). The boundary pressure was applied in increments of 20.7 kPa (3 psi). For each incremental load, the displacement of each nodal point and stresses and strains within each element were computed. The modulus-of-elasticity values for each element were then computed and updated based on the state of stress using equation [1]. This process was continued until the total boundary pressure was applied. At this point, the soil was unloaded in one step to complete the simulation of the first wheel pass. The moduli of elasticity during unloading in the case of clay and sand were 40,300 kPa (5840 psi) and 110,000 kPa (15,900 psi) respectively. Successive wheel passes were simulated by reloading and unloading in one step. The increase in soil stiffness due to repeated tire passes was simulated by increasing the magnitude of K_{ur} in equation [2] by 250 after each simulated pass. Loading and unloading was done five times to simulate five passes of a wheel. At the end of each loading and unloading cycle, the total volumetric strain experienced by each element was obtained.

All three cases listed were analyzed using the same procedure; however, boundary pressure, size of elements, and value of soil parameters were changed depending upon the case under consideration.

RESULTS AND DISCUSSION OF RESULTS

Results of the finite element analysis included information on nodal point displacement and, for each element, the values of various stress components, major and minor principal stresses, and volumetric strain. Since the effects of the number of passes, contact area, and soil type on soil compaction are of primary interest, they are illustrated by presenting the results on volumetric strain.

Two checks were made to ensure that the program developed was functioning properly. First, an elastic analysis of circular footing problem was conducted. The vertical stress distribution obtained from the analysis was compared against that obtained from the closed form solutions. The agreement between the two was very good, with only a slight discrepancy at the corner of the loaded area. As a second check, from the results of the nonlinear finite-element analysis, the stress-strain relationship was developed for one element directly below the loaded area (Fig. 3). The fact that this relationship is similar to the stress-strain relationship used for the finite element analysis also assured us that our program was functioning properly. Fig. 3 also shows that due to loading and unloading of the soil, the deviatoric stress approaches zero as it undergoes a permanent strain. This residual strain increased with each loading and unloading cycle.

Figs. 4, 5, and 6 are contours of volumetric strain that were developed from the results of finite element analysis for a 18.4-38 bias ply tractor tire in clay. In all the three cases the maximum volumetric strain, or the zone of maximum compaction, occurred at a finite depth rather than at the surface near the axis of symmetry, where the principal stresses were maximum. Thus for wheels with a certain contact area operating in clay, the maximum compaction form wheel loading may not occur on the surface directly beneath the wheel but at some finite depth. Chancellor et al. (1962), during a laboratory study, made similar observation beneath a loaded piston. Threadgill (1982) plotted contours of maximum penetration resistance in areas loaded by equipment. Penetration resistance was maximum at depths ranging from 15 to 30 cm. Assuming that these readings were

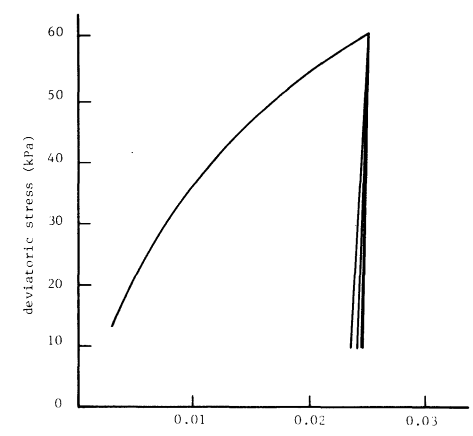

Fig. 3—Stress-strain relationship from the results of the finite element analysis for element 131 in clay.

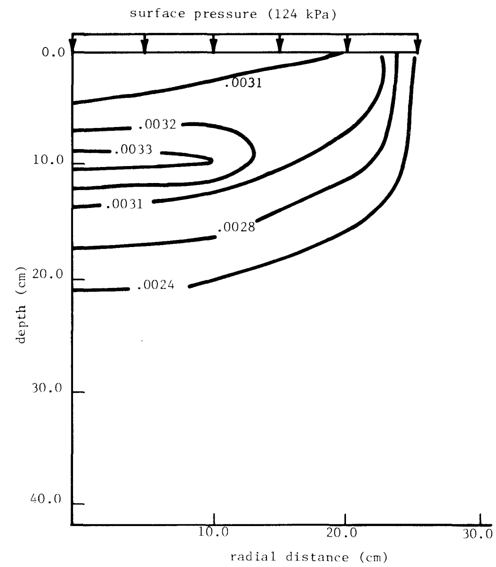

Fig. 4—Contours of volumetric strain after one pass of an 18.4-38 bias ply tractor tire in clay.

taken in the same soil type and at the same moisture content, maximum penetration resistance may mean maximum soil density. The high penetration resistance was attributed to hardpan formation in Tifton sandy loam soil due to vehicle traffic. Comparison of Figs. 4, 5, and 6 shows how volumetric strain increases and how contours expand as a function of number of passes. A major portion of the total volumetric strain from five passes occurred during the first wheel loading. Additional loadings yielded smaller increments in strain due to stiffening of the soil (Fig. 7). A soil bin study conducted by Koger et al. (1983) also indicated maximum change in bulk density as a result of the first pass of a wheel. In this study, among the three soil types considered, in only one (Lakeland loamy sand) was significant difference in density reading observed between the second and third passes. The results from a field study by Burger et al. (1983) also showed maximum change in bulk density during the first pass of a vehicle.

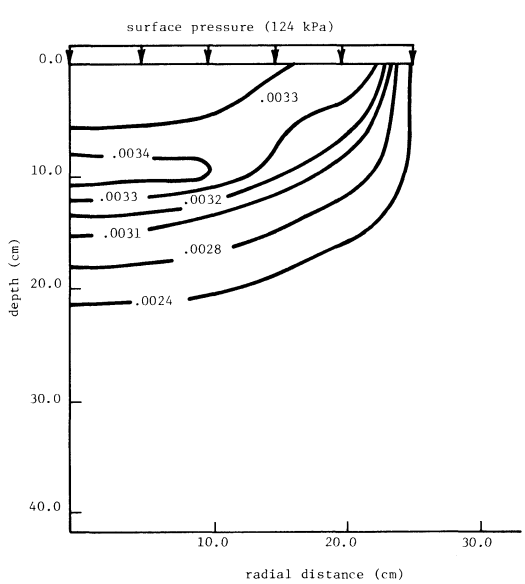

Fig. 5—Contours of volumetric strain after three passes of an 18.4-38 bias ply tractor tire in clay.

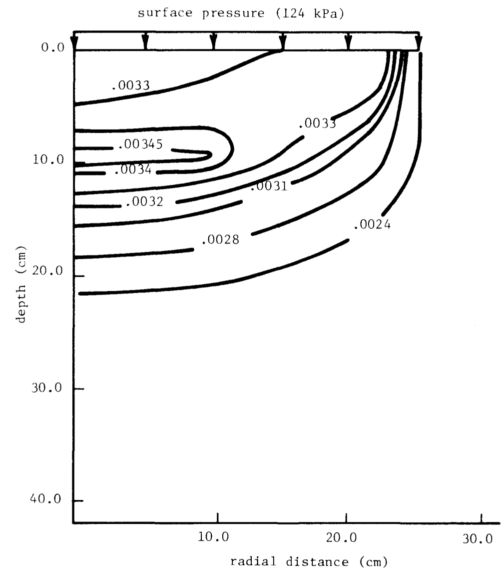

Fig. 6—Contours of volumetric strain after five passes of an 18.4-38 bias ply tractor tire in clay.

This observation from our study as well as from others may mean that, if an operation requires multiple passes of a vehicle (for example, forest harvesting), in order to minimize soil compaction, it may be desirable to traverse the same track over and over (controlled traffic) instead of exposing new areas to vehicle traffic. However, multipasses can cause rut formation and increased soil erosion.

The volumetric strain contours developed from results of analysis in sand are different (Figs. 8 and 9). In sand, the volumetric strain was maximum at the soil surface directly beneath the load. Comparison of Figs. 8 and 9 shows the expansion of strain contours as well as the development of new ones from additional wheel loading. The magnitude of maximum volumetric strain in sand was lower than that observed in clay. This lower

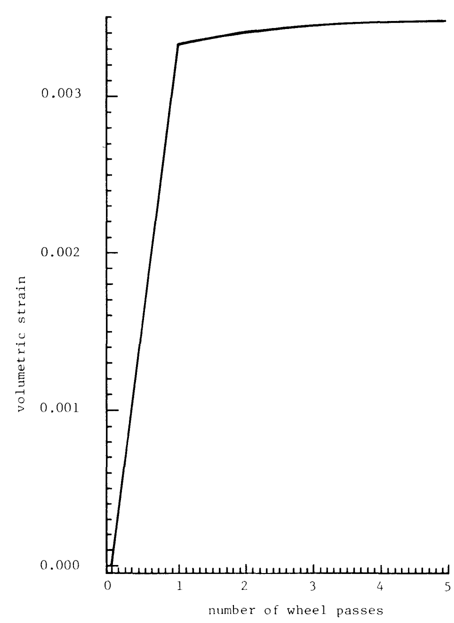

Fig. 7—The effect of number of wheel loadings on volumetric strain for element 144 beneath an 18.4-38 bias ply tractor tire in clay.

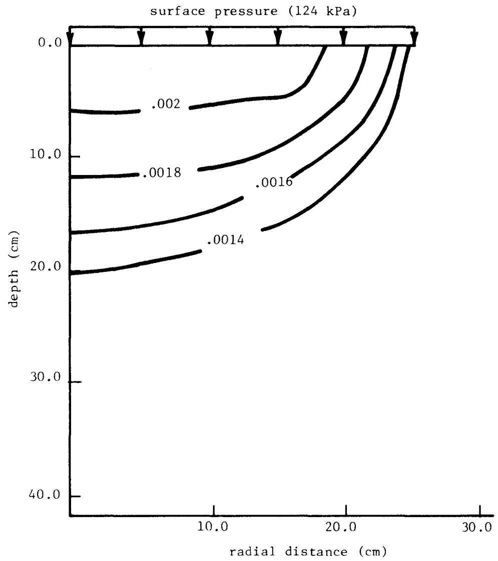

Fig. 8—Contours of volumetric strain after one pass of an 18.4-38 bias ply tractor tire in clay.

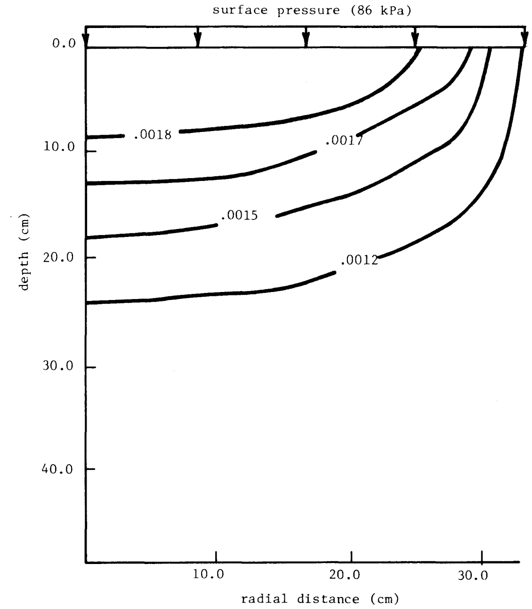

Fig. 10—Contours of volumetric strain after one pass of a simulated larger tractor tire in clay.

magnitude probably was due to the difference in the stiffness between the two soil types. The initial modulus of elasticity value for sand was considerably higher than that for clay. Effect of the number of wheel loadings on volumetric strain for sand was the same as that observed in clay. Comparison of results obtained under the two soil conditions clearly indicates that the zones of maximum compaction may depend on soil type.

Contours of volumetric strain in Figs. 10 and 11 are those developed from the results of analysis with increased contact area simulating the use of larger tires on clay. These contours are different from those obtained for 18.4-38 bias ply tires in clay. A shift in the zone of maximum volumetric strain from a finite depth to the soil surface was observed when the contact area was increased keeping the loading constant. This shift may mean that the location of maximum soil compaction due to vehicle traffic depends on contact area and/or contact pressure. Comparing Figs. 10 and 11 with Figs. 4 and 6, it can be seen that for the case with larger contact area, the volumetric strain is considerably lower than that encountered under 18.4-38 bias ply tires. With a 30.6% increase in contact area, the maximum volumetric strain is decreased by 58.3%. This reduction is expected because the magnitude of boundary pressure decreased as a result of increase in contact area. From the results of this analysis one may conclude that the use of wider tires helps to reduce the degree of soil compaction resulting from wheel loading. The increase in volumetric strain as a function of the number of passes was found to be similar to the increases obtained for the other cases considered.

Since the contact-area and contact-pressure combinations were found to have a significant influence

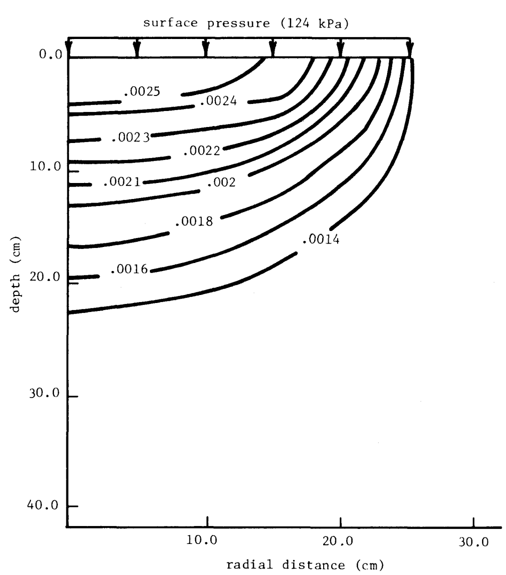

Fig. 9—Contours of volumetric strain after five passes of an 18.4-38 bias ply tractor tire in sand.

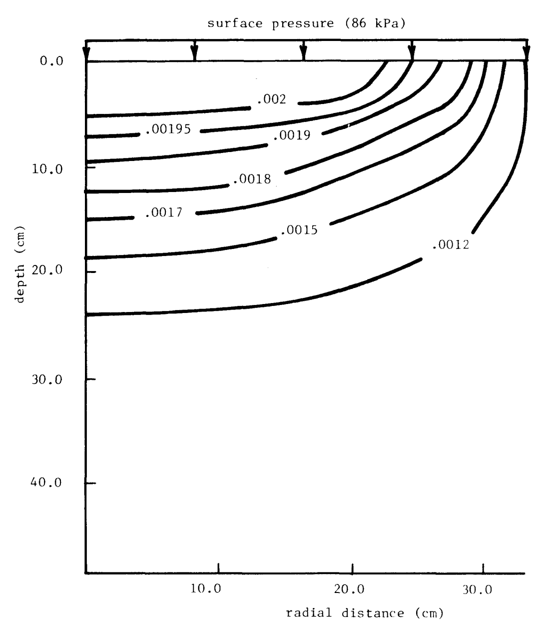

Fig. 11—Contours of volumetric strain after five passes of a simulated larger tractor tire in clay.

on the location of maximum volumetric strain, additional analyses were made for the following combinations of contact area and contact pressures:

1. Diameter 53.3 cm (21 in.); Pressure 112 kPa (16.3 psi)
2. Diameter 55.9 cm (22 in.); Pressure 103 kPa (14.9 psi)
3. Diameter 58.4 cm (23 in.); Pressure 93.8 kPa (13.6 psi)

An analysis and comparison of results from these runs indicated that the location of maximum volumetric strain shifted from within the soil to the surface directly beneath the loaded area when the diameter of the contact area was increased from 53.3 cm to 55.9 cm. The reasons for this shift are not fully known, and further study is planned to observe the effect of increase in contact area on maximum stress as well as deviatoric stress distribution.

CONCLUSIONS

Finite element analysis of soil compaction from multiple wheel loading has led to the following conclusions:

1. The finite element method appears to be a viable procedure for successfully simulating multiple wheel loadings. However, experimental verification of the model is needed before the procedure can be recommended for wider use.
2. The finite element method can be used to locate the zones of maximum compaction and to illustrate the propagation of compaction zones due to multiple wheel loading.
3. The location of maximum volumetric strain depends on contact area, contact pressure, and soil type.
4. The effect of soil type and soil condition on soil compaction can be studied using finite element procedure if appropriate constitutive relationships for the soils are available.
5. Results of this study show that a major portion of the total soil compaction which can be expected from multiple wheel loading will occur during the first pass. Subsequent wheel loadings yields relatively smaller increases in soil compaction.
6. This study demonstrates the effect of tire size on soil compaction. For the case considered in this study, a 31% increase in contact area yielded approximately a 58% decrease in the magnitude of maximum volumetric strain.

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