548 kg/ha. These represented a range of 2.6 to 10.1% of the forage dry matter yield. Based on an average crude protein (CP) content of 34% (Table 2), the potential quantity of CP that could be extracted in juice is 46 to 186 kg/ha. By setting the initial alfalfa CP content at 18% (bloom stage), the proportion of CP extracted in juice is in the range of 8.5 to 17.2%: this juice extraction resulted in a decrease of alfalfa CP content from an initial value of 18% to a final value between 17.3% and 16.4% after processing.

These values are likely a close approximation of the potential in-field juice extraction with a forage superconditioner. Field prototypes are being designed with processing components (macerator, belt-press) similar to those used in the stationary environment. The main issue is to evaluate whether it is economical to recuperate and process the juice extracted from the superconditioner or to simply leave the juice on top of the drying mat. Collecting forage juice in the field will cause delays during the mowing operation due to periodically emptying of the juice holding tank. The treatment costs of juice may include preservative acids, coagulation agents or dehydration. There is an additional loss in lower nutrient value and quantity of the remaining forage fiber. It would be expected that the juice should have a relatively high value to justify its harvest and processing. This might occur if juice dry matter is fed to non-ruminants, and if some high value products such as high-quality proteins, chlorophyll or pigments can be extracted efficiently. Otherwise, with a relatively low value, juice extracted in the field is likely to best be recuperated by poured on the top of the forage mat.

CONCLUSIONS

1. With a stationary macerator-press, the proportion of juice extracted varied between 6.2 and 25.5% of the fresh mass with an average of 14.6%. More juice was extracted from wetter or more severely macerated forage, and from lighter windrows.
2. Juice dry matter content varied between 7.5 and 11.9% with an average value of 9.5%. The juice dry matter was on average high in crude protein (34.4%) and low in acid detergent fiber (4.5%).
3. Simulation of field conditions showed that between 1.06 and 6.15 t of juice/ha could be extracted depending on forage yield, initial forage moisture content and windrow density (or press feed rate). For one maceration pass, potential amount of dry matter extracted ranged between 135 and 548 kg/ha (46 to 186 kg proteins/ha). Economics will dictate whether to recuperate and process the juice or pour it back onto the forage mat.

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REFERENCES

ASAE Standards, 37th ed. 1990. St. Joseph, MI: ASAE.

Collins, M., R.G. Koegel, N.A. Jorgensen and H.W. Ream. 1981. Wet fractionation of alfalfa: a direct forage-harvesting system. Proc. of the XIV International Grassland Congress: 648-650. Lexington, KY.

Koegel, R.G., K.J. Shinners, F.J. Fronczak and R.J. Straub. 1988. Prototype for production of fast-drying forage mats. *Applied Engineering in Agriculture* 4(2):126-129.

Savoie, P. and S. Beauregard. 1991. Forage mat making: species and compression effects on drying. *Canadian Agricultural Engineering* 33(1):113-118.

Schoney, R.A. and J.T. McGuckin. 1983. Economics of the wet fractionation system in alfalfa harvesting. *American J. Agr. Econ.* 65:38-44.

Shinners, K.J., R.G. Koegel and R.J. Straub. 1987. Drying rates of macerated alfalfa mats. *Transactions of the ASAE* 30(4):909-912.

A RATIONALE FOR MODELING SOIL COMPACTION BEHAVIOR: AN ENGINEERING MECHANICS APPROACH

R. L. Schafer, A. C. Bailey, C. E. Johnson, R. L. Raper

ABSTRACT

Modeling agricultural soil compaction is important as one input to a system of effective management of soil physical condition to improve crop production. The desired degree of compaction depends on the intended purpose; for example, the requirements for traction and mobility are quite different from those for infiltration and root propagation. Our goal is to develop a compaction model and related soil and soil-machine behavior models which can be used to design systems for effective management of soil physical condition. In this article we discuss our rationale in modeling soil compaction and related soil-machine systems. The status of the various modeling efforts is discussed, as are plans and needs for the future.

KEYWORDS. Soil compaction, Modeling.

INTRODUCTION

In our haste to use modern research tools, such as computers and numerical methods, to develop new knowledge and to solve problems, we often forget the historical perspective of our work. A historical perspective of modeling material behavior is important as a reminder that it is a difficult task. The *easy things* have been done; the *tough tasks* remain.

Man has long sought to understand and to model material behavior for it is intrinsic in engineering design. In the early 1600s Galileo Galilei described his concepts of modeling material behavior in "Discourses and Mathematical Demonstrations concerning Two New Sciences pertaining to Mechanics and Local Motions" (Crew and de Salvio, 1914). Galileo was interested in how beams break. He developed concepts of the resistance of solid bodies to fracture by external forces and used these concepts to determine the nature of the strength of structures and machines.

Modeling material behavior, such as soil compaction, is more important today than in Galileo's time because modern engineering tools, such as computer analysis and simulation techniques, require behavior models. New uses of existing materials or use of new materials may simply require the determination of parameters for existing behavior descriptions. This task is relatively easy compared to the task of determining new descriptions of material behavior.

Knowledge of soil compaction is important in today's agriculture, and a model of soil compaction is an important tool for the effective management of soil physical condition for improved crop production. Modeling the compaction of agricultural soils requires new relationships and quantitative descriptions of the soil's response to compactive stresses. These tasks must be accomplished if we are to make progress in the design, use, and management of agricultural machines. Proper procedures and tools of science and engineering must be used.

The purpose of this article is to present a rationale, using an engineering mechanics approach, for modeling soil compaction behavior and other related soil and soil-machine behaviors.

GOAL

An accurate model of agricultural soil compaction is an important input to a total system of effective management of soil physical condition to improve crop production. The degree of compaction that is desired depends on the intended purpose. The requirements for traction and mobility are quite different than those for infiltration and root propagation. Of considerable interest at this time is soil that has been so compacted in the crop zone that production is adversely affected. When considering compaction, four facets must be included:

1. The sources of the force systems causing the compaction;
2. The propagation and distribution of the stresses within the soil mass which are caused by these force systems;
3. The soil's response to the stresses (compaction behavior); and
4. The relationship (and consequences) of the resulting compaction state to the cropping system (the plant, the fluid and gaseous movements, and the biological and chemical activities).

The hierarchy of the relation of these four facets is shown in figure 1. In figure 1 and in other figures, we only use one box to represent the interface between the complex soil dynamics and plant or crop response relationships.

Our goal is to develop a compaction model and other complementary soil and soil-machine behavior models which can be used to design systems for effective management of soil physical condition for improving cropping systems. To achieve this goal, we have specific

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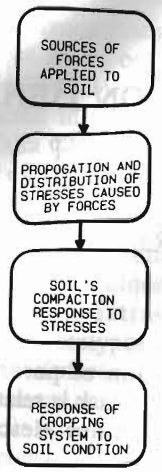

Figure 1–Block diagram of the hierarchy of four important facets in modeling soil compaction.

research objectives for developing a more complete understanding of facets 1, 2, and 3 so that the resulting models can be interfaced with models being developed for facet 4.

MATERIAL BEHAVIOR

Soil is compacted when a force system exceeds the soil's "strength". Successful modeling of soil strength or any strength phenomenon depends on the adequacy of the stress-strain equations used to describe behaviors governing the phenomenon. Identifying these behaviors and developing mathematical descriptions have been very difficult challenges for the complex agricultural soil-machine systems.

CONSTITUTIVE EQUATIONS

The stress-strain equations that are used to describe behaviors are sometimes called constitutive equations. It is imperative that the constitutive equations be the best possible descriptions of the behaviors governing the phenomenon so that the model has integrity and robustness. A model can be no better than the constitutive equations on which it is based.

A behavior may require more than one constitutive equation for description, and a phenomenon may involve more than one behavior. Thus, the model may be based on one or more constitutive equations. Model development can be very complicated, especially if there is interaction among the behaviors. The fact that a soil often exhibits two or more behaviors concurrently in response to mechanical loading complicates the development of usable models of soil mechanical behavior.

SOIL MECHANICAL BEHAVIOR

Experience has demonstrated that the stress-strain behavior of agricultural soils is complex and very difficult to describe. Koolen and Kuipers (1983) described this complexity and the difficulty of quantitatively describing mechanical behavior of agricultural soils. They observed that soil behavior can often be accurately described for a particular test type, but that the same description is not valid when a different test type is used. Bailey and Weber (1965) and Dunlop et al. (1966) found this same result when comparing methods of measuring soil shear strength. Thus, these descriptions, developed under one loading condition (a test type), are often inadequate for predicting the behavior for another loading condition (another test type). Likely, this discrepancy occurred because the understanding of the soil behavior was not adequate. The dilemma is that an understanding of the soil behavior is necessary for designing the test, while at the same time the test is necessary for developing an understanding of the soil behavior.

What appeared to be simple has proven to be very difficult. The development of quantitative behavior equations applicable generically under various loading conditions has proven to be a complex research endeavor and continues to be a major challenge. This knowledge is of fundamental importance for developing successful models of the system represented in figure 1.

AN APPROACH TO MODELING MATERIAL BEHAVIOR

In a book chapter entitled "Modeling the Behavior of Geomaterials," Prevost (1987) commented:

> "A useful mathematical model of material stress-strain-strength behavior is one that can be employed to *predict* satisfactorily the material performance in all circumstances at hand. Such a mathematical model does not purport to describe the *real material* behavior exactly, but it is said to represent an *ideal material*. It is important to realize the distinction between the ideal material model representation and the behavior of the real material which is being modeled."

Prevost recognized that modern tools, such as computers and finite element techniques, provide additional capabilities for attacking problems associated with material behavior. But, he emphasized that,

> "Further progress in expanding analytical capabilities in geomechanics now depends upon consistent mathematical formulations of generally valid and realistic material constitutive relations."

Prevost further stated that a material model should possess the following *necessary* characteristics:

1. The model should be *complete*, i.e., able to make statements about the material behavior for all stress and strain paths, and not merely restricted to a single class of paths (e.g., axial symmetry or pure shear).
2. It should be possible to identify the model parameters by means of a *small number* of standard, or simple material tests.
3. The model should be founded on some *physical interpretations* of the ways in which the material is responding to changes in applied stress or strain (e.g., the material should not be modeled as elastic if permanent deformations are observed upon loading).

Characteristics 1 and 2 are highly desirable but may not always be possible to achieve. Realistically, with limited resources (e.g., time, money, and equipment) a model which meets Characteristic 1 is a long term goal.

Bailey and Weber (1965) and Dunlop et al. (1966) found that "simple" tests that reveal pertinent parameters are very difficult to define and to implement. Thus, satisfying Characteristic 2 for agricultural soils continues to be a challenge.

Prevost's explanation of Characteristic 3 is very astute. Many contemporary models contain relationships resulting from curve fitting techniques. This approach, although sometimes valuable, does not include consideration of physical interpretations of material behavior. Thus, models containing such relationships are restricted in their application and often are not valid beyond the range and limits of the data used to develop them. As an example, a constitutive equation widely used to describe stress-strain behavior of soil is of the following form (Bailey and Vanden Berg, 1968; Larson et al., 1980; Gupta and Allmaras, 1987):

$$(1/BD) = m \log \sigma + b, \qquad (1)$$

where

BD = bulk density,
m = compressibility coefficient,
σ = applied stress, and
b = (1/BD) at an applied stress of 1.0.

Our purpose is not to criticize those that have used equation 1. However, two interesting observations can be made about equation 1 with regard to Characteristic 3. First, as σ approaches zero, BD becomes undefined. Certainly agricultural soils are often found in a loose state (freshly tilled), and considerable compaction occurs when small stresses (near zero) are applied. Thus, the equation is not adequate for describing this physical situation.

Further, the BD calculated from Equation 1 continues to increase as σ becomes large. But, we know that soil becomes rigid as the compaction stresses get very large. In this state soil acts as an elastic rigid body, and changes in volume are small. Again, the equation is not adequate for describing this physical situation.

Experience has shown that equation 1 often fits soil stress-strain data well for a range of σ starting at about 150 kPa. Although equation 1 may fit compaction data over a stress range well, it is obvious that the equation has conceptual limitations. Thus, it appears that what might have been a curve fitting exercise at some point in time resulted in a "universal" equation, or at least an equation which has been used frequently.

Prevost's thoughts are not profoundly new; others have expressed similar views. For example, Vanden Berg (1961) outlined the requirements of a soil mechanics for agricultural soils. However, Prevost has delineated an approach for, and stated the challenges of, developing models of material behavior in a clear and concise manner.

SOIL COMPACTION BEHAVIOR

Gill and Vanden Berg (1967) classified four types of behaviors exhibited by unsaturated agricultural soils when reacting to mechanical forces. They are compaction, shear, plastic flow, and tension failure. In their book on agricultural soil mechanics, Koolen and Kuipers (1983) listed reactions of agricultural soils to mechanical forces as: compaction, deformation (apart from volume change), break (failure), and displacement (as a rigid body). Although the terminology is different, the classifications are essentially the same. In this classification framework, soil compaction is a behavior, and a compaction model is a constitutive equation. We will view a compaction model as a constitutive equation.

Although soil compaction behavior is well defined conceptually as a reduction of the volume occupied by a given mass of soil, constitutive equations for soil compaction are not well defined. Thus, constitutive equations which describe soil compaction behavior must be determined. A complicating factor is that agricultural soils extend over a broad range of types, and they are found in a wide range of conditions. Thus, it seems that theoretically "correct" constitutive equations may be very difficult, if not impossible, to define. This is why it is important to remember Prevost's comments about a *real material* and an *ideal material*. An acceptable approach seems to be to delineate the range of soil types and soil conditions important to a particular problem and then use the available information along with proper engineering mechanics and mathematics to develop "workable" constitutive equations. This approach may seem to be empirical in nature, but empirical equations are not new to quantitative description of material behavior (Murphy, 1946).

Another factor which complicates the development of useable constitutive equations for soil is that soil may exhibit both compaction and shear behaviors concurrently. In many conditions, a soil mass will undergo compaction before yielding in shear, and the final shearing stress may depend on the amount of compaction that preceded shear. The development of models that adequately describe both soil compaction and shear has been hindered by the difficulty of dealing with the interaction between these two behaviors.

AN APPROACH TO MODELING SOIL COMPACTION BEHAVIOR

Contemporary efforts to develop a stress-compaction model have involved consideration of both the form of the model and the nature of the compaction stresses. Soehne (1958) considered the major principal stress, and Vanden Berg (1961) considered the mean normal stress as the dominant stress controlling compaction. The general form of their models presented bulk density or specific volume as a logarithmic function of stress (similar to eq. 1). Both approaches were partially successful, but each had significant limitations. These studies demonstrated that classical definitions from continuum mechanics were not adequate for describing compaction of agricultural soils.

In early soil compaction modeling at Auburn, Bailey, and Vanden Berg (1968) combined concepts of continuum mechanics and critical state soil mechanics to develop a concept in which they defined soil compaction and failure surfaces. A modification of equation 1 was used to attempt to describe the compaction surface. As the work progressed, it became clear, as previously discussed, that equation 1 did not describe the physical phenomenon that was occurring. Thus, a different approach was charted for developing a better description of agricultural soil compaction.

The conceptual approach was to develop a constitutive equation which was defined at zero stress and which described the observed soil behavior over a stress range found in agricultural soils. The first step was to describe the compaction behavior of soil subjected to a hydrostatic stress state and then to include shear stresses and loading paths in the model. Also, it was decided not to try to model the "universe" but to restrict the development to the soil types and conditions that represented a large percentage of the soils that were experiencing significant compaction problems in crop production.

The Hydrostatic Model

The results of the work on a hydrostatic model were first reported by Bailey et al. (1984) in terms of linear volumetric strain. After consideration of the magnitude of the strains involved and consideration of discussions by Gill and Vanden Berg (1967) and Rosenthal (1974), the equation was modified for natural strains and presented by Bailey et al. (1986) as:

$$\ln(V/V_i) = (A + B\sigma_h)(1 - e^{-C\sigma_h}), \qquad (2)$$

where

V_i = initial volume,
V = volume,
σ_h = hydrostatic stress, and
A, B, C = compactibility coefficients.

In terms of bulk density equation 1 becomes:

$$\ln(BD) = \ln(BD_i) - (A + B\sigma_h)(1 - e^{-C\sigma_h}), \qquad (3)$$

where

BD = bulk density, and
BD_i = bulk density at zero pressure.

The form of equations 2 and 3 was chosen because, over the range of applied hydrostatic stresses from 0 to 500 kPa, the equations:

1. Represented compaction data well;
2. Met the boundary condition of zero strain at zero stress; and
3. Exhibited pseudo elastic behavior at large stresses.

Data for model development were obtained from cylindrical soil samples in a triaxial apparatus in which only cell pressure was applied. A continuing concern with the use of the triaxial apparatus is the influence of the sample size and shape on the results. Grisso et al. (1984) conducted a study of the influences of sample geometry on hydrostatic compaction and concluded the equations were valid for the sample geometries that were used in the equation development.

Equations 2 and 3 are limited to hydrostatic load conditions. These equations must be expanded to include more complex load conditions.

The Deviatoric Stress Model: Phase I

Grisso et al. (1987) studied the effect of shearing stress on soil compaction. Data were obtained from cylindrical soil samples in a triaxial test apparatus using two stress loading patterns. Shearing stress loading patterns were applied to obtain a maximum principal stress ratio (PSR) of 3.0. (Principal stress ratio is the ratio of the major principal stress and the minor principal stress). Grisso et al. (1987) modified equation 2 by including a multiplicative factor, β, which was a function of PSR, and by replacing σ_h with octahedral normal stress σ_{oct}. This equation was:

$$\ln(V/V_i) = \beta(A + B\sigma_{oct})(1 - e^{-C\sigma_{oct}}), \qquad (4)$$

where

$$\beta = M_f(PSR - 1) + (M_0 - M_f)(PSR - 1)(e^{-F\sigma_{oct}}) + 1 \qquad (5)$$

and

σ_{oct} = octahedral normal stress,
PSR = principal stress ratio (σ_1/σ_3),
M_f, M_0, F = soil parameters, and
A,B,C = compactibility coefficients which were determined from hydrostatic tests.

Equation 4 described the compaction of the cylindrical triaxial test samples well for each PSR<3.0, but maximum densities were not attained at these PSRs. PSRs>3 were not possible because in the stress controlled proportional tests that were used, the sample became unstable for PSR>3.

The question remained as to what maximum PSR could be expected under wheel loads and other field loading situations. If PSRs>3.0 were encountered in the field, then there was the question as to how the equation should be changed or modified to respond to these stress states, because maximum densities were not attained at a PSR of 3.0. The task remained to quantify PSRs under wheel loads.

Quantifying Soil Stress States

Nichols et al. (1987) and Bailey et al. (1988) reported the development and use of a three-dimensional soil stress state transducer (SST) to measure stress states in a soil profile. The SST provides information from which the complete stress state at a location in the soil profile can be determined.

The SSTs were used at several depths in loose soil in the path of a rear tractor tire operating under different conditions of load and slip. An important observation from these studies was that large shearing stresses existed beneath the tire operating in loose soil even when the tire was generating little net traction (useful pull). This observation was verified by Bailey and Burt (1988).

Octahedral stress ratios (OSR) greater than 1.0 were calculated from the SST data. The octahedral plane is perpendicular to the octahedral normal stress (mean normal stress), and the octahedral stress ratio (OSR) is the ratio of octahedral shearing stress to the octahedral normal stress. An OSR of 1.0 was equivalent to a PSR of 8.24 for the cylindrical stress state of the triaxial test. Thus, these studies established that a model of soil compaction behavior must be valid for PSRs>8.0 or for PSRs large enough to attain maximum density if this condition was attained for a PSR<8.0. This further established the guidelines for the physical situation that the model must represent (Prevost's Characteristic 3).

The Deviatoric Stress Model: Phase II

Bailey and Johnson (1988) proceeded to develop further the model so that it described better the compaction behavior of soil subjected to a stress state which included shear stresses. They used the experimental procedure described by Grisso et al. (1987). Based on analysis of the experimental data, they added a linear function of OSR to equation 2 and proposed a model of the form:

$$\ln(V/V_i) = (A + B\sigma_{oct})(1 - e^{-C\sigma_{oct}}) + D(\gamma_{oct}/\sigma_{oct}), \qquad (6)$$

where D = coefficient for the component of natural volumetric strain due to shearing stress.

The boundary condition of zero strain at zero stress, proposed by Bailey et al. (1984), was maintained in equation 6. However, equation 6 does not have an upper limit on compaction strain as shearing stress increases. When soil reaches maximum compaction (maximum density), it continues to strain at constant volume as shear stresses are increased, a criterion of plastic flow. Equation 6 predicts an increase in compaction for this situation, and its use must be terminated at the octahedral shearing stress for maximum compaction. Bailey and Johnson (1989) proposed that the following equation described this part of the phenomenon:

$$\tau_{oct_y} = K\sigma_{oct} \qquad (7)$$

where

τ_{oct_y} and τ_{oct} = stress values at maximum density, and
K = coefficient representing soil plastic flow yield.

Note that Bailey and Johnson (1988) initially proposed a slightly different form of equation 7.

When dealing with large octahedral stress ratios, equation 7 could be used to determine the octahedral shearing stress beyond which equation 6 is no longer valid.

Equation 6 was better than equation 4 for describing soil compaction behavior for an orthogonal loading path. Including a linear term to account for the additional compaction caused by shearing stresses did not adversely affect the accuracy of the model for predicting compaction under a hydrostatic stress state. The deviations between measured and predicted bulk densities during loading with shear stresses were within the same range as the deviations obtained with the hydrostatic model (eq. 2 and 3). However, equation 6 was not perfect. There were systematic deviations between measured and predicted bulk densities as octahedral normal stress increased.

The Deviatoric Stress Model: Phase III

Previous work (Bailey et al., 1984) demonstrated that the coefficients A, B, C, and BD_i vary with moisture content. It is not known how the coefficient D varies with moisture content. At present, the coefficients can only be determined by conducting one or more triaxial tests and fitting equation 6 to the data. The model needs to be verified using data from triaxial tests conducted at constant cell pressure (σ_3 = constant), and compared with data from confined compression tests. Models for unloading and reloading must also be developed to represent multiple pass vehicular traffic.

A System of Models

Our goal is to develop compaction and other soil and soil-machine behavior models which are useful in a system for effective management of soil physical condition. A compaction model by itself is of little use; it must be coupled to the cropping system through the use of other models that deal with associated physical phenomena. Several of these models are under development. A block diagram of an overview of the relation of the compaction, soil behavior, and soil-machine behavior models is shown in figure 2. The block diagram in figure 3 shows the relationship between these models and the cropping system. A brief description of these modeling efforts follows in terms of the four facets of compaction which were previously discussed with regard to goals.

Modeling the Source of Compaction Forces

Wheel traffic in fields has been recognized as a major source of forces causing undesired soil compaction (Soane et al., 1981a, 1981b, and 1982; Soane, 1985; Taylor and Gill, 1984; Taylor and Burt, 1984). Ashmore et al. (1987), Bailey and Burt (1976), Bailey et al. (1976), Burt et al. (1974), Burt and Bailey (1975), Burt et al. (1979), Burt and Lyne (1985), Burt and Bailey (1985), Burt et al. (1987), Lyne and Burt (1987), and Wood and Burt (1987a and 1987b) have been modeling the forces exerted by wheels on soil. Robbins et al. (1987, 1988) modeled soil-material sliding resistance. It is anticipated that these efforts will result in a "traction" model which will provide adequate prediction of wheel-soil forces.

Propagation and Distribution of Stresses

The "traction" model will predict the forces applied to the surface of the soil, but the propagation and distribution of the stresses in the soil caused by these forces must be known in order to predict the stress state which in turn can be used to predict compaction. Predicting stress propagation in the soil due to surface loads is not new.

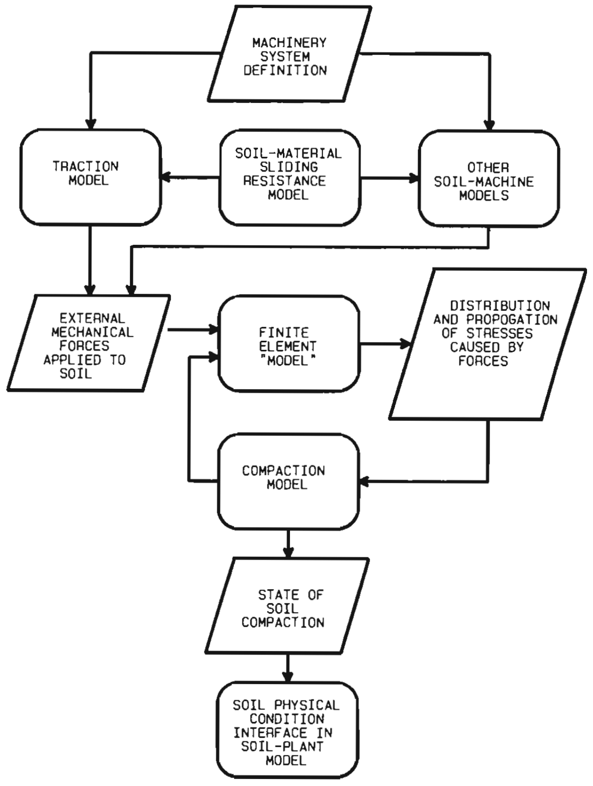

Figure 2–Block diagram of the relationship of soil behavior and soil-machine behavior models to cropping systems.

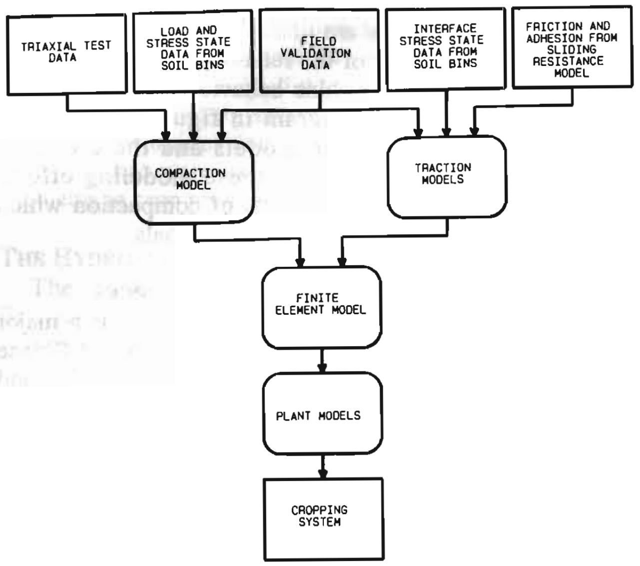

Figure 3–Block diagram of the relationship of compaction and traction models to cropping systems.

Boussinesq in 1885 (Taylor, 1948) developed a set of equations for predicting the stress state in the soil based upon a point load at the surface. He assumed a semi-infinite medium with linear-elastic properties. Froelich (1934) modified the Boussinesq equations to incorporate concentration factors. Soehne (1958) assigned different concentration factors for soils of different soil strength and calculated the stress state under a tire load. The most significant limitation of these approaches was the assumption that soil had linear-elastic material properties. Agricultural soil rarely behaves in a linear-elastic manner. Better methods of predicting stress in the soil due to surface loads must be developed which duly account for non-linear stress-strain behavior.

The finite element technique is a numerical method that can be used to calculate stress-strain behavior of a material. Although the finite element method is most often used for analysis of linear-elastic materials, non-linear stress-strain behavior can be incorporated into the finite element analysis. Further, the finite element method has been primarily used to calculate stress states in a material; however, the finite element method can also be used to calculate and evaluate the strain distribution in a material. We are interested in compaction strain. Thus, the finite element method, modified for non-linear stress-strain behavior, may be an important link between the "traction" model and soil compaction.

Raper and Erbach (1988) modified a "standard" finite element method computer program to model soil as a non-linear material. They used equation 3 as the constitutive relationship (equation 6 was not fully developed when they conducted their research). They used an incremental loading scheme in which the usual elastic properties were incrementally calculated in a technique to simulate non-linear behavior. Young's modulus and Poisson's ratio were calculated for each increment of load and for each element based upon the current stress state of each element.

A tangential Young's modulus, E_t, was calculated using the following equation:

$$E_t = \left[\frac{d\varepsilon_v}{d\sigma_h}\right]^{-1} = \left[\exp\left[(A+B\sigma_h)(1-e^{-C\sigma_h})\right]\left[(B+e^{-C\sigma_h}(AC-B+BC\sigma_h)\right]\right]^{-1} \quad (8)$$

Poisson's ratio, υ, was calculated from the following equation developed by Duncan and Chang (1970):

$$v = \frac{\Delta\varepsilon_1 - \Delta\varepsilon_v}{2\Delta\varepsilon_1} \quad (9)$$

where

$\Delta\varepsilon_1$ = incremental axial strain, and
$\Delta\varepsilon_v$ = incremental volumetric strain.

To test the finite element approach, Raper and Erbach (1988) loaded the surface of a soft soil with circular plates. Stress measurements were made in the soil using the SSTs reported by Nichols et al. (1987), and strain was measured by characterizing the surface depression. Stress and strain distribution in the soil was predicted using the finite element method and assuming an axisymmetric load.

Good predictions of stress and strain distribution were obtained for most of the loading situations investigated by Raper and Erbach. This indicated that their approach has considerable merit. However, there were discrepancies in prediction of both the stress and strain that indicated their approach needed further development.

Discrepancies in results might be attributed to several sources. One source could be the large strain values that are typically found in compaction of loose soil. In some cases Raper and Erbach (1988) found volumetric strains greater than 30%. Small strain theory restricts each component of linear strain to be less than about 4%. In the incremental loading technique they controlled linear strain to be less than 4% for each increment of applied load. However, they approximated total strain for the total load by summing the strain from each load increment, and this approximation may not have been adequate.

Another source of error could have resulted from using the mean normal stress of each element to estimate new linear-elastic parameters. The compaction model used in this analysis was developed using hydrostatic stress; however, a hydrostatic stress state did not exist in the situation that was used for the tests. It was assumed that the mean normal stress state of each element in the finite element model closely resembled the hydrostatic stress state of the compaction model.

At the time of this work, Raper and Erbach did not have access to the recent advances in the compaction model; further development and refinement of the finite element model will incorporate these advances.

MODELING COMPACTION BEHAVIOR

The compaction model appears to be nearly ready for predicting compaction states for plant models or other aspects of the fourth facet of compaction previously discussed. However, there are important aspects of the compaction model that need to be addressed to make it useful.

With regard to the three characteristics that Prevost stated that a material model should possess, the status of compaction modeling is as follows:

Characteristic 1. Considerable progress has been made on incorporating stress-strain paths.

Characteristic 2. No recent attempts have been made to define and to develop simple material tests. As previously stated, Bailey and Weber (1965) and Dunlop et al. (1966) found that "simple" tests which have physical significance are very difficult to define and implement. Thus, Characteristic 2 will be difficult to achieve.

Characteristic 3. The model was founded on physical interpretations of the manner in which the soil responds to changes in applied stress or strain. All development of the model has been based on physical interpretations.

INTERFACING TO THE CONSEQUENCES OF COMPACTION

According to Rogers (1988), linking the compaction and associated models to cropping systems is "Limited by our basic understanding of the soil-plant interaction and the rhizosphere as well as our inability to describe soil compaction with respect to its influence on plants". Rogers further stated that for many reasons, the rhizosphere has not been studied as extensively as the aboveground regions. He reasoned that soil compaction is synonymous to "universal modification" in that all physiochemical and biological aspects of a volume of soil are altered when the volume is reduced by being compacted. Our ability to link crop simulation models to soil compaction models depends upon our knowledge of which independent characteristics of compacted soil influence crop response. The degree of interaction between soil and weather variables make field studies quite unwieldy with respect to interpretation. Another complication is that plants possess a remarkable potential to compensate for changes in environment. Thus, relating a given process, such as compaction, with usable product yield may be impossible at worst and difficult at best.

FUTURE

Most of the modeling effort at Auburn has been directed towards developing models that deal with traffic induced compaction, because field traffic was perceived as the major cause of adverse compaction. Some tillage tools can cause compaction, especially if they are used improperly. Limited efforts are underway to model the performance of soil-machine systems, including soil-force relationships (Chapman et al., 1988; Schafer et al., 1987; Tice and Hendrick, 1986; Tice et al., 1987). A block diagram of the relationship of the soil-machine models to cropping systems is shown in figure 4.

The forces exerted by many machines on the soil and the performance of machines can be changed significantly by changing machine geometry and/or operating parameters. Thus, automatic control of machinery systems is important as a means of controlling forces and optimizing performance. The models which are being developed, as well as the development of sensor concepts and sensors, are important to the development of control systems. Block diagrams of traffic and tillage control systems are shown in figures 5 and 6.

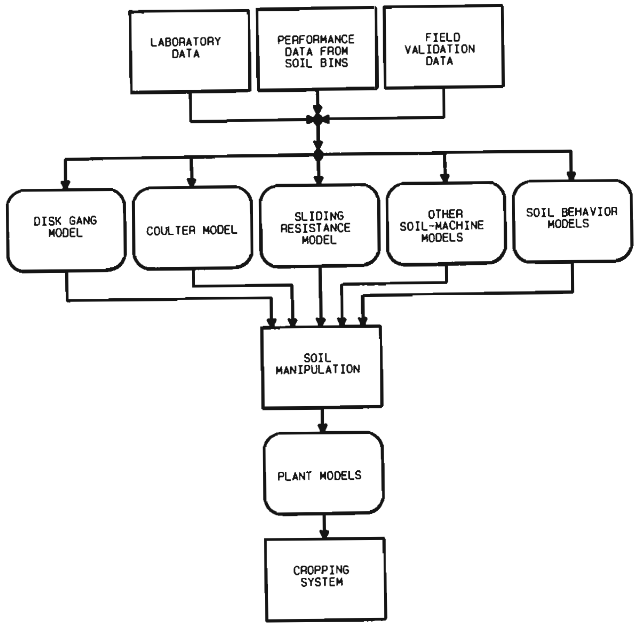

Figure 4–Block diagram of the relationship of soil and soil-machine behavior models to soil manipulation and cropping systems.

Soil compaction modeling and soil-machine models ("traffic" models and "tillage" models), along with development of control systems and sensor systems, are important in developing an overall system and strategy for achieving the goal of effective management of soil physical condition. When all four facets of compaction can be linked together so that the agronomic implications of moving the wheels and machines across fields can be predicted with an acceptable level of confidence, our goal and purpose for developing the soil compaction model will have been realized.

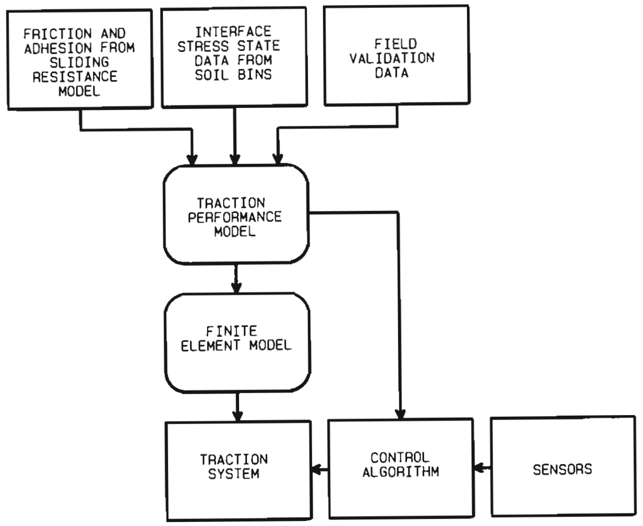

Figure 5–Block diagram of the relationship of compaction and traction models to controlling traction systems.

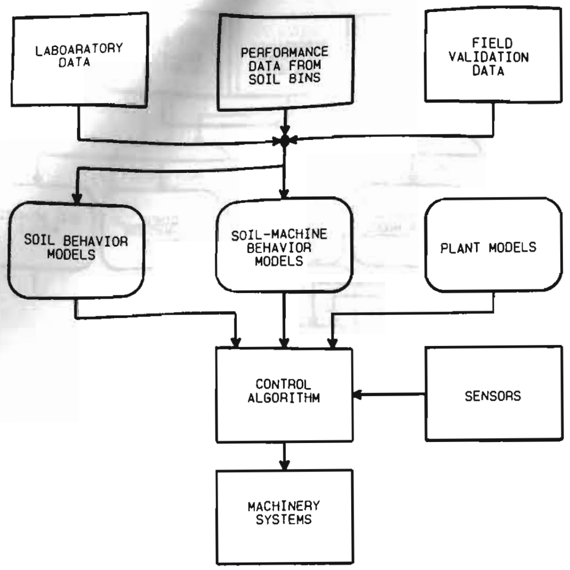

Figure 6–Block diagram of the relationship of soil and soil-machine behavior models to control of soil manipulation systems.

REFERENCES

Ashmore, C.E., E.C. Burt and J.L. Turner. 1987. An empirical equation for predicting tractive performance of log-skidder tires. *Transactions of the ASAE* 30(5):1231-1236.

Bailey, A.C. and J.A. Weber. 1965. Comparison of methods of measuring soil shear strength using artificial soil. *Transactions of the ASAE* 8(2):153-156, 160.

Bailey, A.C. and G.E. Vanden Berg. 1968. Yielding by compaction and shear in unsaturated soils. *Transactions of the ASAE* 11(3):307-311, 317.

Bailey, A.C. and E.C. Burt. 1976. Theoretical considerations of a rigid wheel mechanics. *Transactions of the ASAE* 19(6):1005-1007.

Bailey, A.C., E.C. Burt and J.H. Taylor. 1976. Thrust-dynamic weight relationships of rigid wheels: II. The effects of soil and wheel surface. *Transactions of the ASAE* 19(1):37-40.

Bailey, A.C., C.E. Johnson and R.L. Schafer. 1984. Hydrostatic compaction of agricultural soils. *Transactions of the ASAE* 27(4):952-955.

———. 1986. A model for agricultural soil compaction. *Journal of Agricultural Engineering Research* 33:257-262.

Bailey, A.C. and E.C. Burt. 1988. Soil stress states under various loadings. *Transactions of the ASAE* 31(3):672-676, 682.

Bailey, A.C. and C.E. Johnson. 1988. A soil compaction model for cylindrical stress states. ASAE Paper No. 88-1018. St. Joseph, MI: ASAE.

Bailey, A.C., T.A. Nichols and C.E. Johnson. 1988. Soil stress state determination under wheel loads. *Transactions of the ASAE* 31(5):1309-1314.

Bailey, A.C. and C.E. Johnson. 1989. Personal communication. Auburn, AL: National Soil Dynamics Laboratory.

Burt, E.C., R.L. Schafer and J.H. Taylor. 1974. Similitude of a model traction device: Part I – Prediction of dynamic traction ratio; Part II– Prediction of wheel sinkage. *Transactions of the ASAE* 17(4):658-665.

Burt, E.C. and A.C. Bailey. 1975. Thrust-dynamic weight relationship of rigid wheels. *Transactions of the ASAE* 18(5):811-813, 817.

Burt, E.C., A.C. Bailey, R.M. Patterson and J.H. Taylor. 1979. Combined effects of dynamic load and travel reduction on tire performance. *Transactions of the ASAE* 22(1):40-45.

Burt, E.C. and P.W.L. Lyne. 1985. Velocity effects on traction performance. *Transactions of the ASAE* 28(6):1729-1730.

Burt, E.C. and A.C. Bailey. 1985. Determining thrust from wheels and tires. In *International Conference on Soil Dynamics Proceedings* 4:643-655. Auburn University, Auburn, AL.

Burt, E.C., A.C. Bailey and R.K. Wood. 1987. Effects of soil and operational parameters on soil-tire interface stress vectors. *Journal of Terramechanics* 24(3):235-246.

Chapman, M.L., C.E. Johnson, R.L. Schafer and W.R. Gill. 1988. Some performance characteristics of disc gangs. *Journal of Agricultural Engineering Research* 39:1-7.

Crew, H. and A. de Salvio. 1914. *Dialogues Concerning Two New Sciences*. A translation of *Discourses and Mathematical Demonstrations concerning Two New Sciences pertaining to Mechanics and Local Motions* by Galileo Galilei. New York: Dover Publications, Inc.

Duncan, J.M. and C.Y. Chang. 1970. Nonlinear analysis of stress and strain in soils. *Journal of Soil Mechanics and Foundations Division, Proceedings of American Society Civil Engineers* 96(5):1629-1653.

Dunlop, W.H., G.E. Vanden Berg and J.G. Hendrick. 1966. Comparison of soil shear values obtained with devices of different geometrical shapes. *Transactions of the ASAE* 9(6):896-900.

Froelich, O.K. 1934. *Pressure Distribution in Foundation Soils*. Waterways Experiment Station. Vicksburg, MS.

Gill, W.R. and G.E. Vanden Berg. 1967. Soil dynamics in tillage and traction. *Agricultural Handbook* 316, USDA.

Grisso, R.D., C.E. Johnson, A.C. Bailey and T.A. Nichols. 1984. Influences of soil sample geometry on hydrostatic compaction. *Transactions of the ASAE* 27(6):1650-1653.

Grisso, R.D., C.E. Johnson and A.C. Bailey. 1987. Soil compaction by continuous deviatoric stress. *Transactions of the ASAE* 30(5):1293-1301.

Gupta, S.C. and R.R. Allmaras. 1987. Models to assess the susceptibility of soils to excessive compaction. *Advances in Soil Science* 6:66-100.

Koolen, A.J. and H. Kuipers. 1983. *Agricultural Soil Mechanics*. New York: Springer-Verlag.

Larson, W.E., S.C. Gupta and R.A. Useche. 1980. Compression of agricultural soils from eight soil orders. *Soil Science Society of America Journal* 44:450-457.

Lyne, P.W.L. and E.C. Burt. 1987. Real time optimization of tractive efficiency. ASAE Paper No. 87-1624. St. Joseph, MI: ASAE.

Murphy, G. 1946. *Advanced Mechanics of Materials*. New York: McGraw-Hill Book Co., Inc.

Nichols, T.A., A.C. Bailey, C.E. Johnson and R.D. Grisso. 1987. A stress state transducer for soil. *Transactions of the ASAE* 30(5):1237-1241.

Prevost, Jean H. 1987. Modeling the behavior of geomaterials. In *Geotechnical Modeling and Applications*, ed. S. M. Sayed. Houston, TX: Gulf Publishing Co.

Raper, R.L. and D.C. Erbach. 1988. Prediction of soil stresses using the finite element method. ASAE Paper No. 88-1017. St. Joseph, MI: ASAE.

Robbins, D.H., C.E. Johnson and R.L. Schafer. 1987. Modeling soil-metal sliding resistance. ASAE Paper No. 87-1580. St. Joseph, MI: ASAE.

———. 1988. Modeling soil-metal sliding resistance. AG ENG 88 Paper No. 88.196. Paris: International Conference on Agricultural Engineering.

Rogers, H.H. 1988. Personal communication. National Soil Dynamics Laboratory. Auburn, AL.

Rosenthal, D. 1974. *Resistance and Deformation of Soil Media*. New York: Pergamon Press.

Schafer, R.L., C.E. Johnson, M.L. Chapman and W.R. Gill. 1987. Disk spacing model for optimizing gang performance. ASAE Paper No. 87-1560. St. Joseph, MI: ASAE.

Soane, B.D. 1985. Traction and transport systems as related to cropping systems. In *International Conference on Soil Dynamics Proceedings* 5:863-935. Auburn University, Auburn, AL.

Soane, B.D., P.S. Blackwell, J.W. Dickson and D.J. Painter 1981a. Compaction by agricultural vehicles: A review. I. Soil and wheel characteristics. *Soil & Tillage Research* 1(3):207-237.

———. 1981b. Compaction by agricultural vehicles: A review. II. Compaction under tyres and other running gear. *Soil & Tillage Research* 1(4):373-400.

Soane, B.D., J.W. Dickson and D.J. Campbell. 1982. Compaction by agricultural vehicles: A review. III. Incidence and control of compaction in crop production. *Soil & Tillage Research* 2(1):3-36.

Soehne, W. 1958. Fundamentals of Pressure Distribution and Soil Compaction Under Tractor Tires. *Agricultural Engineering* 39:276-281.

Taylor, D.W. 1948. *Fundamentals of Soil Mechanics*. New York: John Wiley & Sons, Inc.

Taylor, J.H. and W.R. Gill. 1984. Soil Compaction: State-of-art report. *Journal of Terramechanics* 21(2):195-213.

Taylor, J.H. and E.C. Burt. 1984. Flotation tires and subsurface compaction. *Proc. of 8th International Conference of International Society of Terrain-Vehicle Systems* 2:751-759. Cambridge, England.

Tice, E.M. and J.G. Hendrick. 1986. Coulter operating characteristics. ASAE Paper No. 86-1535. St. Joseph, MI: ASAE.

Tice, E.M., R.L. Schafer and C.E. Johnson. 1987. Pressure distribution on the soil-coulter interface. ASAE Paper No. 87-1578. St. Joseph, MI: ASAE.

Vanden Berg, G.E. 1961. Requirements of a soil mechanics. *Transactions of the ASAE* 4(2):234-238.

Wood, R.K. and E.C. Burt. 1987a. Soil-tire interface stress measurements. *Transactions of the ASAE* 30(5):1254-1258.

———. 1987b. Thrust and motion resistance from soil-tire interface stress measurements. *Transactions of the ASAE* 30(5):1288-1292.