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

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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-machinery 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-machinery 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 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 qualitative 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-machinery 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 the 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 transformation (and consequences) of the resulting compaction state to the cropping system (the plant, the fluid and gaseous movements, and the biological and chemical actions).

The hierarchy of the relations 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-machinery behavior models which can be used in systems for effective management of soil physical condition for improving cropping systems. To achieve this goal, we have specific

REFERENCES


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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 models have been very difficult challenges for the complex agricultural soil-machinery 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 soil system 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 implicates 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 the 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 result when comparing methods of measuring soil structure 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 generally 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 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 real 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 the analytical capabilities in geomechanics now depends upon consistent mathematical formulations of generally valid and realistic material behavior.

Prevost further stated that a model must possess the following necessary characteristics:

1. The model shall be complete, i.e., able to make statements about the stress-strain response and strain paths, and not merely restricted to a single class of paths (e.g., axial symmetry or pure shear).
2. It should be based on realistic 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 unloading).

Characteristics 1 and 2 are highly desirable but may not always be possible to achieve. Realistically, with limited resources (e.g., time, money) 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 essential soil behavior 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 derived from curve fitting techniques. This approach, although sometimes valuable, does not include consideration of physical interpretations of material behavior. Thus, models contain assumptions that are not based on relationships that describe the soil in the field. Any application and often are not valid beyond the range and limits of the data used to develop them. As an example, a comprehensive description of the stress-strain behavior of soil is of the following form (Bailey and Vanden Berg, 1968; Larson et al., 1980; Gupta and Allmanna, 1987):

\[
(1/BD) = m \log_{10} b + h,
\]

where

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

Our purpose is not to criticize those that have used equation coding to describe soil response, but it is made about equation 1 with regard to Characteristic 3. First, \( a \) 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 valid for stresses that adequately describe both.

Further, the BD calculated from Equation 1 continues to increase as \( BD \) becomes large. But, we know that soil becomes rigid as the compaction stresses get very large. In this state, BD 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 stress-strain data well for a range of \( \sigma \) starting at about 150 kPa. Although equation 1 may fit compaction data over a stress range equal to or less than Vanden Berg and Vanden Berg (1961) considers the mean normal stress as the dominant stress controlling compaction. The general form of equation 1 is the same as a common soil constitutive model relationship 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 of soil mechanics for agricultural soils are inadequate for describing compaction of agricultural soils.

In early soil compaction modeling at Auburn, Bailey, and Vanden Berg (1961) considered the principal stress, and Vanden Berg (1961) considered the mean normal stress as the dominant stress controlling compaction. The general form of equation 1 is the same as a common soil constitutive model relationship 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 of soil mechanics for agricultural soils are inadequate for describing compaction of agricultural soils.

**Soil Compaction Behavior**

Gill (1987) 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-up, and cohesion loss (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 develop 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 exist over a wide 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 that are 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 approach is to develop the use of equations for soil compaction, 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 of the form of the model and the nature of the compaction stresses. Soil compaction in a Berg (1961) considered the mean normal stress as the dominant stress controlling compaction. The general form of equation 1 is the same as a common soil constitutive model relationship 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 of soil mechanics for agricultural soils are inadequate for describing compaction of agricultural soils.

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the compaction behavior of soil subjected to a hydrostatic stress state and then to include shearing stresses and loading paths in the model. Also, it was decided not to try to model the "universe" but to develop 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 Vander Roest (1975), the equation was modified for normal strains and presented by Bailey et al. (1986) as:

\[
\ln(V/V_0) = (A + B \varepsilon_0) - (1 - e_0) \varepsilon_0
\]

(2)

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\[ V_0 = \text{initial volume}, \]
\[ V = \text{volume}, \]
\[ \varepsilon_0 = \text{hydrostatic stress}, \]
\[ A, B, C = \text{compatibility coefficients}. \]

In terms of bulk density equation 1 becomes:

\[
\ln(BD) = \ln(BD_0) - (A + B \varepsilon_0) - (1 - e_0) \varepsilon_0
\]

(3)

where

\[ BD = \text{bulk density}, \]
\[ BD_0 = \text{bulk density at zero pressure}. \]

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 of stress loading paths. They were applied to obtain a maximum principal stress ratio (PSR) of 3.0. (Principal stress ratio is the ratio of the major principal stress to the minor principal stress). Grisso et al. (1987) modified equation 2 by including a multiplier factor, \( \beta \), which was a function of PSR, and by replacing \( \varepsilon_0 \) with \( \varepsilon_{oc} \), with octahedral normal stress \( \sigma_{oc} \). This equation was:

\[
\frac{\ln(V/V_0)}{V_0} = (A + B \varepsilon_0) - (1 - e_0) \varepsilon_0 + \Delta Y_{PSR}/\sigma_{oc}
\]

(4)

where \( \Delta Y_{PSR} \) is the stress strain at zero stress proposed by Bailey et al. (1984), was maintained in equation 6. However, equation 6 does not have an upper limit or compaction strain as shearing stress increases. When soil reaches maximum compaction (maximum density), it continues to strain at constant volume as shearing stresses are increased, a criterion of plastic flow. Equation 6 is valid only for the magnitudes of stress, 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:

\[
\sigma_{oc} = K \varepsilon_{oc}
\]

(7)

where \( K \) is stress values at maximum density, and \( \varepsilon_{oc} \) is 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. In addition, the appropriate value for the octahedral stress 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 II

Bailey and Johnson (1988) proceeded to develop further the model to use the results of 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 PSR to equation 2 and proposed a model of the form:

\[
\frac{\ln(V/V_0)}{V_0} = (A + B \varepsilon_0) - (1 - e_0) \varepsilon_0 + \Delta Y_{PSR}/\sigma_{oc} + D \varepsilon_{oc} + \gamma \varepsilon_{oc}^2
\]

(5)

where \( D = \text{coefficient for the component of normal volumetric strain due to shearing stress}. \)

The boundary maximum strain at zero stress proposed by Bailey et al. (1984), was maintained in equation 6. However, equation 6 does not have an upper limit or compaction strain as shearing stress increases. When soil reaches maximum compaction (maximum density), it continues to strain at constant volume as shearing stresses are increased, a criterion of plastic flow. Equation 6 is valid only for the magnitudes of stress, 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:

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The Deviatoric Stress Model: Phase III

Previous work (Bailey et al., 1984) demonstrated that the coefficients A, B, C, and D, 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 using 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 (\( \varepsilon_0 \) is constant), and compared with data from confined compaction tests. Models for unloading and reloading must also be developed to represent multiple pass vehicular traffic.

A System of Models

Several of these models are under development. A block diagram of an overview of the relationship 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 the 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 soil compaction (Soane et al., 1981, 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 precision of wheel-soil forces.

Propagating 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.
Boussinesq in 1883 (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. Forlisch (1980) extended the solution developed by Boussinesq for incorporating concentration factors. Soehne (1958) assigned different concentration factors for soils of different soil strength and calculated the stress state under a flat load. The most significant limitation of these approaches was the assumption that soil had linear-elastic material properties. Real 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 stress 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. This relationship was used for the tests 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 module and Poisson's ratio were calculated for each increment of load and for each element based on the current stress state of each element.

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

$$ E_T = \left[ \frac{d\Delta e}{d\Delta e} \right]^{-1} = \exp\left[(A+B\Delta e)(C+D\Delta e)^{-1}\right]^{-1} (B+e^{-1})(A+C\Delta e)$$

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

$$ \nu = \frac{\Delta e_x - \Delta e_y}{2\Delta e_z} $$

where $\Delta e_x = $ incremental axial strain, and $\Delta e_y = $ 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 SSSIs reported by Nipper 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 axi-symmetric load.

Good predictions of stress and strain distribution were obtained for most of the loading situations investigated by Raper and Erbach. They 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 (95%) and 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 linear-strain elements 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 material. 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 of and refinement of the finite element model will incorporate these advances.

**Modelling 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 soil must possess, the status of compaction modeling is as follows:

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

**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 developments of the model has been based on physical interpretations.

**Interacting with 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 our inability to describe soil compaction with respect to its impact 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 synonomous 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 characteristic 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 this 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 subsoil mechanized systems, including soil-force relationships (Chapman et al., 1988; Sacher et al., 1987; Tice and Hendrick, 1986; Tice et al., 1987). A block diagram of the relationship of the soil-machinery systems to cropping systems is shown in figure 4.

The forces exerted by many machines on the soil and the resulting stress-strain states 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 3** - Block diagram of the relationship of compaction and traction models to cropping systems.

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

**Figure 5** - Block diagram of the relationship of compaction and traction models to controlling traction systems.
REFERENCES
Froelich, O.K. 1934. Pressure Distribution in Foundation Soils. Watersways Experiment Station. Vicksburg, MS.