Soil Damage Models for Off-Road Vehicles

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ABSTRACT: Off-road vehicles such as ATVs, SUVs, dirt bikes, and hauling trucks cause damage to soft soils in unpaved areas within parks, forests, wetlands, and tundra. These vehicles can form deep ruts which result in destruction of vegetation, changes in water absorption/retention, and reduction in aesthetical land values. Large areas of particularly vulnerable soils are becoming increasingly common in northern regions, where permafrost is disappearing as a result of climate change. In this paper, theoretical models that predict the effect of material properties, wheel geometry, and wheel load on wheel penetration and rutting in cohesive soils are presented. The effects of tire flexibility are considered, as well. The models are approximate, yet predict similar response as that obtained from comprehensive numerical simulation.

INTRODUCTION

The growing usage of off-road vehicles (ORVs) like ATVs, dirt bikes, SUVs, and hauling trucks is resulting in damage to soil in parks, forests, and wetlands and stimulating growing societal concerns. Excessive use of these vehicles leaves scars to soil, visible as deepening grooves or ruts negatively affecting vegetation, water infiltration and runoff characteristics, and aesthetics. As a consequence of global climate change, the extent of frozen regions is decreasing and the depth of the permafrost active layer is increasing, exposing vast areas of soft, saturated or partly saturated soils for which bearing capacity is very low. Hauling trucks sink and become difficult to operate, and the land is destroyed.

Notwithstanding the significance of educational and regulatory efforts to minimize the negative impacts of ORVs, limited knowledge exists as to a quantifiable relationship between vehicle characteristics and the degree to which the soil is damaged. This paper is an attempt to arrive at such a relationship by proposing theoretical, soil mechanics-based models. The interaction between vehicle wheels and soil has been of interest in the field of terramechanics, as exemplified in a number of sources (cf. Bekker 1960; Wong 2001). Accurate prediction of rutting, however, has been of secondary importance in this field, and empirical methods predominate.

The objective of this paper is to relate the force exerted on a wheel to the depth to which the wheel sinks when being indented or rolled. The analysis is limited to wheels not transmitting torque, examples being towed wheels and front wheels of dirt bikes, trucks, and some ATVs. This paper is an extension of work on test rolling, a quality assessment technique used in road construction (Hambleton 2006; Hambleton and Drescher 2007, 2008). The results pertain only to purely cohesive soils, which are likely to be encountered in thawing northern regions of land where fine-grained soils may have large water content. Hambleton and Drescher (2008) include results for frictional/cohesive soils.

Modeling the problem of wheel-induced damage to soil is difficult, due primarily to the three-dimensional nature of the problem. The wheel is fully or partly surrounded by soil that is pushed forward and sideways, leaving a permanent, narrow rut and berms. Rigorous solutions to three-dimensional problems are very scarce, and two-dimensional approximations are often introduced. In the approach presented in this paper, the three-dimensional character of the problem is fully preserved, albeit several approximations are made. The models presented are semi-analytic and should be viewed as first approximations to more accurate predictions based on numerical simulations (Liu and Wong 1996; Chiroux *et al.* 2005; Hambleton 2006; Hambleton and Drescher 2007, 2008).

THEORETICAL MODELS

The theoretical models proposed are based on the assumption that indentation can be regarded as a sequence of plastic states in the soil, induced by an increasing load (force) on the wheel, equivalent to plastic states beneath shallow, rigid, rectangular footings. Likewise, rolling is regarded as a steady plastic state analogous to a footing with inclined loading. It is further assumed that the load can be evaluated by using the generalized bearing capacity equation of Meyerhof (1963), which is based on the well-known formula proposed by Terzaghi (1943). Meyerhof's approximate equation accounts for the depth and shape of a footing, as well as load inclination, by introducing depth, shape, and inclination factors. For frictionless soils with cohesion c and with the factors as in Das (2005), the equation becomes

$$q_u = \left(1 - \frac{2\beta}{\pi}\right)^2 \left[5.14c\left(1 + 0.19\frac{B}{L}\right)\left(1 + 0.4\frac{D}{B}\right)\right] \tag{1}$$

where q_u is the average ultimate stress acting on the footing, L is the footing length, $B < L$ is the footing width, $D < B$ is the embedment depth, and β is the load inclination angle. Soil unit weight is unimportant for very shallow footings in cohesive soil and is therefore disregarded.

Expression (1) gives the average stress acting over the footing-soil contact area. When applied to wheel indentation/rolling, proper choice of the contact area is the key aspect of the model. First, it is assumed that the contact region is rectangular, with the resulting force calculated as

$$Q = q_u BL \tag{2}$$

Next, the dimensions B and L are taken as corresponding to the projection of the wheel at sinkage s, with the latter defined as the vertical distance between the soil undisturbed by the wheel and the lowest point of the wheel (Fig. 1). As contributions of elastic (small) deformation are disregarded, the sinkage s is equivalent to rut depth.

Indentation

When the stiffness of a wheel is sufficiently large to prevent noticeable wheel deformation in relation to induced soil deformation, the wheel can be regarded as rigid. Highly inflated and stiff tires satisfy this condition (Bekker 1960), although their shape and tread arrangement differ significantly. In the following, the shape of tires is approximated by a right cylinder (Fig. 1).

For a rigid, right-cylindrical wheel, the contact length h is related to the wheel diameter d and sinkage s by

$$h = 2\sqrt{sd - s^2} \tag{3}$$

and the equivalent footing lengths B and L (see Fig. 1c) are

$$\left.\begin{matrix} B = h \\ L = b \end{matrix}\right\} \text{ for } h \le b \ ; \quad \left.\begin{matrix} B = b \\ L = h \end{matrix}\right\} \text{ for } h > b \tag{4}$$

where b is the width of the wheel. The volume displaced by the indented wheel V, and the resulting depth of the uplifted material D, can be approximated by

$$V = 2bhD \ ; \ D = \frac{s}{6} \tag{5}$$

Eqs. (3)-(5) are substituted into Eqs. (1) and (2) to find that the vertical indentation force, denoted Q_V, is given as a function of s, b, d, and c by

$$Q_V = 10.28bc\sqrt{ds - s^2}\left(1 + 0.39\frac{\sqrt{ds - s^2}}{b}\right)\left(1 + \frac{0.03s}{\sqrt{ds - s^2}}\right) \text{ for } 2\sqrt{sd - s^2} \le b \tag{6a}$$

$$Q_V = 10.28bc\sqrt{ds - s^2}\left(1 + \frac{0.1b}{\sqrt{ds - s^2}}\right)\left(1 + 0.07\frac{s}{b}\right) \text{ for } 2\sqrt{sd - s^2} > b \tag{6b}$$

When the wheel is flexible, its deformation depends on how the soil deforms. The sinkage, too, is therefore affected. The problem is coupled and cannot be solved accurately without knowing the inflation pressure and deformability characteristics of the tire itself, with the latter often being proprietary. Motivated by the work of Fujimoto (1977), Karafiath and Nowatzki (1978), and Qun *et al.* (1987), a simplified approach is proposed, in which the shape of the portion of the tire in contact with the

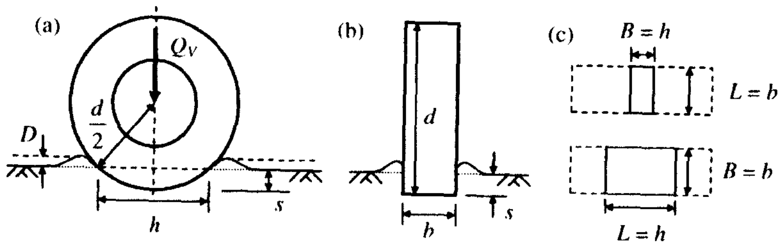

FIG. 1. Schematic of rigid wheel indentation: (a) cross section in plane of wheel diameter; (b) cross section in plane of wheel width; (c) evolution of contact area.

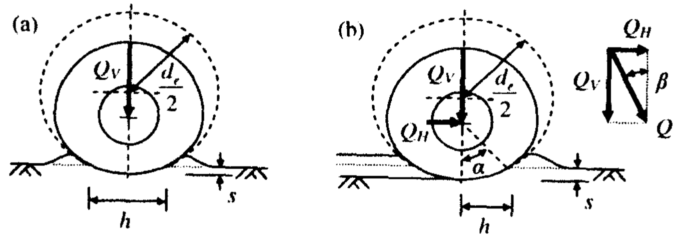

FIG. 2. Schematic of flexible wheel: (a) indentation; (b) rolling.

soil is approximated by a circle of diameter d_e larger than the tire diameter d (Fig. 2). It is assumed that flattening of the wheel only affects the contact length h.

A linear relationship is postulated between the diameter d_e and d

$$d_e = d + \lambda_i Q \tag{7}$$

where λ_i, is the wheel flexibility coefficient; $\lambda_i = 0$ implies a rigid wheel. One can expect that λ_i decreases with increasing inflation pressure, increasing carcass stiffness, or decreasing soil strength. The resulting length of contact is then

$$h = 2\sqrt{d_e s - s^2} = 2\sqrt{s(d + \lambda_i Q) - s^2} \tag{8}$$

With h as in Eq. (8), the resulting expressions for Q_V in the flexible wheel case are

$$Q_V = 10.28bc\sqrt{s(d + \lambda_i Q_V) - s^2}\left(1 + 0.39\frac{\sqrt{s(d + \lambda_i Q_V) - s^2}}{b}\right) \times \left(1 + \frac{0.03s}{\sqrt{s(d + \lambda_i Q_V) - s^2}}\right) \text{ for } h \le b \tag{9a}$$

$$Q_V = 10.28bc\sqrt{s(d+\lambda_i Q_V)-s^2}\left(1+\frac{0.1b}{\sqrt{s(d+\lambda_i Q_V)-s^2}}\right)\left(1+0.07\frac{s}{b}\right) \quad \text{for } h>b \tag{9b}$$

As a reflection of the coupling between wheel deformation and soil deformation in the flexible wheel case, Eqs. (9a) and (9b) are implicit with respect to Q_V.

Rolling

In the steady state of rolling, the contact area is reduced, and the total force Q is inclined at angle β. The angle β is assumed to bisect the angle α subtending the arc of the wheel in contact with the soil (Fig. 2b). This assumption is supported by experimental results (Onafeko and Reece 1967), which indicate that the distribution of normal contact stresses is close to symmetrical and that of the shear stresses is roughly antisymmetrical. The deformability of the wheel is modeled by (7), with the coefficient λ_i replaced by λ_r, as the apparent flexibility of a wheel in rolling is, in general, different than in indentation. The resulting expression for β is then

$$\beta = \frac{\alpha}{2} \approx \sqrt{\frac{s}{d_e}} = \sqrt{\frac{s}{d+\lambda_r Q}} \tag{10}$$

The contact length h is assumed to be half of that for indentation, resulting in the expression

$$h = \sqrt{d_e s - s^2} = \sqrt{s(d+\lambda_r Q)-s^2} \tag{11}$$

Combining Eqs. (1), (2), (4), (5), (10), and (11) results in the following expressions for the inclined force Q in the case of a rolling, flexible wheel:

$$Q = 5.14bc\sqrt{s(d+\lambda_r Q)-s^2}\left(1+0.19\frac{\sqrt{s(d+\lambda_r Q)-s^2}}{b}\right)\left(1+\frac{0.07s}{\sqrt{s(d+\lambda_r Q)-s^2}}\right) \times\left(1-0.64\sqrt{\frac{s}{d+\lambda_r Q}}\right)^2 \quad \text{for } h\le b \tag{12a}$$

$$Q = 5.14bc\sqrt{s(d+\lambda_r Q)-s^2}\left(1+0.19\frac{b}{\sqrt{s(d+\lambda_r Q)-s^2}}\right)\left(1+0.07\frac{s}{b}\right) \times\left(1-0.64\sqrt{\frac{s}{d+\lambda_r Q}}\right)^2 \quad \text{for } h>b \tag{12b}$$

Again, expressions (12a) and (12b) are implicit in Q; however, both Q and its vertical component $Q_V = Q\cos\beta$ can be easily calculated numerically.

DAMAGE/RUTTING PREDICTIONS

The theoretical models presented allow for construction of response curves relating wheel sinkage/rut depth to the weight (Q_V) exerted on a wheel. To demonstrate the correctness of the models, a comparison is made in Fig. 3a with results from three-dimensional numerical simulation using the finite element code ABAQUS. The numerical simulations were performed as described in Hambleton (2006) and Hambleton and Drescher (2007). A three-dimensional wheel declared as an analytical, rigid body was indented, or rolled under the condition of constant wheel weight, on an elastoplastic soil bed defined by the von Mises material model. Elastic properties in the simulations were such that elastic effects could be considered negligible. Frictional interaction was declared on the soil-wheel interface.

Fig. 3a compares the sinkage-weight response from ABAQUS with Eqs. (6) and (12), using the dimensionless quantities s/d and Q_V/cd^2. Numerical results for rolling are given as discrete points corresponding to sinkage at steady state under constant weight. The qualitative agreement between the formulas and the numerical results is surprisingly good, given the approximate nature of the analytic approach. Clearly, the response curves are strongly nonlinear (roughly quadratic), and it is evident that for a given wheel weight, rolling results in much greater sinkage than indentation.

Fig. 3b gives the theoretical predictions of sinkage as a function of wheel weight, in indentation and rolling, for a wheel with a size representative of those on SUVs and light trucks operating on a medium consistency soil (c = 50 kPa). For such a wheel size and soil type, Figs. 4 and 5 reveal how sinkage is affected by changes in cohesion, flexibility, and wheel geometry. Results are shown for two weights: 6 kN and 10 kN. The former might represent an empty full-sized SUV or truck, and the latter may be the same vehicle carrying cargo.

Fig. 4a plots sinkage against cohesion (holding b, d, and Q_V fixed) for the case of a rolling, rigid wheel, showing that sinkage increases rapidly when the cohesion is low; again, the relationship is strongly nonlinear. Fig. 4b shows sinkage versus the wheel flexibility coefficient λ_r (holding b, d, and Q_V fixed). Flexibility of the wheel clearly reduces sinkage, which agrees with a well-known fact that deflated tires are less prone to sinking. Fig. 5 similarly plots the variation in sinkage with changing wheel diameter and width. Expectedly, a decrease in the wheel diameter increases the sinkage, and narrow wheels sink more than wide.

CONCLUSIONS

As demonstrated in the paper, the theoretical models proposed capture the expected dependence of soil damage, identified as sinkage/rut depth, on soil strength and wheel weight, geometry, and flexibility. By incorporating the varying contact area and shape factors, the models account for three-dimensionality of the wheel-soil interaction. The results presented are limited to wheels whose geometry can be approximated by a right cylinder, which seems warranted for SUV and hauling truck tires. As shown in Hambleton (2006), the models can be extended to toroidal tires, such as those used on ATVs and dirt bikes, by modifying the prescription for how the contact area at the soil-wheel interface evolves with sinkage.

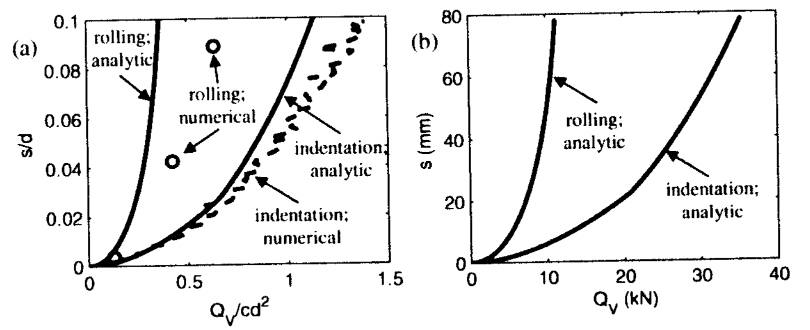

FIG. 3. Sinkage *vs* weight for indenting and rolling rigid wheels: (a) dimensionless analytic and numerical results; (b) dimensional analytic results for b = 0.26 mm, d = 0.78 m, and c = 50 kPa.

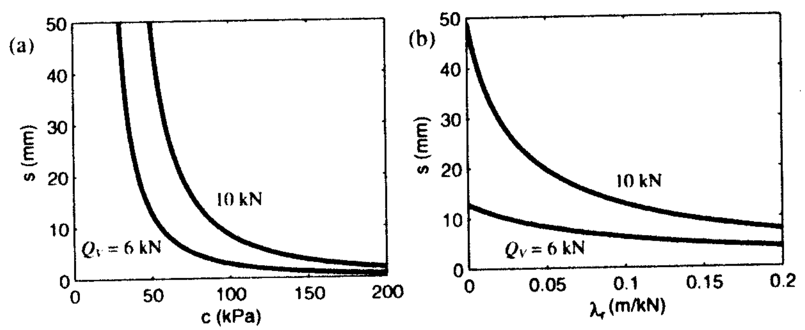

FIG. 4. Sinkage of rolling wheel (b = 0.26 m and d = 0.78 m) for varying (a) cohesion (λ_r = 0) and (b) varying wheel flexibility coefficient (c = 50 kPa).

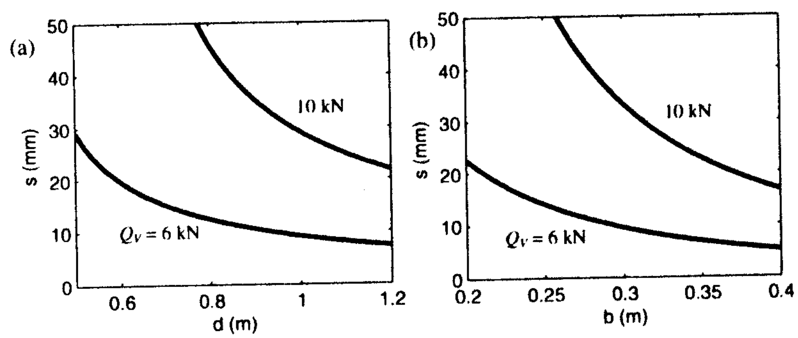

FIG. 5. Sinkage of rolling, rigid wheel (c = 50 kPa): (a) effect of diameter (b = 0.26 m); (b) effect of wheel width (d = 0.78 m).

The models are approximate; however, numerical studies support the findings. Improvements to the approach leading to better agreement are discussed in Hambleton (2006) and Hambleton and Drescher (2008). With proper improvements, the theoretical models have potential to form the basis for load restrictions and appropriate tire selection for minimizing the negative impacts of off-road vehicles.

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