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Geotechnics and Terramechanics

A. Drescher and J.P. Hambleton
Department of Civil Engineering, University of Minnesota, Minneapolis, Minnesota

ABSTRACT: Links between geotechnics (geotechnical engineering) and terramechanics are discussed. Albeit both subjects deal with similar materials, the former became a recognized branch of engineering much earlier than the latter. Terramechanics concentrates on the interaction of tools (wheels, tines) and soil or snow, with emphasis on analyzing and modeling processes characterized by very large deformations. In geotechnics, the deformations are usually small, or of limited interest, and critical states rather than processes attract engineering attention. Common areas exist, however, with an example being material properties evaluation for vehicle mobility and adequacy of field compaction, and greater interaction benefitting both disciplines gradually emerges. This is demonstrated by the similar analytic and numerical tools used in geotechnics and terramechanics, with the well-known bearing capacity theories and finite element methods occupying a central role. The material models used are also similar. The potential exists to embark on joint efforts to analyze, model, and prevent soil distress in environmentally sensitive areas of deserts, forests, and tundra where off-road vehicles may induce significant damage.

1 INTRODUCTION

With no claim as the origin, one can find the term geotechnics in a classical book of Krynine and Judd (1957). Its use appears to be common in Europe and the UK in particular, exemplified by the title of the leading journal *Geotechnique*. In the US, the term geotechnical engineering is found much more frequently, and it appears in the internationally renowned *Journal of Geotechnical and Geoenvironmental Engineering ASCE* as well as in the titles of many academic texts and conference proceedings. In the following, the term geotechnics is used for its brevity.

Geotechnics encompasses an enormous variety of problems related to the design, construction, and operational safety of civil structures placed on soils (foundations), interacting within soils (culverts, tunnels), or made of soils (embankments, slopes). The three-phase nature of soils (gas-air, liquid-water, and solid-skeleton) makes their mechanical behavior exceedingly complex. The presence of water affects many problems *via* undesirable pore-pressure buildup (liquefaction), growths of settlements in time (consolidation), or flow-induced erosion and loss of stability (dams). In solving geotechnical problems soil mechanics plays a fundamental role, and its finding confronted with vast empirical experience and data banks make engineering solutions possible and successful. K. Terzaghi (1883–1963) can be credited with the onset of modern soil mechanics (Terzaghi 1943), and he greatly stimulated its progress.

Terramechanics became a recognized field of engineering with the emergence in 1964 of the *Journal of Terramechanics*. Originally, with strong links to mechanical engineering, the emphasis of terramechanics concentrated on the interaction of wheeled and tracked civilian and military vehicles with soil and snow. Presently, the interests also include the interaction of the variety of farming tools (tines) and earth-moving parts (blades, buckets) of bulldozers and backhoes. The interest expands even further, beyond the earth, by including analysis and design of planetary rovers (Fig. 1). Likewise in geotechnics, the complexity of soil (and snow) behavior affects the methods and solutions of terramechanics problems, and M.G. Bekker (1905–1989) can be recognized as father of their rational analysis and design (Bekker 1969).

2 DIFFERENCES AND SIMILARITIES

The differences between geotechnics and terramechanics begin with methods of material testing. In geotechnics, both the laboratory and field testing play significant role in determining soil physical and mechanical properties. Among the laboratory tests, the basic physical tests (gradation, consistency limits), and the triaxial compression, direct shear, and one-dimensional (oedometric) compression provide ample information on the type of soil as well as its strength and deformability. These are supplemented by permeability tests for evaluating soil hydraulic conductivity. In the field, the various types of penetration tests (SPT, DCP) combined with sample extraction are indispensible for assessing the type of soil and spatial variation in mechanical parameters.

In terramechanics, the objective of determining parameters for vehicle mobility prediction is realized predominantly through field tests. The basic field test is the bevameter test, which makes use of two devices (Fig. 2). The first device involves rotating a ring-plate and measuring the corresponding torque as a function of vertical load and angular displacement of the plate. In the second, a rectangular plate is gradually pressed into the soil in the vertical direction, and vertical load on the plate as a function of penetration (sinkage) is recorded. The response curves obtained from these tests are used to determine three parameters that characterize empirically-based relationships between wheel load and wheel sinkage. Although two of the parameters (k_c and k_ϕ) appear to be related to the friction angle and cohesion, there is no clear connection to these fundamental strength parameters. Another field test makes use of the cone penetrometer, from which the cone index is determined. However, this test utilizes different cone angle compared to DCP, and instead of applying impact load, the load is increased gradually.

Geotechnics and terramechanics also differ in spatial (geometric) domain of their interests. In geotechnics, the domain ranges from shallow to deep deposits, and knowledge of geological history and variability of properties are absolutely essential. In terramechanics, the focus is on the soil or snow layer next to the surface, and depth-related variation in properties is usually of little or no importance.

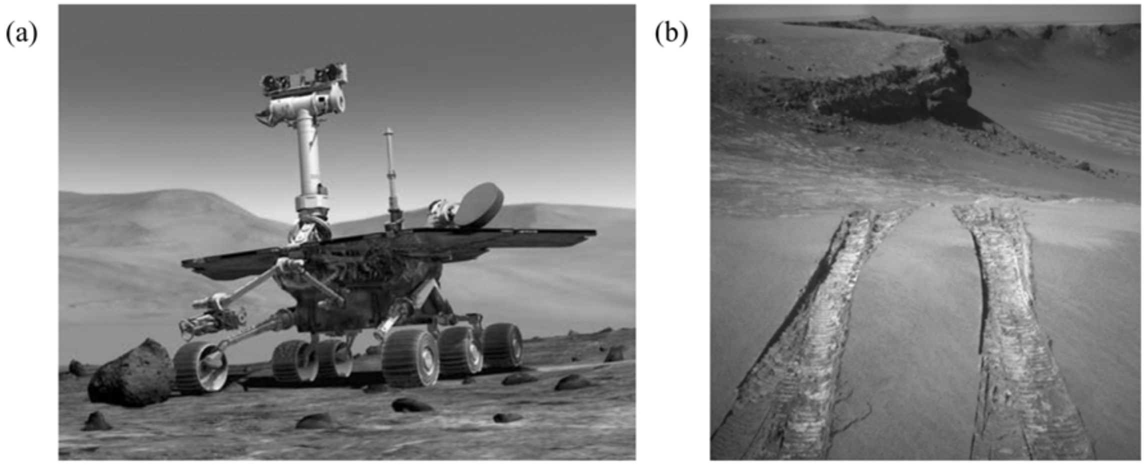

Figure 1. (a) Artist's rendering of a Mars Exploration Rover; (b) ruts left by Mars rover Opportunity near the Victoria Crater. Image credit: NASA/JPL-Caltech.

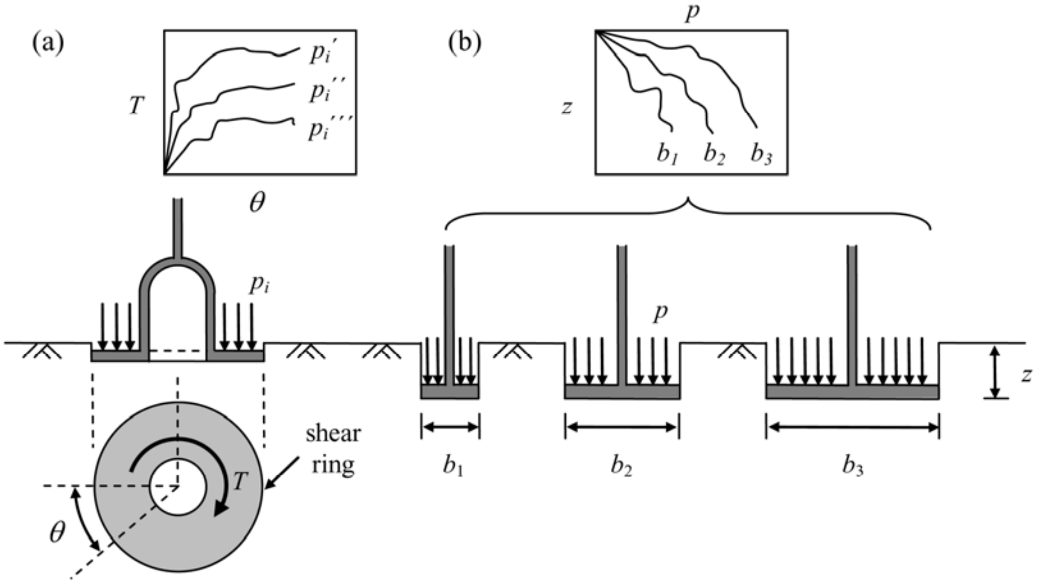

Figure 2. Bevameter tests: (a) ring rotation; (a) plate indentation.

There is yet another significant difference, and it pertains to the emphasis in geotechnics placed on final (critical) *states* rather than *processes*, as considered in terramechanics. Here, application of the term "critical" reflects states that are important in usage and safety of a civil structure, examples being immediate and long-term acceptable settlements of buildings, assessment of earth and rock slopes failures, or guaranteed retention of water in upstream reservoirs. Dealing with states circumvents the question of how a critical situation is reached and focuses attention on what characterizes the critical situation, whether it can occur or not, and how it can be prevented. In particular, the whole history of stresses and strains up to the critical state can in many cases be disregarded. An example is the limit equilibrium approach to analyzing stability of slopes (methods of slices) and retaining walls (Rankine and Coulomb theories), or bearing capacity of foundations (Terzaghi/Mayerhof formulae), Fig. 3a. In all these examples the critical state is evaluated without the actual knowledge of corresponding strains. In other problems considering small strains is sufficient and fully acceptable.

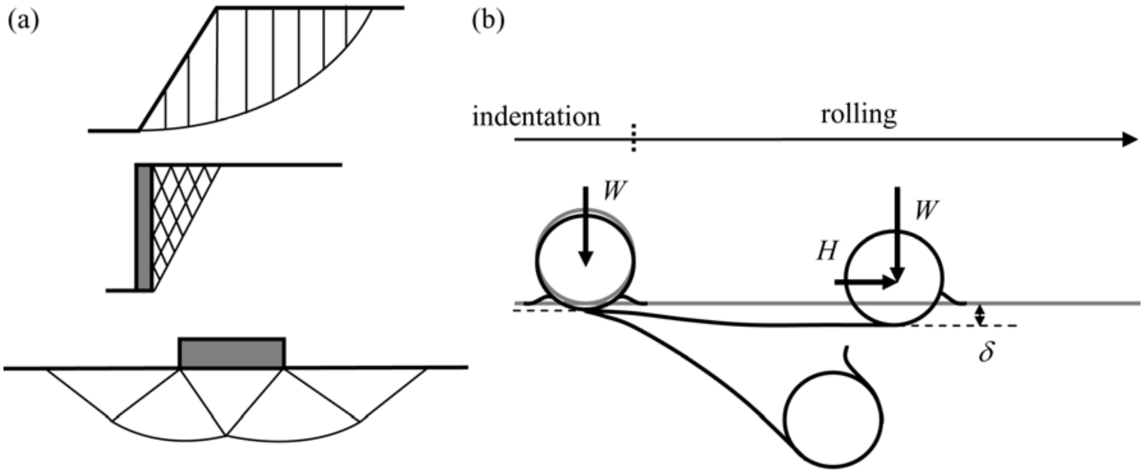

Figure 3. (a) Critical failure states in geotechnics; (b) wheel indentation and rolling processes.

In terramechanics, the essence of the analysis and design derives from considering the interaction between a wheel or tool and soil (snow) as a temporal or steady process, Fig. 3b. If temporal, the interaction has its origin (placement of a vehicle on soil, turning on the wheels), and it progresses in time. In a mechanistic approach, knowledge of the stresses and strains at each stage of this process is essential for evaluating the feasibility and efficiency of the process. Even if only the final, steady state is of interest, its form often cannot be correctly predicted without considering the preceding history of stresses and strains. In both cases, the deformation (strains) may be very large.

In spite of all the differences listed, the factor that strongly links both disciplines is the dominant material – soil. Whichever approach is used, be it mechanistic or empirical, the properties of soils profoundly affect the outcome of the analysis and design. In the mechanistic approach, the soil mechanical properties must be known to arrive at a reasonable and physically sound result. The mechanical properties alone are insufficient, however, and a rational methodology that does not violate the basic principles of mechanics must be utilized. More specifically, a particular approximate or rigorous theory of the mechanics of soils must be used. In general, in geotechnics, the theory of elasticity or poroelasticity is used when small deformations are of interest and the theory of plasticity when failure is of importance. In terramechanics some analyses concentrate on small elastic strains, with plastic or elasto-plastic theories dominating and indeed necessary for accurate evaluation of processes.

Both fields of engineering use rigorous and approximate analytic methods. Numerical methods are becoming more popular, however, for they provide more detailed and more accurate information. Application of both methods to a problem of interest to terramechanics and to geotechnics is discussed in the next section.

3 ROLLING OF A WHEEL

Rolling of a wheel on a deformable soil is a classical, if not the fundamental, problem in terramechanics, and has been extensively researched using field and laboratory experiments as well as theoretical methods. Of interest is relating the force and moment applied to a rolling wheel to the wheel's penetration (sinkage), denoted here by δ. Two particular cases can be distinguished: a wheel that is pulled or pushed without applying any torque and a torque-driven wheel. In both cases there are vertical and horizontal forces, denoted W and H respectively, acting on the wheel and transmitted onto the soil (Fig. 3b), where vertical force W exists due to vehicle weight. The wheel may or may not slip along the soil surface. If the applied vertical force is excessive, the wheel may burry itself, and for excessive torque the wheel may spin without lateral motion.

The wheels of vehicles and earth moving machinery differ significantly in size and to a lesser extend in shape. A right cylinder is often used to approximate the wheel's shape, albeit toroidal shapes have also been considered. Most wheels are deformable (pneumatic tires) but assuming perfect rigidity in many cases leads to insignificant if not small errors, especially on soft soils. A factor that may have profound effect on test or analysis results is the wheel aspect ratio, i.e., the ratio of the width b to diameter d (or radius r). If this ratio is large (drum rolling), a plane strain condition is typically assumed, and the analysis is two-dimensional. For a small aspect ratio, three-dimensionality of the induced deformations and stresses cannot be disregarded. Unfortunately, three-dimensional analyses are very difficult or even impossible to perform, and they are very rare and often controversial.

An approach that offers the possibility of theoretically analyzing three-dimensional wheel indentation and rolling with reasonable confidence and rigor is the finite element method (FEM), with first attempts reported by Chiroux et al. (2005). As the deformations in a rolling process are large, explicit (dynamic) versions of FEM appear to be better suited than implicit methods. To account for the formation of ruts by a rolling wheel, simple elastic soil models must be replaced by more involved elasto-plastic models. There is a plethora of elasto-plastic models for soils and choosing a right one is a subject of discussion. A physically and practically reasonable approach is to consider a simplified elasto-plastic model that captures the most essential features of soil behavior yet involves a few parameters that are relatively easy to determine. A model that satisfies these requirements is the elastic-perfectly plastic model, commonly employed in solving numerically a variety of stability and bearing capacity problems (Fig. 3a). This model requires knowledge of five parameters: Young's modulus and Poisson's ratio, cohesion, friction angle and dilatancy angle (the last two angles often are taken as equal in geotechnics).

Figure 4 shows an example of extensive numerical simulations conducted by the authors (Hambleton and Drescher 2009a) using the FEM code ABAQUS/Explicit. The soil is purely cohesive (saturated clay) with cohesion c = 67 kPa, and the wheel is towed/pushed (no torque). The simulation involves a wheel with b = 0.3 m, r = 0.5 m loaded by a constant vertical force W = 10 kN representing the weight on the wheel of a truck. Figure 4a illustrates the formation of a rut, side berms, and front bow. Figure 4b depicts the variation of the horizontal force with horizontal distance, u, of the traveling wheel, and it illustrates the development of a steady state at which the horizontal force is constant. Detailed information on the strains and stresses in the soil beneath and around the wheel can be obtained, and they are not presented here. Similar simulations for different aspect ratios allowed for constructing graphs (Fig. 5) useful for assessing wheel penetration and horizontal force as a function of applied wheel weight (Hambleton and Drescher 2009b).

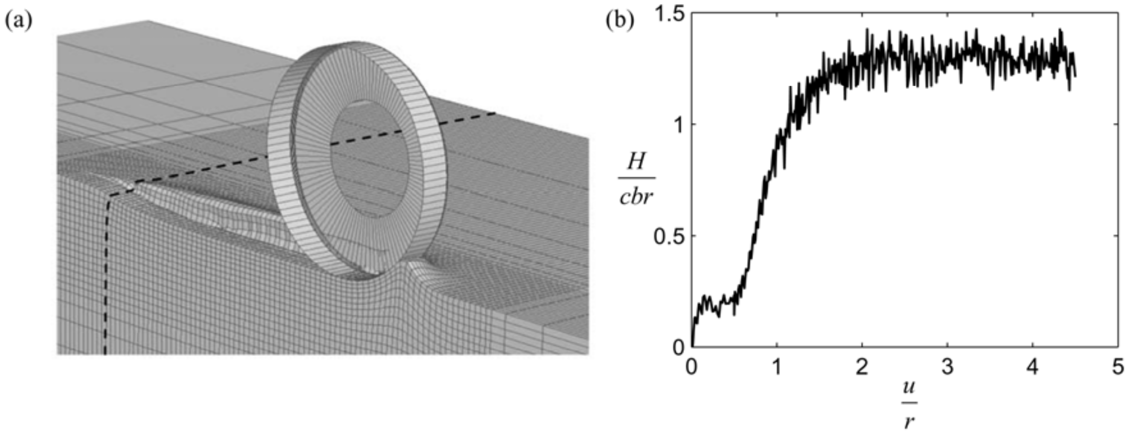

Figure 4. (a) Example of three-dimensional numerical simulation using ABAQUS (plane visible in lower left is the plane of symmetry—the midplane of the full three-dimensional configuration); (b) normalized horizontal force versus horizontal displacement.

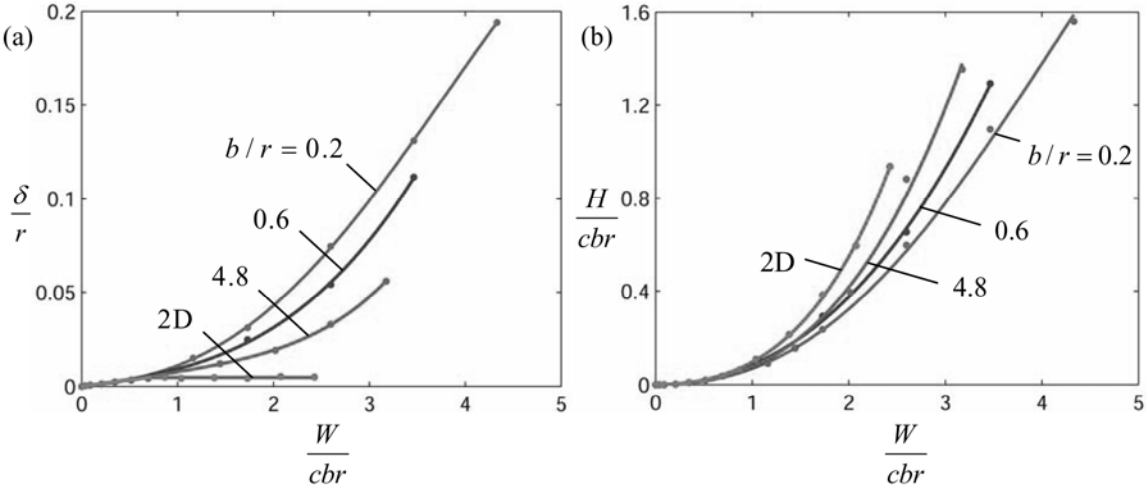

Figure 5. Normalized (a) penetration and (b) horizontal force versus normalized wheel weight for steady-state rolling on cohesive soil. Each curve corresponds to a different wheel aspect ratio, and two-dimensional (2D) results based on the assumption of plane strain are also shown.

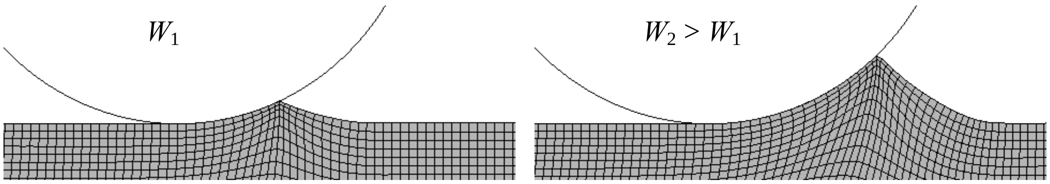

Figure 6. Steady-state configurations from two-dimensional analysis on cohesive material showing zero penetration

A somewhat surprising result was obtained when the wheel width became very large, and the process could be modeled as two-dimensional. In this case, after initial penetration the wheel moves upwards and rolls at steady state at the level of undisturbed soil (Fig. 6). In other words, disregarding very small elastic deformations, there is no wheel penetration and no permanent vertical displacement behind the rolling wheel, and the volume of the steady bow in front of the wheel equals the volume of material displaced during the initial indentation phase. Qualitatively similar results were obtained for frictional/cohesive soils, and they could not be readily anticipated without conducting numerical simulations. It should be stressed, however, that the soil model assumed prohibits compaction. Incorporation of this effect via cap plasticity models is possible and is presently being investigated.

Application of FEM to the wheel rolling process, while enlightening and valuable, may appear difficult and somewhat cumbersome for direct practical applications. An alternative is to introduce simplifications that allow for constructing an approximate analytic solution. Such an approach has been demonstrated by the authors (Hambleton and Drescher 2009a). In this approach, the steady state of rolling of a narrow wheel (small aspect ratio when a rut is present) was modeled as the problem of bearing capacity of a one-side embedded rectangular foundation. The magnitude of the inclined force then is determined from the generalized bearing capacity formula of Mayerhof (1963) accounting for inclination of the footing. This allows for relating the vertical force W (weight on wheel) to penetration δ. An example of the lengthy yet straightforward expressions resulting from this approach is

$$\begin{aligned}
W = b\sqrt{2r\delta}\cos\left(\sqrt{\frac{\delta}{2r}}\right)\Bigg\{ & cN_c\left(1+\frac{\sqrt{2rs}}{b}\frac{N_q}{N_c}\right)\left(1+0.07\frac{\delta}{\sqrt{2r\delta}}\cos\left(\sqrt{\frac{\delta}{2r}}\right)\right)\left(\frac{N_q e^{-2\sqrt{\frac{\delta}{2r}}\tan\varphi}-1}{N_q-1}\right) \\
& +\left[0.17\gamma\delta N_q\cos\left(\sqrt{\frac{\delta}{2r}}\right)\left(1+\frac{\sqrt{2r\delta}}{b}\tan\varphi\right)\left(1+0.33\tan\varphi(1-\sin\varphi)^2\cos\left(\sqrt{\frac{\delta}{2r}}\right)\frac{\delta}{\sqrt{2r\delta}}\right)\right. \\
& \left.+\gamma\sqrt{2r\delta}N_\gamma\left(0.5-0.2\frac{\sqrt{2r\delta}}{b}\right)\right]\left[1-\tan\left(\sqrt{\frac{\delta}{2r}}\right)\right]^2\Bigg\}
\end{aligned}$$

where γ is the unit weight, c is the cohesion, φ is the friction angle, and N_q, N_c, and N_γ are the well-known bearing capacity factors. When compared with the results of numerical simulation using FEM, a satisfactory agreement was observed (Hambleton and Drescher 2009a). It is worth mentioning that curves with a similar shape derive from empirical expressions favored in terramechanics (Bekker 1969).

The overall findings of numerical and analytic studies indicate that sinkage is approximately inversely proportional to the width of the wheel for sandy soils and inversely proportional to the width squared for cohesive soils. For both types of soil, sinkage is nearly inversely proportional to wheel diameter, which implies for fixed wheel force a two-fold increase in sinkage with either soil when wheel diameter is reduced by half.

The analysis of torque-free wheel rolling has direct application in assessing quality of subgrade compaction for construction of roads. In fact, the research and results described above were stimulated by open questions related to the test rolling procedure employed in Minnesota, with detailed results reported in (Hambleton and Drescher 2008a,b). As the formation of permanents ruts behind the wheel (Fig. 1b) is a manifestation of plastic deformation related to strength rather than soil elasticity, the test rolling field experiment is a valuable technique for soil strength determination. More specifically, results of numerical and approximate analytic solutions curves can be used to relate friction angle and cohesion to the observed penetration for given wheel load and geometry (Fig. 7). It then follows that test rolling, or a specifically designed test, can be regarded as a method for obtaining a continuous log of soil strength over large areas. This offers an alternative to local strength determination based on the use of penetrometers, and such applications certainly fall within the area of geotechnics.

4 LAND DAMAGE

An area where closer ties can develop between terramechanics and environmental geotechnics is land damage in deserts, forests, and tundra. The last few decades have witnessed explosion in off-road vehicles (ORVs) for commercial and recreational use. Hauling trucks, all terrain vehicles (ATVs), trail (dirt) bikes, and sand buggies, when used carelessly become a source of permanent and detrimental changes to the soil surface, thereby reducing the economic and societal value of the land. The main cause for these changes is the stripping of organic matter and vegetation, characterized by formation of permanent ruts induced by rolling and spinning wheels (Webb an Wilshire 1983). Vegetation provides strengthening (reinforcement) of the top layer of soil, and its disappearance exposes the soil to wind and water erosion. Ruts affect aesthetics and vehicle safety in recreational areas (Fig. 8a). In open and arid regions, ruts channel water during spring run-offs and increase flow velocity and soil erosion. Fine particles can be carried a long distance, causing siltation in lakes and ponds. In forests, ruts expose tree roots, collect water, and make logging and recreational roads impassable.

Areas that are particularly sensitive to damage from ORV traffic are tundra and permafrost regions, as thawing of permafrost in northern regions (Fig. 8b) leaves terrain particularly vulnerable to ORV traffic (Abele et al. 1984, Slaughter et al. 1990). After thawing, the top soil is weak and often saturated with water, and a rolling wheel may easily damage the vegetation and produce deep ruts. In some areas, the presence of shallow permafrost protects the soil from rutting. However, a substantial active (top) layer, which undergoes seasonal freezing/thawing cycles, reduces the ability of the soil to sustain wheel loads and resist rutting.

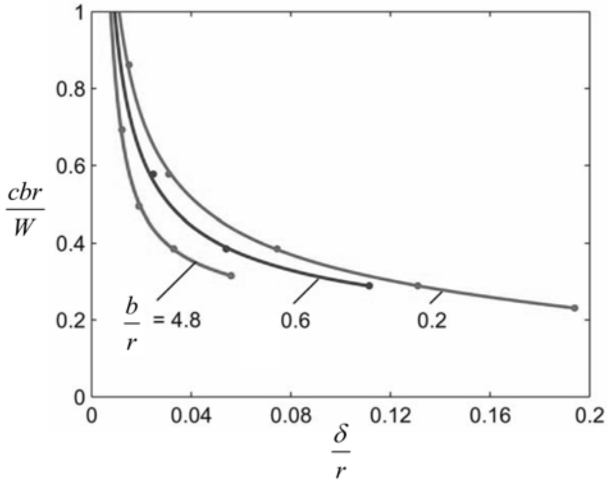

Figure 7. Relationship between normalized cohesion and steady-state penetration of a rolling wheel in cohesive soil, determined from numerical simulations.

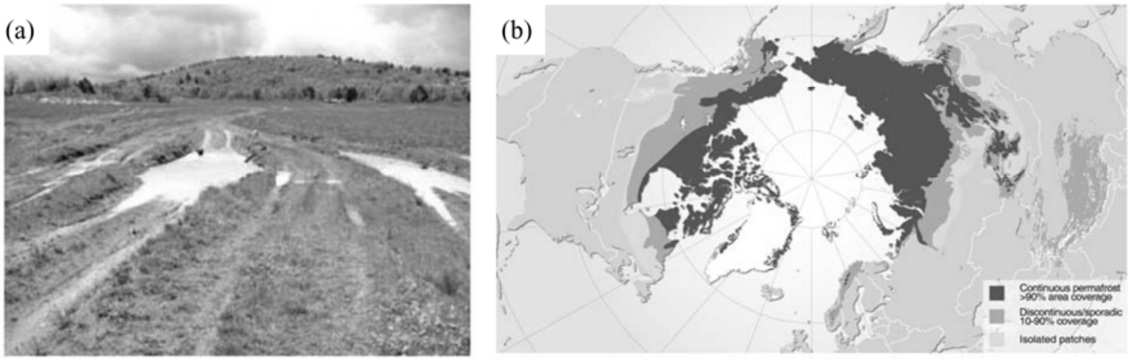

Figure 8. (a) Region in the Wasatch-Cache National Forest (Utah) with land damage caused by ORVs Photo credit: Dan Schroeder, Ogden Sierra Club. (b) Map of permafrost, which exists in 24% of exposed land area in the Northern Hemisphere. Credit: Hugo Ahlenius, UNEP/GRID-Arendal.

The negative impact of ORVs has been long recognized, and regulatory laws have been enacted or are being discussed. Missing is a mechanistic approach for understanding rut formation in sensitive areas. Only empirical approaches, or methods which are mostly descriptive and devoid of technical data, have been promulgated so far. As discussed elsewhere by the authors (Hambleton and Drescher 2008c), it appears that expanding the approaches illustrated in the previous section could contribute to a better understanding of the mechanics of rut formation. This would allow for formulating better guidelines on the design and use of ORVs.

5 CLOSING REMARKS

As with every field of engineering, links exists between geotechnics and other areas. As discussed in this paper, a particularly valuable connection may be made to terramechanics. In-situ strength evaluation and prevention of land damage are examples of potential interest. The latter seems particularly important, as it pertains to vast areas in many countries and its significance rapidly increases.

Findings presented in this paper for the wheel rolling process are theoretical (numerical and analytical) in nature, although small scale experiments that support these results also have been conducted (Hambleton and Drescher 2009b). Even though the results are preliminary, they are encouraging and provide a rational mechanistic approach that can be applied as a basis for improved or novel in-situ strength evaluation methods. It is evident that plastic deformations related to soil strength contribute greatly to wheel penetration and the formation of permanent ruts; however, the effect of additional soil compaction should be investigated.

ACKNOWLEDGEMENTS

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