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Comparison of SPH simulations and cone index tests for cohesive soils

Christopher Goodin *, Jody D. Priddy

Geotechnical and Structures Laboratory, U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, USA

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Abstract

The cone penetrometer test has been used for decades to quantify the soft soil mobility performance of ground vehicles. As physics-based methods for modeling soil are developed, it is necessary to validate these simulations against databases relating Cone Index (CI) to vehicle mobility. However, in order to make this comparison, the relationship between the engineering properties of the soil (density, bulk modulus) and the cone index must be determined. To that end, in this work, simulations of cone penetrometer tests in cohesive soil using the smoothed particle hydrodynamics (SPH) method are presented. Three dimensional simulations were conducted and compared to laboratory measurements of cone index in soft soil. The SPH model is parametrized using the elastic moduli of the soil (bulk and shear modulus), the soil density, and the soil cohesion. A novel method which includes skin friction is employed to calculate the forces exerted on the cone tip by the soil. The simulations give good agreement with the measurements, with a coefficient of determination $R^2 = 0.76$. These results indicate that SPH may be viable for simulating soft soil in conditions relevant for vehicle mobility considerations.
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Keywords: Cone index; SPH; Mohr–Coulomb

1. Introduction

The U.S. Army is currently pursuing research aimed at development of numerical methods for simulating soil response under dynamic ground vehicle loadings. The soil modeling will be used in computational software that enables simulation of vehicle systems interacting in complex urban and off-road environments by coupling various models together in a federated co-simulation architecture (Goodin et al., 2012). Models integrated in the computational testbed will include multi-body physics for vehicle dynamics, powertrain models, running gear models (i.e., wheels, tracks, etc.), and driver and controls models in addition to the soil models. Numerical methods that are being explored for the soil modeling include smoothed particle hydrodynamics (SPH). This article describes a study conducted to evaluate the capabilities of SPH for modeling soil trafficability characteristics based on standard trafficability cone penetrometer measurements.

1.1. The trafficability cone penetrometer

Cone penetrometers are some of the most widely used instruments for assessing the suitability of soil for supporting traffic of ground vehicles. They are especially useful for assessing trafficability of natural *in situ* soil conditions. For ground vehicles in natural terrain, the soil characteristics in the top meter of the soil profile are typically what influence mobility performance, especially in very soft soil. High spatial variability in soil shear strength characteristics related to bearing capacity often exists in soft near-surface soils. High strength variability leads to a need for numerous soil strength measurements distributed spatially over an area of

* Corresponding author.
E-mail address: christopher.t.goodin@usace.army.mil (C. Goodin).

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interest and at various depths throughout the soil profile in order to assess representative strength characteristics that control trafficability. Cone penetrometers provide an indicator of the soil state based on penetration resistance of the cone that relates to moisture content, shear strength, and bearing capacity, and they can be used to rapidly gather numerous soil state measurements at various depths and over large areas. These soil characterization capabilities are what make cone penetrometers so ideally suited and appealing for soil trafficability assessments.

The U.S. Army developed a specialized trafficability cone penetrometer (TCP) near the end of World War II in an effort to quantify soil trafficability as it relates to the mobility of ground vehicles (Meyer and Beverly, 1945; Foster, 1945). The TCP was designed based on the North Dakota Cone Bearing device, which was developed around the early 1940s for evaluation of the bearing capacity of soil subgrades in road pavement design (Boyd and Middlebrooks, 1943). The TCP design evolved somewhat over the next two decades based on experience gained in soil trafficability measurements with numerous ground vehicles (Anon., 1947–1974; Anon., 1959; Nuttall et al., 1966). Similar cone penetrometer variants based on the TCP have been developed for use in agricultural and construction applications, and various manufacturers offer automated versions. The U.S. Army's last revisions to the TCP were made in 1964, and that design closely resembles the simple, manual cone penetrometer specifications described in related Anon. (2004a,b).

The characteristics of the current TCP are shown in Fig. 1. The TCP shafts are typically graduated with recessed-groove markings to enable cone index readings at fixed penetration depths of 0, 2.54, 5.08, 7.62, 10.16, 12.7, 15.24, 22.86, 30.48, 38.1, 45.72, 60.96, 76.2, and 91.44 cm from the ground surface (relative to the base of the cone, which also provides the visual cue for the zero depth reading). Multiple TCP tests distributed around an area of interest are used to determine the average cone index value within controlling soil layers for the area. The average cone index within the 0-to-15.24 and

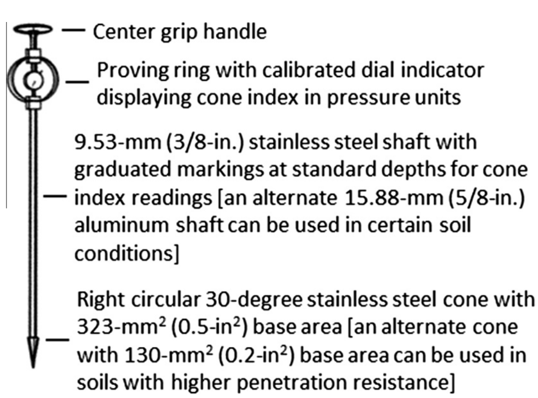

Fig. 1. Characteristics of the standard trafficability cone penetrometer developed by the U.S. Army.

15.24-to-30.48 cm layers are usually the most critical layers for predicting mobility performance in natural terrain environments.

1.2. Importance of the Trafficability Cone Penetrometer (TCP) for terramechanics modeling

Various terramechanics relationships have been developed over the last seven decades based on TCP soil state measurements. Accurate vehicle mobility predictions require additional information related to soil grain size distribution, plasticity characteristics, sensitivity to strength loss under the remolding action of vehicle traffic, and slippery surface condition indicators, but average cone index values from TCP measurements provide the crucial indicator for the controlling mass soil strength. Most terramechanics relationships currently implemented in modeling and simulation (M&S) for the U.S. military are based on empirical correlations rather than analytical models. The empirical correlations are fit to the controlling physical interactions involved in traction, motion resistance, sinkage, etc., as controlled by the response characteristics of soil terrain to ground vehicle loadings, and they have been robustly founded on large quantities of physical measurements with various vehicles and single running-gear elements (i.e., wheels and tracks). The robust physical underpinning based on real-world measurements provides high prediction confidence for mobility M&S, but correlations will, of course, always be limited in applicability to the empirical range of the underlying data and the bounding assumptions behind the relationships. To enable predictions beyond the empirical range of current relationships, more fundamental physics-based simulations for vehicle-soil interactions are being pursued that can take advantage of recent advancements in numerical modeling techniques for soil and high performance computing.

In order to provide similar prediction confidence for physics-based relationships, the wealth of physical vehicle-soil interaction data that have been collected to date will be used to ensure that the new relationships are producing realistic performance predictions. This will require the ability to define the soil state for mechanics-based shear strength and constitutive relationships in a manner that is compatible with the original TCP-based soil data. In addition, methods used for forecasting realistic terrain properties in theaters of interest around the globe for soil trafficability and vehicle mobility predictions are largely enabled through the relative simplicity of TCP-based soil state indicators. So it is likely that TCP-based soil state indicators will be the only viable terrain data for many years to come that will be readily obtainable for enabling future mobility predictions for force projection operations around the globe. Therefore, material parameters for physics-based definitions of soil state based on TCP simulations are desirable for bridging the past to the future of mobility M&S.