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Micromechanics of granular materials – A tribute to Ching S. Chang

Numerical prediction of soil compaction in geotechnical engineering

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ABSTRACT

Soil compaction involves a reduction in volume of the soil mass instead of settlement, which has been considered as one of the most important methods to increase geomaterials' strength in geotechnical engineering practice. This paper presents a numerical model to simulate soil compaction using the finite-element method with finite deformation. The fundamental formulations for soil compaction are introduced first. Then the model is employed to simulate the compaction process and predict spatial density, in which the soil is modeled as elastoplastic material. The Drucker–Prager/Cap model is integrated in the large-deformation finite-element code and used to model the gradual compaction process of soil. Representative simulations of practical applications in geotechnical/pavement engineering are provided to demonstrate the feasibility of predicting soil compaction density using the proposed large-deformation finite-element model.

1. Introduction

Soil compaction is a mechanical process by which mass of soil consisting of solid soil particles, air, and water is reduced in volume by the momentary application of loads, such as rolling, and vibration. Compaction of soils generally increases their shear strength, and decreases their compressibility and permeability. Soil compaction should be differentiated between cohesive soil (e.g., clay) and cohesionless soil (granular materials), which will be compacted using different compaction methods. Cohesive soils contain sufficient quantities of silt or clay to render soil mass virtually impermeable when properly compacted. Clay can be compacted using sheep foot compactor. Cohesionless soils include sand and gravel with relatively larger particle diameter can be compacted using vibratory compactor, and they still remain pervious even after being well compacted. An important characteristic of cohesive soils is that compaction improves their shear strength and compressibility properties. In geotechnical engineering, laboratory compaction standards have been followed to compact cohesive soils, such as Standard Proctor, which is used to estimate the maximum density of soils. For each compaction procedure, there exists an optimum water content, which corresponds to the maximum dry density. At any other water content, the resultant dry density is less than the maximum density.

During the past few decades, soil compaction has received increasing attention in the field of terramechanics, geotechnical and pavement engineering. The majority of research efforts has been focused on experimental device developments and field testing [1,2]. Some analytical and empirical approaches on soil compaction were also investigated [3–7]. These developments have facilitated the development of soil compaction technology and are beneficial to pavement construction.

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However, these analytical models oversimplify the dynamic soil/roller interaction, and therefore do not accurately capture the dynamic compaction process. It becomes evident that more efforts are needed for developing numerical models for soil compaction. As a robust numerical tool, the finite-element method has widely been used for stress and deformation analysis. The finite-element method has also been effectively applied to predict soil compaction [8–10].

Based on the available literature on geomaterial compaction, it seems that although the finite element has been used to study soil/asphalt compaction the background theory was not well introduced. It is therefore necessary more efforts should be devoted to developing efficient numerical model for soil compaction. This paper focuses on introducing the fundamental finite-element formulations for drained soil compaction. This paper is organized as follows. First, the fundamental formulation of large deformation for the calculation of density is introduced, which is followed by the introduction of the linearized weak form for updated Lagrangian formulation and finite-element formulation. The numerical integration of the constitutive equation for large deformation is then presented. Several numerical example studies are provided to demonstrate the efficiency of the numerical approach. Concluding remarks are finally presented based on the findings from this study.

2. Finite deformation and change of density

In order to predict the density change, it is necessary to recognize that the deformation of the soil medium could be relatively large during a loading–unloading cycle. This necessitates the clear distinction between the undeformed configuration and deformed configuration after soil compaction. For a typical time step, the updated configuration of the body at step $t_n + \Delta t$ may be written as a function of the configuration at step t_n and the incremental displacement $\Delta\mathbf{u}$ during the time step Δt. When common origins and directions for the coordinate configurations are used, an updated position vector can be given as

$$\mathbf{x}_{n+1} = \mathbf{X} + \mathbf{u} = \mathbf{x}_n + \Delta\mathbf{u} \tag{1}$$

where $\mathbf{u}$ is the total displacement vector with respect to the original configuration. The deformation gradient or intermediate deformation gradient is defined as follows:

$$\mathbf{F} = \frac{\partial\varphi}{\partial\mathbf{X}} = \mathbf{1} + \frac{\partial\mathbf{u}}{\partial\mathbf{X}} \quad \text{or} \quad f = \frac{\partial x_{n+1}}{\partial x_n} \tag{2}$$

where $\mathbf{1}$ is the identity unit tensor. Ω_{n+1} denotes the current configuration for updated Lagrangian formulation and the reference configuration is denoted by Ω_0. The volume relationship between reference and current configurations can be established as

$$\mathrm{d}\Omega_{n+1} = \det\mathbf{F}_{n+1}\,\mathrm{d}\Omega_0 = J_{n+1}\,\mathrm{d}\Omega_0 \tag{3}$$

Therefore, with the large-deformation updated Lagrangian formulation, one can predict the density change or compaction. In updated Lagrangian formulation, an incremental displacement is defined with respect to the configuration at time t_n, which is considered as the reference configuration for the current load step. The updated Lagrangian formulation can therefore be visualized as a series of intermediate total Lagrangian formulations. Based on the mass conservation, the relative compaction density can be updated at time t_{n+1} by

$$\rho_{n+1} = \frac{\rho_0}{\mathrm{Det}F_{n+1}} \quad \text{or} \quad \rho_{n+1} = \frac{\rho_n}{\mathrm{Det}\,f_{n+1}} \tag{4}$$

Here ρ_0 is the initial density and ρ_{n+1} is the relative density at time step t_{n+1}. Therefore, large-deformation analysis has many advantages in predicting soil compaction in civil engineering.

3. Updated Lagrangian formulation

Continuum based formulations for large deformation analysis can be written either in the material or in the spatial configuration. Discretization of the formulations written in the material/referential configuration or in the spatial/current configuration leads to the so-called total-Lagrangian or the updated-Lagrangian method, respectively. The principle of virtual work consisting of internal and external work can be expressed in the reference configuration at time t_0 as:

$$\delta W(\delta\mathbf{u}, V_0) = \int_{V_0} \mathbf{S} : \delta\mathbf{E}\,\mathrm{d}V - \int_{V_0} \delta\mathbf{u}\cdot\mathbf{b}_0\,\mathrm{d}V - \int_{\Gamma_0} \delta\mathbf{u}\cdot\mathbf{t}_0\,\mathrm{d}\Gamma \tag{5}$$

where $\mathbf{S}$ is the second Piola–Kirchhoff stress tensor and is related to the Cauchy stress tensor via the standard relation $\boldsymbol{\sigma} = \mathbf{FSF}^{\mathrm{T}}/J$; $\mathbf{E}$ is the Green–Lagrange strain tensor and is defined by $E_{ij} = (u_{i,j} + u_{j,i} + u_{k,i}u_{k,j})/2$; and $\mathbf{b}_0$ and $\mathbf{t}_0$ are the body force vector and the traction vector in the reference configuration, respectively. Eq. (5) can be linearized and cast in the Newton–Raphson framework as

$$\delta W(\delta\mathbf{u}, V_0) + D_{\mathrm{int}}\delta W(\delta\mathbf{u}, V_0)\Delta\mathbf{u} = 0 \tag{6}$$