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Numerical modeling on vibroflotation soil improvement techniques using a densification constitutive law

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ABSTRACT

The densification phenomenon in dry or completely drained sands mainly occurs when these materials are subjected to dynamic loadings. This fact induces a reduction of voids volume and consequently the compaction of the soil. The Generalized Endochronic densification law, formulated in cylindrical coordinates, has been used in a finite element model for simulating vibroflotation soil improvement techniques. The effects of vibrations at a point inside the soil mass, like those applied in vibroflotation treatment, are reproduced with this code. Absorbing boundary conditions are established at those borders where spatial domain finishes, aiming to avoid spurious, artificial reflections of stress waves, which otherwise come into the domain, disturbing the computed results. A mean densification function is defined for each spatial domain, to evaluate the effect of this technique, and also employed to optimize the distance between vibration points. This is a new rational design approach, which represents a step forward development if it is compared with the usual empirical employed procedures.

1. Introduction

Vibroflotation is a technique for improving the strength and bearing capacity of unsaturated, granular soils. This technique consists of the application of punctual vibrations at different depths inside a soil layer, produced by a device called "vibrator". These vibrations can have different amplitudes and frequencies, causing dynamic loadings inside the soil (Fig. 1). This soil improvement technique was first used in Germany in the 1930s, and later, in USA. It is specially recommended for soils with very small fines content and for deep layers, taking into account that the vibrator can be introduced within the soil until 20 m, approximately. For a given soil and vibrator, with its particular amplitude and frequency of loading, this procedure requires the definition of several geometrical parameters, i.e. the vertical distance between vibrating points at the same hole, as well as the horizontal distance between them, or the time of vibration at each location. In practice, these magnitudes are usually defined by means of empirical approaches, trials before the complete treatment, and by using data derived from successful past experiences. Although this technique has been successfully applied in many cases [1,2], it seems to be necessary the development of a rational design approach.

It is well known that, when loose sandy soils are subjected to dynamic loadings, they tend to acquire denser states, reorganizing their grains. This phenomenon is known as densification.

To model this kind of processes, several approaches can be adopted. On one hand, there are empirical and semi-empirical based models, which extrapolate the results of densification found in laboratory for a particular material. These models usually give good results, but they are far from reproducing the physical mechanisms governing the real soil behavior [3–5].

On the other hand, it is possible to find in the literature other different cases aiming to model that phenomena in granular soils. Bement and Selby [6] studied experimentally the problem of soil densification during pile driving and emphasized the role of stress level and granulometric properties of the soil to be treated. Arnold and Herle [7] developed a numerical model to simulate the soil densification obtained throughout the vibrocompaction technique, comparing deep and top vibrators. Their model was based on a mix of dynamic FE calculation at first, to obtain strain paths, and hypoplasticity theory [8,9] with intergranular strains applied to the soil to be improved in the second step. This model required a huge computational time since a 3D FE approach was employed, and the agreement between numerical simulations and field data was not good. Finally, other models like generalized plasticity have not still been widely tested in vibroflotation models for granular

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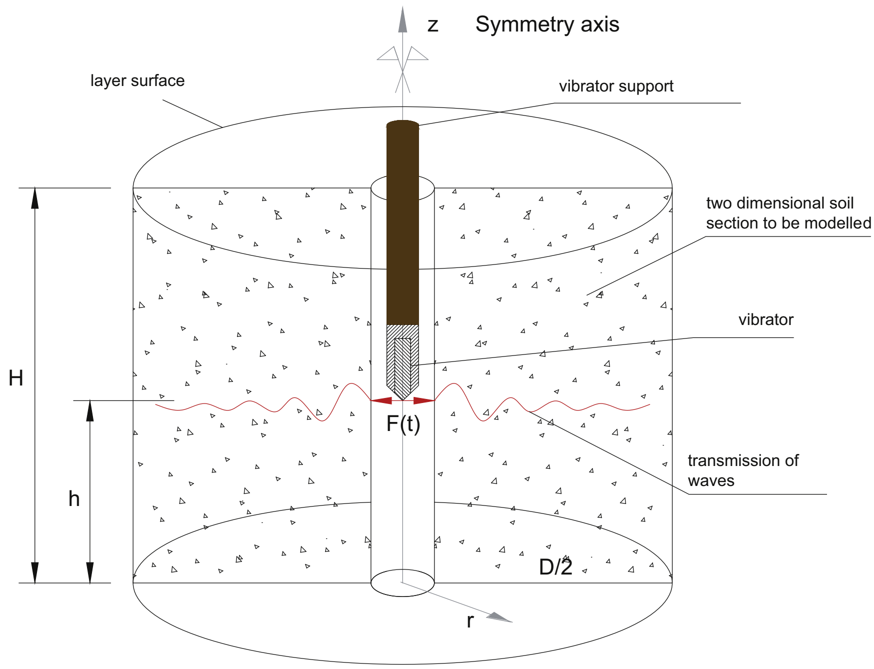

Fig. 1. Sketch of the vibroflotation soil improvement technique. Details of a hole, including the vibrator inside.

soils, and their feasibility for this kind of problems is still to be explored.

In this research, an endochronic based densification law for sandy material is used. The Endochronic Theory, first developed for metals, was successfully applied to sandy materials subjected to vibrations by Cuéllar [10,11]. This law, based on the definition of two monotonic functions which increase as the number of harmonic shear strain cycles progresses, has been recently updated and generalized for non-harmonic loadings and high number of cycles [12].

The above-mentioned endochronic based densification law has been implemented in a Finite Element code, formulated for axi-symmetric problems. In this paper, a single hole and its surrounding soil have been modeled. The axis of symmetry has been placed in the hole, where punctual vibrations could take place at different depths. Aiming to avoid the unrealistic reflection of stress waves into the domain of interest, absorbing boundary conditions have been established at those boundaries which mark the limits of the numerical domain but are surrounded by soil in real field situations.

At the beginning, the paper shows the particularities of the numerical model, including the employed constitutive law, the axi-symmetrical formulation of FE code, as well as the implementation of absorbing boundary conditions. After that, the model is applied to different materials and the optimal spacing of the vibration points is established.

2. Description of the numerical model

2.1. Constitutive law

In his pioneer work, Cuéllar (1974) established that the densification of sand is due to the irreversible rearrangement of grain configurations associated to the application of a deviatoric strain. In mathematical form:

$$d\xi = f(d\varepsilon_{ij}) \tag{1}$$

where ξ is called *rearrangement measure*, which is a function of the deviatoric component of the strain tensor, ε_{ij}. In order to account for the monotonically increasing trend of ξ, the differential expression given by Eq. (2) must be a quadratic and finite function:

$$d\xi = (P_{ijkl} \cdot d\varepsilon_{ij} \cdot d\varepsilon_{kl})^{1/2} \tag{2}$$

where P_{ijkl} denotes a tensor, the components of which are material state dependent.

Neglecting the dependence of $d\xi$ on the third invariant of the increment of strains tensor, it is hence possible to uncouple Eq. (2) as follows:

$$d\xi = [P_1 \cdot I_1^2(d\varepsilon_{ij}) + P_2 \cdot J_2^2(d\varepsilon_{ij})]^{1/2} \tag{3}$$

where $I_1(\ldots)$ and $J_2(\ldots)$ respectively represent the first and second invariant of the tensor between brackets, and P_1 and P_2 are model parameters. It is demonstrated that dynamic volumetric strains cause a small effect on the amount of densification [13], so the term $I_1^2(d\varepsilon_{ij})$ can be neglected in Eq. (3), yielding:

$$d\xi = [P_2 \cdot J_2^2(d\varepsilon_{ij})]^{1/2} \tag{4}$$

Moreover, a monotonic function ζ, called *densification measure*, is also defined, and like ξ is time independent. This function depends on ξ, and is incrementally defined:

$$d\zeta = F_1(J_2(d\varepsilon_{ij})) \cdot d\xi \tag{5}$$

where F_1 denotes an analytical function, and $d\varepsilon_{ij}$ represents the increment of the strain tensor.

Finally, the densification ε'_y (volumetric strain) is incrementally defined as follows:

$$d\varepsilon'_y = -F_2(\zeta, Dr_0) \cdot d\zeta \tag{6}$$

where F_2 is a function, and Dr_0 is the initial relative density of the sand before it is subjected to dynamic loading. Cuéllar [10] proposed the next expressions for F_1 and F_2:

$$F_1 = \frac{n}{4} \cdot |100 \cdot \gamma|^{n-1} \tag{7}$$

$$F_2 = \frac{1}{1 + \alpha \cdot \zeta} \tag{8}$$

where n and α are parameters and γ denotes the shear strain expressed in per one.