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Improvement parameters in dynamic compaction adjacent to the slopes

Elham Ghanbari, Amir Hamidi*

School of Engineering, Kharazmi University, Tehran, Iran

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ABSTRACT

Dynamic compaction is a cost-effective method commonly used for improvement of sandy soils. A number of researchers have investigated experimentally and numerically the improvement parameters of soils using dynamic compaction, such as crater depth, improvement depth, and radial improvement, however, these parameters are not studied for improvement adjacent to the slopes or trenches. In this research, four different slopes with different inclinations are modeled numerically using the finite element code ABAQUS, and impact loads of dynamic compaction are applied. The static factors of safety are kept similar for all trenches and determined numerically by application of gravity loads to the slope using strength reduction method (SRM). The analysis focuses on crater depth and improvement region which are compared to the state of flat ground. It can be observed that compacted area adjacent to the slopes is narrower and slightly away from the slope compared to the flat state. Moreover, crater depth increases with increase in slope inclination.

1. Introduction

Dynamic compaction pioneered by Menard and Broise (1975) has been used for improvement of deep soil layers for decades. In this method, through falling a tamper of 5–30 t from 10 to 30 m height, improvement depths of 3–9 m are obtained (Lukas, 1995). Soil improvement has been investigated by assessing the experimental tests like standard penetration test (SPT), cone penetration test (CPT) and pressure meter test (PMT) before and after compaction (Mayne et al., 1984; Rollins et al., 1998; Zou et al., 2005; Rollins and Kim, 2010; Zekkos et al., 2013). Also numerical modeling has been performed to investigate soil improvement after compaction (Pan and Selby, 2002; Lee and Gu, 2004; Ghassemi et al., 2010; Mostafa, 2010; Ghanbari and Hamidi, 2014). Dynamic compaction has not been applied near the slopes due to the instability problems. Zou et al. (2005) reported an application of dynamic compaction in placement of a road embankment with 41 m height made of loessial silty clay in China, wherein dynamic compaction was performed at distance of 6 m from the slope heel in soil layers. Few researchers studied the dynamic compaction process near the slopes experimentally (Zhou et al., 2010; Vahidipour, 2014). To the authors' knowledge, there is rare numerical investigation of dynamic compaction near the slopes in the literature. In this study, simulation of dynamic compaction method is performed near the sandy slopes with the same initial factors of safety.

2. Numerical modeling

In this study, two-dimensional (2D) plain strain slope models are used in a finite element code, ABAQUS. Slope models consist of 4 different slope inclinations of 45°, 60°, 75° and 90° with a height of 6 m and appropriate compaction energy of 4000 kN m. Compaction is performed in two steps: the first step is application of gravity load to the whole model in a static manner, and the second one is to apply impact load of the tamper in an implicit dynamic analysis, wherein the tamper is simulated as a rigid body free-falling from a specified height. The latter method was used in previous studies (Pourjenabi et al., 2013; Ghanbari and Hamidi, 2014). In order to keep the similar stability conditions of slopes, the static factors of safety for 4 slope models are kept constant as 1.2, and for this purpose friction angle of soil models is kept to be 30° as a typical value for loose sandy soils and cohesion of soil is changed. Indeed, the soil cohesion has more influence on the factor of safety of the slope, e.g. keeping the factor of safety as 1.2 for 45° and 60° slopes, the soil cohesion changes from 4.5 kPa to 8.0 kPa. Hence the slope model with larger slope inclination should have higher soil cohesion. To determine the static factors of safety in the finite element method (FEM), strength reduction method (SRM)

* Corresponding author. Tel.: +98 21 88830891.
E-mail address: hamidi@khu.ac.ir (A. Hamidi).

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first applied by Matsui and San (1992) is used in this study. In this method, the soil gravity is firstly applied to the whole slope model, and then the soil parameters are reduced gradually by different trial factors of safety to reach the failure. Initial parameters at which slope failure occurs at factor of safety of 1.2 are picked. The onset of failure in slope models is assumed when a sudden increment in nodal displacements is observed. This criterion was used by previous researchers (Griffiths and Lane, 1999; Khosravi and Khabbazian, 2012).

For each slope model, there is a relevant flat model with the same soil properties for comparison. Compaction is simulated for each model at distances of 1–33 m per 4-m interval. Table 1 presents geometry variables of slope models and the compaction energy. Fig. 1 shows definition of slope geometry variables used in numerical analysis, in which x is the tamping distance between tamper edge and slope heel. Lateral and fixed boundaries are also shown in this figure.

The mesh type is quadrilateral 4-noded plain strain elements. The mesh size is finer around the tamper and adjacent to slope with the size of 0.2 m and gradually increases to 1 m at boundaries. Fig. 2 shows mesh type used in the analysis.

3. Constitutive model

Cap plasticity model has been used successfully for simulation of dynamic compaction (Thilakasiri et al., 2001; Gu and Lee, 2002; Pak et al., 2005; Ghassemi et al., 2010; Ghanbari and Hamidi, 2014). The model has a number of advantages compared with Mohr–Coulomb model, especially for simulation of compaction phenomenon of soils (Pourjenabi et al., 2013). In this study, the cap plasticity model is used with two yield surfaces, consisting of the fixed yield surface of Drucker–Prager model to indicate shear failure, and the moving caps defining hardening with change in volumetric strains. The yield surfaces are shown in Fig. 3. The fixed and moving yield surfaces for this model can be expressed as follows, respectively:

$$f_1 = \sqrt{J_{2D}} - \alpha J_1 - \kappa = 0 \quad (1)$$

$$f_2 = (J_1 - l)^2 + R^2 J_{2D} - (M - l)^2 = 0 \quad (2)$$

where α and κ are Drucker–Prager constants, J_1 is the first invariant of stress tensor, $\sqrt{J_{2D}}$ is the second invariant of deviatoric stress tensor, l is the coordinate of cap-fixed yield surface intersection on J_1 axis, R is the radius of cap surface in stress space, and M is the hardening parameter of soil depending on plastic volumetric strain (ε_v^p) and initial mean effective stress (M_0). Parameter of R is defined as

$$M = -\frac{1}{D}\ln\left(1 - \frac{\varepsilon_v^p}{w}\right) + M_0 \quad (3)$$

where w and D are the cap plasticity parameters which are dependent on soil compressibility. These parameters were previously calculated by curve fitting with oedometer test results of Oshima and Takada (1997) on a loose sandy soil by Gu and Lee (2002).

Table 1
Geometry variables of slope models and compaction energy.

Height of slope base (m)	Slope height, H (m)	Slope inclination, θ (°)	Compaction energy (kN m)
6	6	45, 60, 75, 90	4000

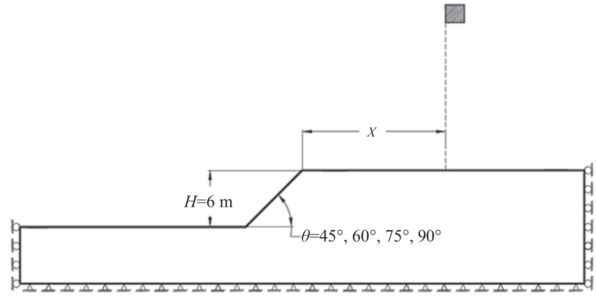

Fig. 1. Slope geometry variables.

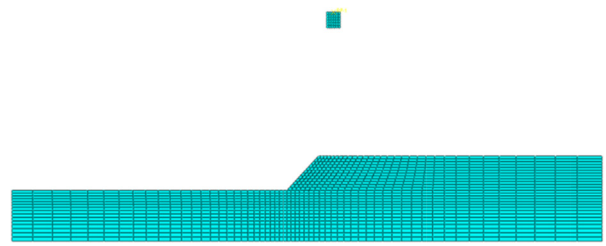

Fig. 2. Mesh type used in numerical analysis.

As mentioned above, the soil cohesion in each slope model is varied in order to maintain the slope in the same initial factor of safety. The soil cohesions calculated by SRM in finite element are given in Table 2 together with the soil strength parameters and static factors of safety calculated by a limit equilibrium method (LEM). The LEM presented by Morgenstern and Price (1965) has been applied in the program of Geo-Studio software. As it can be seen, the factors of safety obtained by LEM are in good agreement with those obtained by SRM, and the maximum difference is less than 3%.

4. Crater depth results

Fig. 4 shows variation of crater depth versus compaction energy in each blow at different compaction distances from the slope heel. As is observed, the crater depth increases with increase in compaction energy. At the distance of 1 m, the crater depth is higher than that at further distances. As the compaction distance from the slope heel increases, values of crater depth gradually decrease until reaching the values of flat models. It shows that the effects of slopes gradually disappear. Comparing

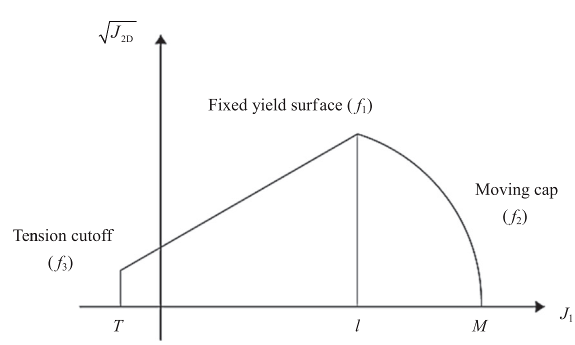

Fig. 3. Yield surface of cap plasticity model in stress space.