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Estimation method for ground deformation of granular soils caused by dynamic compaction

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ABSTRACT

A numerical investigation into the performance of ground deformation due to dynamic compaction (DC), and a developed method of estimating ground deformation of granular soils caused by DC are presented. Firstly, a 2D numerical model is created in LS-DYNA and the result is verified by variables measured in a real field case using DC treatment. A simplified model for describing ground deformation is presented. Five deformation variables, δ_{vm}, $d_{\delta_v=0}$, $d_{\delta_{um}}$, δ_{um}, $d_{\delta_u=0.01\%\sqrt{W_tH}}$, are defined to describe characteristics of ground surface deformation. An extensive parametric study is then conducted to investigate the effect of each parameter on the five deformation variables. Finally, based on the results obtained, a forecast model is produced to describe ground deformation under DC. The applicability of the proposed procedure is then illustrated by comparing its predictions with a case of DC applied in the field. The results of this comparison indicate that the predictions using the developed method are reasonably realistic. This suggested method can provide some easy and convenient guidelines to determine ground deformation of granular soils due to dynamic compaction.

1. Introduction

Dynamic compaction (DC) is a well-known method of ground improvement used for its efficiency and operability, and which is particularly effective in granular soils, sand and cohesionless soils [1–4]. The performance design and application of DC are still empirical in practice, relying heavily on the designer's experience and judgement [5]. Generally, the degree of improvement is mainly affected by the site conditions and the construction method [6]. The site conditions are determined by the soil properties [7] and the groundwater table [8]. The influence of the construction process is determined by the choice of equipment, and relevant factors include tamper weight, shape, dropping height and interval between tamping points [6].

Since the first practical application of modern DC techniques for ground treatment in 1965, many researchers (Mayne et al. [1], Lukas [2,3], Menard et al. [9], Rollins et al. [10], Feng et al. [11,12], Michalowski et al. [13], Zekkos et al. [14]) have investigated the densification effects of DC on sandy soils. Most of these studies have focused on the densification depth caused by DC impact [10–14]. An empirical expression for the predicted depth of improvement, d, was presented as $d = n\sqrt{W_t \times H}$, where n is the empirical factor, W_t is the weight of the tamper in tonnes and H is the height of drop in metres [3,9]. However, this simple design approach suffers from several drawbacks [15], which may lead to large errors. Mayne et al. [1] and Lo et al. [16] established the relationship between crater depth and total tamping energy per unit area to forecast the effect of ground improvement. But these approaches were also empirical, which means that they cannot be extended and applied to more general situations. Hence, a number of approaches for selecting the design parameters in DC have been put forward based on numerical models [17,18]. More recently, several FE (Finite Element) models under dynamic compaction have been developed, but these mainly focus on numerically analysing the physics of this ground improvement technique or on validating certain computational procedures [19–24]. Lee et al. [15] have studied the influence of various tamper properties (e.g., shape, weight and height of tampers) and different initial soil states on ground improvement based on numerical studies. This led them to establish a predictive model to evaluate the degree of ground improvement with depth.

With an increase in tamping times, the soil beneath the tamper becomes denser, and the ground heaves simultaneously by lateral extrusion. When tamping energy reaches a certain level, the soil will not be compacted further and ground heave continues to develop. It is important to note that ground heave generated during DC is unfavourable to the utilisation of the tamping energy, especially in a high energy level project (e.g., Feng et al. [11,12]). Most previous design formulas focused mainly on the effective depth and the improvement effect (e.g., Poran et al. [6], Lee et al. [15], Ghassemi et al. [20]). These methods

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Nomenclature

H	height of drop
W_t	weight of tamper
r	tamper radius
N	the standard penetration number
E_s	compression modulus
w	natural water content
e_0	initial void ratio
I_P	plasticity index
I_L	liquidity index
ρ	the soil density
E	Young's modulus
G	shear modulus
K	bulk modulus
v	Poisson's ratio
c	soil cohesion
ϕ	the frictional angle
I_1	the first stress invariant
J_2	the second invariant of deviatoric stress tensor
α, γ, β, θ	failure envelope parameter
W, D, R	soil parameters in cap model
T	maximum hydrostatic tension
δ_{vm}	depth of crater
δ_{um}	the max settlement of ground heave
$d_{\delta_{\mathrm{u}}=0.01\%\sqrt{W_tH}}$	heave area
$d_{\delta_{\mathrm{v}}=0}$	the distance between δ_{v}=0 and impact points
$d_{\delta_{um}}$	the distance between δ_{um} and impact points
δ^s_{vm}, $d^s_{\delta_v=0}$, $d^s_{\delta_{um}}$, δ^s_{um}, $d^s_{\delta_u=0.01\%\sqrt{W_tH}}$	standard values of ground deformation corresponding to 800 T m DC, in which the 40 T tamper with a radius of 1.3 m is dropped from 20 m high.
$\psi_{\delta_{vm}}$, $\psi_{d_{\delta_v=0}}$, $\psi_{d_{\delta_{um}}}$,$\psi_{\delta_{um}}$, $\psi_{d_{\delta_u=0.01\%\sqrt{W_tH}}}$	ground deformation coefficients relevant to the standard values of ground surface deformation
τ	the normalised tamper radius
$\psi^r_{\delta_{vm}}$, $\psi^r_{d_{\delta_v=0}}$, $\psi^r_{d_{\delta_{um}}}$, $\psi^r_{\delta_{um}}$, $\psi^r_{d_{\delta_u=0.01\%\sqrt{W_tH}}}$	proportion coefficients relevant to tamper radius
r^s	the standard tamper radius (1.3 m)
E^R	reference energy
E_t	energy per blow
M	momentum per blow energy
δ^R_{vm}, $d^R_{\delta_v=0}$, $d^R_{\delta_{um}}$, δ^R_{um}, $d^R_{\delta_u=0.01\%\sqrt{W_tH}}$	reference deformation variables
$\alpha^E_{\delta_{vm}}$, $\alpha^E_{d_{\delta_v=0}}$, $\alpha^E_{d_{\delta_{um}}}$, $\alpha^E_{\delta_{um}}$, $\alpha^E_{d_{\delta_u=0.01\%\sqrt{W_tH}}}$	ratio of ground deformation to that of reference case
$\alpha^M_{\delta_{vm}}$, $\alpha^M_{d_{\delta_v=0}}$, $\alpha^M_{d_{\delta_{um}}}$, $\alpha^M_{\delta_{um}}$, $\alpha^M_{d_{\delta_u=0.01\%\sqrt{W_tH}}}$	ratio of ground deformation to that of standard case
$\psi^{E-M}_{\delta_{vm}}$, $\psi^{E-M}_{d_{\delta_v=0}}$, $\psi^{E-M}_{d_{\delta_{um}}}$, $\psi^{E-M}_{\delta_{um}}$, $\psi^{E-M}_{d_{\delta_u=0.01\%\sqrt{W_tH}}}$	proportion coefficients relevant to energy and momentum
ζ	normalised energy per blow
η	normalised SPT value
$\psi^N_{\delta_{vm}}$, $\psi^N_{d_{\delta_v=0}}$, $\psi^N_{d_{\delta_{um}}}$, $\psi^N_{\delta_{um}}$, $\psi^N_{d_{\delta_u=0.01\%\sqrt{W_tH}}}$	proportion coefficients relevant to soil properties
N_i	the number of blows
$\psi^{N_i}_{\delta_{vm}}$, $\psi^{N_i}_{d_{\delta_v=0}}$, $\psi^{N_i}_{d_{\delta_{um}}}$, $\psi^{N_i}_{\delta_{um}}$, $\psi^{N_i}_{d_{\delta_u=0.01\%\sqrt{W_tH}}}$	proportion coefficients relevant to blow count

cannot be readily tailored to the optimum number of tamper blows. In recent years, the ground surface deformation is gradually attracted research attention in DC problems. Derakhshandeh [25] suggested that the value of effective volume, which is equal to the difference between settlement volume and heave volume, is used to determine the optimum number of blows for DC according to ground deformation acquired using the Penetration and Heave Tests. Effective volume would seem to be a useful parameter for determining the optimum number of blows in DC. Ground heave can also serve as a direct indication of the influence radius of DC around impact points and can help to ascertain the optimal spacing of impacts. Currently, most studies on surface ground deformation have been field investigations. Feng et al. [4,11,12] measured the ground settlement and ground heave over several trials. Other filed studies were performed by Shui et al. [26], Wang et al. [27], Nian et al. [28]. However, research regarding the ground deformation mechanisms has previously remained scarce.

In a practical situation, the data for ground surface deformation under DC is usually captured through ground settlement monitoring. However, the measure point near the tamping spot is sometimes broken by the tamping energy and only few measurements is generally obtained [4,11,12]. It is therefore difficult to acquire accurate site data, which would directly impact the design and operation of DC. To date, few studies have been devoted to investigating the DC impact effects on ground deformation. It is also still unclear what happens when mutual influences exist, including soil properties, the number of blows, energy per blow, momentum per blow and tamper radius.

In this paper, a numerical study was carried out using LS-DYNA, with the aim of developing a simple and quick assessment of ground deformation of granular soils caused by dynamic compaction. Firstly, a 2D numerical model was created in LS-DYNA and the numerical results of ground deformation were verified by comparing with measured results. Then, an extensive parametric study was undertaken to investigate the influence of each parameter on the ground surface deformation based on a simplified model. Finally, based on the results obtained, a forecast formula was derived to describe ground deformation under DC. The applicability of the proposed procedure is then illustrated by comparing its prediction with a case of DC applied in the field. This developed method can be directly used in practice.

2. Numerical model for dynamic compaction

Numerical simulation of ground response to dynamic compaction is a complex issue. It is necessary to provide a class of governing equations which takes into account all physical phenomena in a DC process, including the dynamic equation of soil, the nonlinear material behaviour of soil and tamper–soil interaction.

2.1. Dynamic equations

A Lagrangian formulation is adopted for the dynamic equations. The continuum is governed by conservation of mass, linear and angular momentum, and energy [29]. Generally, the motion equation of a deformed body for nonlinear dynamic behaviour can be expressed in a

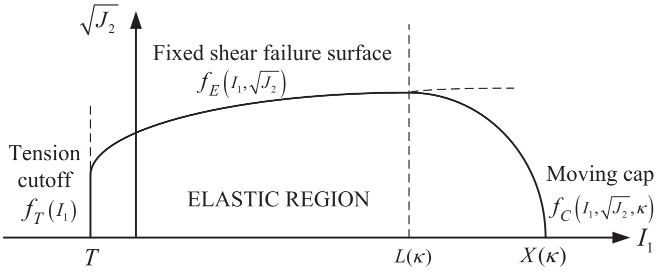

Fig. 1. The cap model.