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Settlement evaluation of explosive compaction in saturated sands

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ABSTRACT

Explosive Compaction (EC) or Blast Densification (BD) has been commonly used as one of the deep soil improvement techniques to densify loose, saturated granular soils. Soil is compacted due to huge compression force of explosion in several depths and the corresponding liquefaction. Among soil characteristics, settlement is important since it is a fast and easy indicator of layer compaction degree. To measure settlement instrumentation can be used but they are expensive and susceptible to damage due to explosion. Predicting settlement using empirical equations is also another method, however, they cannot consider soil complex behavior and are consequently inaccurate. In this study, numerical approach has been used to evaluate settlement and excess pore water pressure (PWP) during and after explosion, using finite element software PLAXIS3D, in which the UBCSAND soil model has been employed to represent saturated sand. This model is capable of calculating PWP buildup due to dynamic loads such as earthquake and explosion. This method was calibrated and compared, using well-known case histories in the literature. Results of settlement from these cases, were compared with both empirical equations and measured site values. Pulses of PWP due to shock wave were also calculated by the model as well as PWP buildup until reaching liquefaction zone. Predictions from this approach were more accurate than empirical equations. Moreover, it was revealed that the rate of settlement and PWP dissipation is proportionate to soil's permeability. Thus, numerical approach can be confidently implemented to evaluate soil characteristics.

1. Introduction

Soil improvement involves modification of soil characteristics by increasing density, reducing volume change variations, and controlling water action [30]. Soil improvement techniques are divided into two main groups: shallow and deep soil improvement methods. Popular deep soil treatment methods are: Deep vibro compaction, Deep dynamic compaction, Deep soil mixing, Jet grouting, and Blast Densification. Some methods such as vibro techniques and grouting are expensive while some other such as deep dynamic compaction is limited to shallow and middle depths. On the other hand, Blast Densification is a method which requires less equipment and can be used in variety of depths. Moreover, it is a fast, simple and cost-effective method of soil compaction [14,30].

Explosive Compaction or Blast Densification is a deep soil improvement method to densify loose saturated sands [24,29]. EC is performed by excavating boreholes, placing explosives in several rows (decks), and detonating explosive charges. Settlement occurs due to both water loss through blast holes and excess pore pressure dissipation after explosion [15]. EC has been practiced for over 70 years and for different purposes, including densifying the soil beneath dam [27,29], densifying tailing ponds [51] and inducing liquefaction in soil [17,2,35,38,50].

EC performance is most effective in soils with low relative density (R_D ≤50–60%). Moreover, EC provides acceptable results when CPT tip resistance of soil is less than 10 MPa. On the other hand, for soils with more than 20 MPa tip resistance, EC acts negatively and loosens the layer [17].

Evaluation of EC effectiveness is done by using various methods. Usually, after explosion, CPT results, excess PWP and settlement is reported. Results from excess PWP is used to assess the extent of soil liquefaction. CPT is used to determine how much strength is achieved by EC. Moreover, settlement provides useful data about the achieved density of the soil. According to case histories, the achieved settlement is 2–10% of the treated soil layer thickness [14]. This range is high in comparison to the settlement induced by earthquake which is approximately 3–4% [19]. Increase in penetration resistance varies from site to site and is based on different factors. In some cases, it has been reported that increase in strength had not been observed after weeks, months, or even years after blasting [20,32].

In this study, settlement and excess PWP due to blast densification in sand deposits has been studied through the numerical approach. The Finite Element software, PLAXIS3D 2016 was used in this study. It is

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capable of calculating deformation under dynamic and static loading. Since EC involves both dynamic (explosion load) and quasi-static (excess PWP dissipation) phases, this software is suitable. UBCSAND soil model has been chosen to model soil complex behavior. This model has been commonly used for soils under dynamic loadings. The results are calibrated and compared with several well-known case history records.

2. Background to EC, performance and evaluation

In 1936, the first EC project was performed to densify soil in Soviet Union. Despite the 440 mm settlement, the project was unsuccessful owing to the cracks on the surface caused by explosion [12]. After several years, EC was successfully performed in Franklin Falls Dam, USA [27]. Since then, many projects has been performed in various locations around the world.

EC is primarily used for soil densification, however, it has also been used for other purposes, such as inducing artificial earthquake for soil response assessment [2]. Recently explosion is used to induce liquefaction in a test site in Christchurch, New Zealand to assess different improvement techniques [50].

The energy released from explosion is consisted of two different types of energies: energy due to shock wave and energy due to gas expansion. Shock wave is an instant load with high pressure which, destroys soil structure. It expands radially in the soil medium. As the shock expands, the corresponding pressure decreases. The energy due to gas expansion is the result of chemical reactions in explosives. It exerts a series of compression and dilation loads with lower stress ratio in comparison to shock wave. This cyclic load induce shear loads and increases PWP, most of the times, until liquefaction [11,9]. After liquefaction, a new structure is formed because of particle's relocation, and with dissipation of excess PWP, more compression takes place [32].

Settlement and PWP, are two main characteristics that are evaluated in EC. Generally, evaluation of EC is done by using empirical approach and site instrumentation. In empirical approaches, empirical equations are used to predict soil response after EC. These equations are obtained by fitting a curve through the results of several case records. Empirical equations are easy to use and require less input, but they provide rough estimation and don’t give accurate results. Table 1 lists some of the equations by Narin van Court [31] and a recent work by Tavakoli et al. [46] for predicting settlement due to EC.

Table 1
A few proposed equations for EC-induced settlement estimation [32].

Reference	No.	Equation	Description
Narin van Court, Mitchell ($year $) [32]		**Based on Hopkinson Number (HN)**	$HN = \frac{W^{1/3}}{R_h}$
	1	$\frac{\Delta h}{\mathrm{h}}(\%) = 7.54 + 6.87\log(\mathrm{HN})$	
	2	$\frac{\Delta h}{\mathrm{h}}(\%) = 8.89(\mathrm{HN})^{0.816}$	
		Based on Normalized Weight (NW)	$NW = \frac{Q^{1/2}}{R_h}$
	3	$\frac{\Delta h}{\mathrm{h}}(\%) = 10.19 + 7.22\log(\mathrm{NW})$	
	4	$\frac{\Delta h}{\mathrm{h}}(\%) = 18.52(\mathrm{NW})^{0.862}$	$Q = \frac{W}{h_0}$
		Based on Powder Factor (PF)	$PF = \frac{1000W}{V}$
	5	$\frac{\Delta h}{\mathrm{h}}(\%) = -1.02 + 3.96\log(\mathrm{PF})$	
	6	$\frac{\Delta h}{\mathrm{h}}(\%) = 0.843(\mathrm{PF})^{0.476}$	
Tavakoli et al. [46]	7	$\frac{\Delta h}{H_0} = \frac{(0.812PF_{avg}^{0.71})(1.285^{\log(N)})}{d^{0.18}}$	

W: charge weight.
h and h_0: Layer thickness.
V: Volume of the treated soil.
R_h: Horizontal distance from center of explosion to the point of measurement.
d: depth of the center of mass of explosives.
Q: unit weight in depth.

Another method of EC evaluation is site monitoring via instrumentation. The shortcoming of instrumentation is its cost and susceptibility to damage. Moreover, evaluation of some characteristics varies over a significant period of time (Rollins, K.M., and Anderson, 2008). For example, Eslami [13] studied CPT data to analyze the extent of soil liquefaction mitigation and strength gain by EC. In some cases, it was reported that CPT results after explosion show small improvement in tip and friction resistance for a significant period of time.

On the other hand, numerical approach is another method that has not been entirely studied in the literature. Until now, there are few works of using numerical approach in EC evaluation. Lee [25] developed a model to predict liquefaction in soil using FHWA soil material model in a hydrocode, LS-DYNA. Results were compared with experimental data from an EC trial performed in Vancouver. The model was capable of calculating PWP but was unable to predict settlement.

An (2010) also wrote a subroutine to predict volumetric strain in saturated sand due to explosion. In this model, saturated sand during liquefaction was considered as fluid, thus an equation of state was written for the soil. The results were compared with data obtained from single blast experiment in saturated sand. The model predicted the volume change correctly. The shortcoming of this model was lack of PWP calculation. Moreover, the model was incapable of PWP dissipation and its corresponding settlement.

Despite the lack of numerical analysis of explosion in soil, there are some researches regarding the effect of buried explosion on structures. Jayasinghe et al. [21] evaluated effects of explosion on a single pile using LS-DYNA. Although soil was modelled, no results regarding soil characteristics variations were presented.

Numerical modelling approach has been proven to be a precise and economical method to evaluate soil behavior in geotechnical problems. With limitation of current evaluation methods, numerical approach can be an essential method to evaluate EC.

3. Case history records

In order to calibrate, validate, and compare the approach used in this study, more than 30 cases of successful EC projects were compiled. The purpose of case histories were whether soil densification or liquefaction inducement. The typical soil layer for densification was loose saturated sand. Water table was reported to be near or at the ground surface. The data for each site includes, target layer thickness, Number of blast phases, Explosive weight, depth and arrangement (Triangular, Rectanglular or Circular), and the resulting settlement. Most of the settlements were in range of 2–10% of the treated layer thickness.

As an example, numerical results of an EC project in South Carolina, which was conducted by Narsilio et al. [33] has been presented here. Fig. 1 shows the soil profile of the area which is typically consisted of six separate layers. A loose, saturated, fine "black sand" in the depth of approximately 7.5–13 m was the target soil for compaction. Water table was approximately 1 m below the surface. Laboratory tests were conducted to obtain soil characteristics in different layers. The soil characteristics include Index properties, hydraulic conductivity etc. Fig. 2 shows the blast area and explosives' configuration. The blast site area was an 18×18 m square. EC was consisted of four explosion phases in a duration of 8 month. Explosives were placed in a rectangular arrangement as shown in Fig. 2. Each explosive was placed at the depth of z=10 m. The weight of each charge in a single borehole varied with each phase from 11 to 34 kg.

Detonation delays were assigned between rows, which has been proven to increase the effectiveness of EC [16]. The 1st and 2nd explosive trials had a 100 and 50 ms delays between each row, respectively. The 3rd and 4th blast phase intervals was 10 min.

In order to obtain data before, during and after each blast, instruments were placed inside and outside the blast area. Surface