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Computer simulation of underground blast response of pile in saturated soil

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ABSTRACT

This paper treats the blast response of a pile foundation in saturated sand using explicit nonlinear finite element analysis, considering complex material behavior of soil and soil–pile interaction. Blast wave propagation in the soil is studied and the horizontal deformation of pile and effective stresses in the pile are presented. Results indicate that the upper part of the pile to be vulnerable and the pile response decays with distance from the explosive. The findings of this research provide valuable information on the effects of underground explosions on pile foundation and will guide future development, validation and application of computer models.

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1. Introduction

Increasing terrorist attacks have led to greater scrutiny of the design of structures to random and unexpected loads such as impacts and blasts. In order to design structures to withstand blast loading, it is necessary to ensure the design is suitable for the level of risk and adheres to the appropriate standards. The understanding of blast effects on piles, combined with structural damage data from historical explosions, as well as information from research on the response of structures under blast loading enables the evaluation of the effectiveness of current design standards and practices.

The performance of underground structures subjected to blast loads is a critical research area, as these structures play an important role in the overall structure response. Underground explosions usually produce a crater, and blast-induced ground shock propagates in the surrounding soil media. If an explosion occurred near a buried structure, the soil pressure and acceleration will result in severe damage or even the collapse of the structure. Therefore, ground vibrations resulting from underground explosion are of great interest to engineers who deal with the design of underground structures.

Although pile foundation is a surface buried structure, it can be assumed as an underground structure in some aspects. Pile foundations transfer the large loads from the superstructure above into deeper, competent soil layers which have adequate capacity to carry these loads. It follows that if these foundations are structurally damaged due to blast loading, the superstructure becomes vulnerable to failure. Despite the importance of blast response of pile foundations, only a few relevant publications can be found in the literature, probably due to the complexities in the material behavior of the soil and the soil–pile interaction.

Many studies have been carried out on the propagation of blast induced waves in the air, soil and rocks [1–3]. The evolution of centrifuge tests had led to many studies on the dynamic response of underground structures under blast loading [4,5]. Shim [6] used centrifuge models to study the response of piles in saturated soil under blast loading. However, with the rapid development of computer programs, it has become possible to carry out detailed numerical simulations of response of underground structures under buried blasts [7,8] and study the effects of controlling parameters. Some past studies have used centrifuge test results to compare finite element (FE) model results [9–15]. Anirban De [9] used numerical simulations with ANSYS Autodyn 13 to study the effects of a surface explosion on an underground tunnel using a 3D FE model. A fully coupled Euler–Lagrangian formulation was used to model the fluid–structure interaction under blast loading. His FE model was verified through typical model tests using a geotechnical centrifuge. This has provided confidence in the procedure used herein.

This paper treats the response of pile foundation to a buried blast loading using numerical simulations through the commercial software package LS-DYNA [16]. The present study adopts the fully coupled numerical simulation approach. A brief description of the background on modeling is presented at the beginning of this paper. Then, the blast wave propagation in soil and the response of a pile to underground explosions are presented. Results from the numerical modeling are validated using those from the centrifuge tests reported in Shim's study [6].

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Table 1
Scaling laws [18].

Parameter	Model at *N*-g's	Prototype value
Length	$1/N$	1
Area	$1/N^2$	1
Volume	$1/N^3$	1
Mass	$1/N^3$	1
Velocity	1	1
Acceleration	N	1
Force	$1/N^2$	1
Pressure	1	1

Table 2
Dimensions and properties of aluminum pile.

Description	Value
Outer diameter	400 mm
Inner diameter	335 mm
Thickness	65 mm
Alloy and temper	3003 H-14
Modulus of elasticity	71 Gpa
Ultimate tensile strength	150 Mpa
Yield strength	145 Mpa

2. Problem description

Tests on the centrifuge model described in Shim's [6] study, are considered in this paper. Shim carried out a series of 70-*g* centrifuge tests to investigate the blast wave propagation and response of piles embedded in saturated sand. The corresponding prototype model dimensions are used for the numerical simulation. Granier et al. [17] have developed the required similitude principles and scaling laws to extrapolate model dimensions to prototype dimensions. Table 1 presents the scaling laws for common parameters which link the model to an equivalent prototype with respect to a centrifuge acceleration of *Ng*, where *N* is the scale factor and *g* is the acceleration due to gravity. For example a 1 kg charge in a model subjected to 70-g's is equal to 343 ton (or 70^3 kg) of prototype (full scale) explosive. Fig. 1 compares the stresses and strains of a prototype and a $1/N$ scale centrifuge model. It can be seen that the stresses and strains are equal in both prototype and the centrifuge model.

Finite element models are developed for treating an aluminum pile of 10 m length (corresponding to 14.3 cm in the centrifuge model dimension) with hollow circular cross section. Table 2 shows the pile's dimension and properties. Configuration of a generic scenario is shown in Fig. 2. The cylindrical shape blast source is considered at mid depth of the soil (i.e. 5 m from top surface) and distance between pile and explosive is equal to 7.5 m.

3. Approach

The present study was carried out using dynamic computer simulation techniques with the FE modeling code LS-DYNA. Considering the symmetries of the geometrical model as shown in Fig. 2, to save computation time, a quarter of the air domain, soil domain and explosive and half of the pile were modeled as shown in Fig. 3 which shows the five different parts. Eight node solid elements were used for all parts in the FE model for the 3D explicit analysis. The global uniform mesh size was set to be 25 cm in the model. However, the pile was meshed with 25 mm long, eight-node hexagonal brick elements.

Eulerian meshes were generated for the explosive, air and for the part of soil that is relatively close to the explosive. This is to eliminate the distortion of the mesh under high strains. On the other hand Lagrangian meshes were used to model the rest of the system including the pile and the soil region away from the explosive. In the Lagrangian method, the numerical mesh moves and deforms with the physical material. No material passes between elements. As all the material is contained in their original cells, time dependent material properties can be well described. The main disadvantage of a Lagrangian method is that severe mesh distortion can occur as the mesh deforms with the material, and this can lead to erroneous results or termination of an analysis. In contrast, Eulerian analysis involves material flow through a stationary mesh. As the mesh is fixed, there is no mesh distortion problem when large deformations occur. However, the Eulerian method is computationally more expensive than the Lagrangian method and hence an appropriate mix of both methods is used. Thus, soil is modeled with both Eulerian and Lagrangian meshes to address the above shortcomings. The 1-point multi material ALE solver (ELFORM = 11) was used for the explosive, air and near field soil, while the default constant stress solid formulation (ELFORM = 1) was used for the pile and far field soil elements. The materials of the explosive, air and near field soil are specified as multi material using LS-DYNA multi material capabilities (*ALE_MULTI_MATERIAL_GROUP).

The blast pressure is applied to the pile foundation indirectly. Blast pressure is generated by an LS-DYNA algorithm, which utilizes the equation of state for high explosives. The JWL (Jones–Wilkin–Lee) equation of state (EOS) was used with the high explosive material model to model the H6 explosive. The JWL equation of state defines the pressure *P* as a function of the relative volume, *V* and initial energy per volume, *E*, such that [16]

$$P = A\left(1 - \frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1 - \frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \quad (1)$$

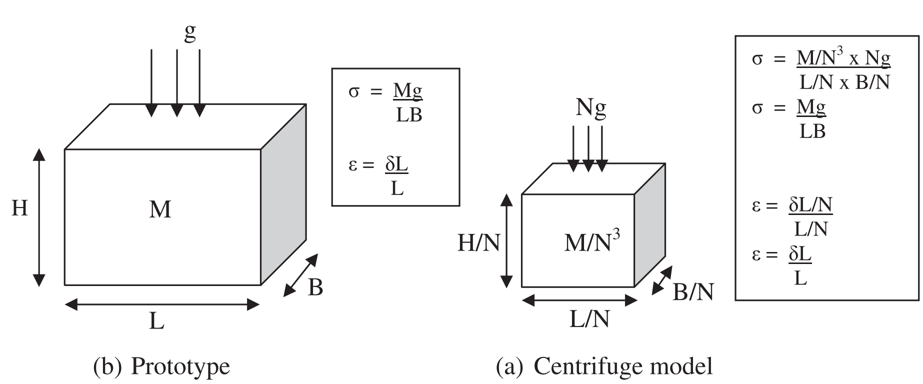

Fig. 1. Stress similarity in prototype model and centrifuge model.

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