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Analysis of hollow steel piles subjected to buried blast loading

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ABSTRACT

Dynamic analyses of hollow steel end bearing piles in sandy soil subjected to buried blast loading are performed herein using the three-dimensional nonlinear finite element method and the coupled Eulerian–Lagrangian technique. Parametric sensitivity studies are performed for different axial load magnitudes on the pile head, elastic moduli, mass densities, different friction angles of soil and Poisson's ratio. The lateral deflection of the pile head decreases with increasing axial load. The peak particle velocity in soil increases with a decrease in elastic modulus, mass density and friction angle of soil and increases significantly if the soil is incompressible.

1. Introduction

A pile is a load bearing component of a structure that transfers the structural load to the hard soil or rock underground. The modern human civilization and smart infrastructure depend largely on the pile foundation for carrying its structural load because the pile foundation reduces the area of load distribution in the surroundings near the ground surface and thus, considered as a suitable foundation system in the regions with more congestion and a higher number of tall buildings. However, failure of a single pile can lead to disaster by causing progressive failure of the superstructure and the surrounding structures [14]. In the recent decades, terrorist attack and bomb blast have caused failure of several structures. A small magnitude of the blast, if it happens in the close vicinity of one pile may lead to progressive failure of the whole structure [5]. Moreover, the failure of the structure often starts from the soil because the soil is the weakest of all civil engineering materials. Hence, it is extremely necessary to understand the response of pile foundation in the soil when subjected to blast loading.

Disastrous events like blast inside ground creates ground shock wave that while travelling through soil gives rise to a high rate of loading (up to 10^2/s to 10^4/s) in the soil and rock [19,5]. Drake and Little [4] experimentally studied ground shock wave propagation due to penetration of weapon and detonation of buried explosive in the saturated and unsaturated soil. Wu et al. [28] investigated the ground shock wave propagation through Granite and proposed an equation for peak particle velocity (PPV) of rock. In the Indian Standard Code of Practice, [7] an equation has been proposed for PPV given by

$$\mathrm{PPV} = K_1 \left(\frac{W^{2/3}}{R} \right)^{1.25} \ \mathrm{mm/s} \tag{1}$$

where K_1 is constant and its value is 880 for soils and weathered or soft rock, W is the charge weight per delay in kg and R is the distance from the blast source in m. Many researchers have performed centrifuge and field tests for blast loading on structures. Tabatabai [24] and De et al. [3] performed centrifuge tests of underground structures under blast loading. Shim [22] carried out centrifuge tests to study the response of piles in soil under blast loading. An et al. [2] studied shock wave propagation through soil numerically using LS-Dyna and an equation-of-state model for soil. Jayasinghe et al. [9] and Jayasinghe [8] performed finite element (FE) analysis of aluminum and concrete pile subjected to underground blast loading in saturated and dry soils; however, they did not study the effect of variation of soil parameters on blast response of the pile.

The objectives of the present work are (i) to perform finite element analysis of hollow steel end bearing pile foundation subjected to blast loading, (ii) to study the displacement response of the pile subjected to blast loading under different magnitudes of axial loads on the pile head, (iii) to study the PPV in soil generated due to blast, and (iv) to investigate the stress magnitude generated in the soil due to blast. Blast response of the pile and the surrounding soil is investigated for different axial load magnitudes (Q) on the pile, different elastic moduli (E_{soil}), mass density (ρ_{soil}), friction

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angle (ϕ) and Poisson's ratio (ν_{soil}) of soil. The three-dimensional (3D) nonlinear dynamic finite element (FE) analyses of pile subjected to blast loading are carried out using the commercially available FE software Abaqus version 6.11 (Abaqus manual version 6.11) and the coupled Eulerian–Lagrangian (CEL) tool. The CEL tool in Abaqus has been previously used in geomechanics problems exhibiting large deformation [21,26,25]. In the present analyses, the soil and the pile are modeled using the Lagrangian elements. The trinitrotoluene (TNT) explosive is modeled using the Eulerian elements. Strain rate dependent material properties have been used for both soil and pile. Soil stress–strain response is simulated using the Drucker–Prager constitutive model [13,15]. The stress–strain response of pile is simulated using the Johnson–Cook constitutive model [10]. The pressure–volume relationship of the trinitrotoluene (TNT) explosive is simulated using the Jones–Wilkins–Lee (JWL) equation of state (EOS).

2. Three dimensional finite element modeling

2.1. Lagrangian finite element modeling of soil and pile

The 3D FE model of the pile and soil are developed in Abaqus/CAE using the Lagrangian elements. A typical FE mesh of the soil, pile and explosive are shown in Fig. 1. In order to place the explosive inside the soil, a rounded hole with the same diameter as that of the explosive has been created in the soil domain. The size of the soil domain considered herein is 20 m × 20 m × 10 m. The soil and pile meshes are generated using the eight-node brick element (C3D8R) with reduced integration, hourglass control, and finite membrane strains. Higher accuracy of the analysis is ensured by using higher mesh density in soil close to the explosive and the pile. The minimum and maximum element sizes in the near field and far field regions are 10 mm and 0.1 m respectively. The node-based general contact option in Abaqus is used to simulate the contact between pile and soil with hard contact in the normal direction and frictionless contact in the tangential direction. Among the boundary conditions, the bottom planes of the soil domain and the pile have been fixed in all Cartesian directions, e.g. x, y and z in order to make the pile end bearing. In the current simulations, the effect of reflected wave from the bottom boundary on pile response, however, has not been considered and only the effect of the direct wave on the piles is taken into account. The vertical side planes and the front and back side planes of the soil domain are provided with horizontal fixity and rotational fixity as detailed in Fig. 1 by constraining the normal displacements perpendicular to the planes (U_x or U_y or U_z) and the rotations ($U_{Rx} = U_{Ry} = U_{Rz} = 0$).

2.2. Eulerian finite element modeling of explosive

The explosive material has been modeled using the Eulerian modeling technique in Abaqus. Fig. 1 shows the position of TNT explosive inside the soil domain. In Abaqus CEL modeling option, the Eulerian material flows through the mesh. Thus, the simulation that generates large deformation and stress in the elements and hence, results in error or inaccuracy in the Lagrangian analysis may be successfully carried out using the CEL tool. Herein, Eulerian continuum three-dimensional eight node reduced integration elements (EC3D8R) are used [1] to model the explosive material. The Eulerian elements containing explosive are completely filled with the explosive material while the rest of the Eulerian grid is filled with void. In the Eulerian analysis, the material is tracked by means of Eulerian volume fractions (EVF) when the material flows through the mesh. The EVF represents the ratio by which each Eulerian element is filled with material, i.e. EVF = 1 representing the element completely filled with material and EVF = 0 representing completely void elements. The Eulerian and Lagrangian elements can interact with each other through the general contact option defined between explosive, pile and soil surfaces. Herein, the free outflow boundary condition has been defined at the boundary of the Eulerian domain, thus, blast pressure when reaches the boundaries of the Eulerian domain, may propagate freely out of the domain without any reflection.

The pressure (p) in the TNT explosive can be calculated using the Jones–Wilkins–Lee (JWL) equation of state (EOS) [12] given by

$$p = A\left(1 - \frac{\omega}{R_1\bar{\rho}}\right)e^{-R_1\bar{\rho}} + B\left(1 - \frac{\omega}{R_2\bar{\rho}}\right)e^{-R_2\bar{\rho}} + \omega\rho e_{int} \quad (2)$$

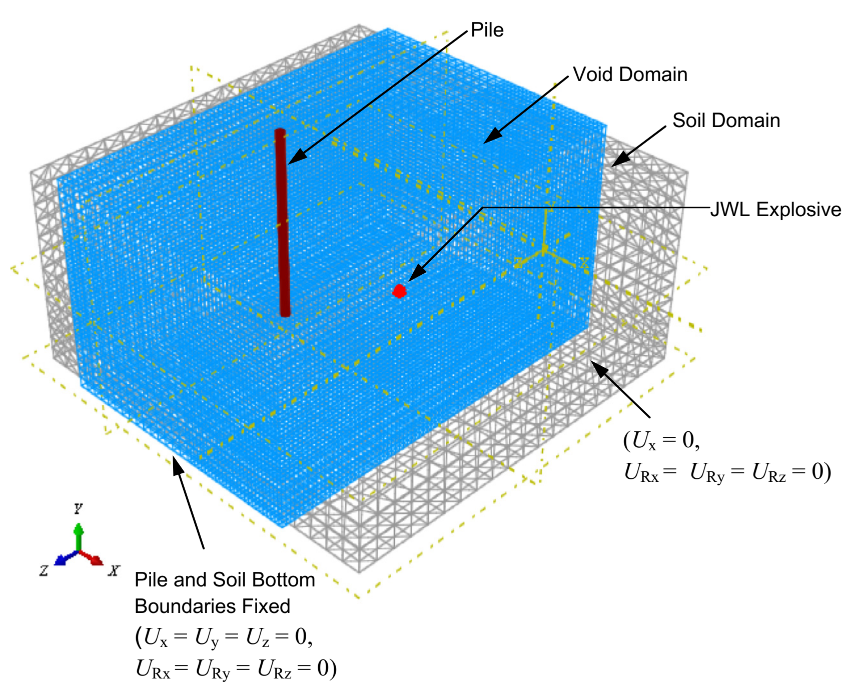

Fig. 1. Typical finite element mesh in a coupled Eulerian Lagrangian (CEL) simulation.