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Blast Induced Ground Shock Effects on Pile Foundations

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Abstract**—**Due to increased number of terrorist attacks in recent years, loads induced by explosions need to be incorporated in building designs. For safer performance of a structure, its foundation should have sufficient strength and stability. Therefore, prior to any reconstruction or rehabilitation of a building subjected to blast, it is important to examine adverse effects on the foundation caused by blast induced ground shocks. This paper evaluates the effects of a buried explosion on a pile foundation. It treats the dynamic response of the pile in saturated sand, using explicit dynamic nonlinear finite element software LS-DYNA. The blast induced wave propagation in the soil and the horizontal deformation of pile are presented and the results are discussed. Further, a parametric study is carried out to evaluate the effect of varying the explosive shape on the pile response. This information can be used to evaluate the vulnerability of piled foundations to credible blast events as well as develop guidance for their design.

Keywords**—**Underground explosion, numerical simulation, pile foundation, saturated soil.

I. INTRODUCTION

MANY countries over the world have confronted a significant increase in terrorist bomb attacks over the past two or three decades. These bombs especially targeted significant and iconic buildings either by indoor and outdoor explosions. The explosion in the World Trade Center in New York on February 26, 1993 is a well-known example of a powerful bomb explosion which occurred inside a building. A truck bomb of 680 kg was detonated in the underground car park causing major damage to the basement of the building as shown in Fig. 1 [1]. However, a car or a truck bomb explosion in the vicinity of the building has attracted significant attention in the recent past. This scenario could result in a very large charge weight 5 to 10 tons TNT equivalency from large vehicles parked very close to a building. Alfred P. Murrah Federal Building bombing incident in Oklahoma City on April 19, 1995 is one of the largest terrorist attack caused by a truck bomb which detonated outside the building. Fig. 2 shows the extensive damage to the Murrah building following the attack [2]. Due in most part to the widely publicized terrorist attacks of September 11, 2001, and the following Bali bombing of October 12, 2002, the general public has an increased awareness of the risk of terrorist attacks, and consequently there exists an increased fear of terrorism [3].

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Fig. 1 WTC tower after the 1993 bomb attack [1]

Fig. 2 Alfred P. Murrah Federal building after the 1993 bomb attack [2]

Currently, Australian and international standards have limited provisions for designing structures for terrorist attacks. It is necessary to determine the level of risk, as well as the probability of an explosion in order to determine whether a blast resistant design is required. It is then advisable to examine the possible blast effects before establishing a blast resistant design method. The risk and probability study should aim to prevent disproportionate explosions where little effort is required to inflict a significantly greater impact on the structure. Another recommended outcome would be the provision of a budget for the prevention of explosion induced damage or injury.

Historical records indicate that the majority of terrorist incidents have occurred using a car or a truck bomb where the height of detonation of the bomb is small. In such cases the explosion occurs near the ground surface. This will cause various types of waves to be generated and these waves propagate radially from the initial charge point. A surface explosion generates both ground shock and air blast pressure on structures which are close to detonated point. However, wave propagation velocities are different for geo-materials and air, and hence the ground shock excites the structure foundation earlier than the air blast pressure exciting the structure. In some cases, both the ground shock and the air blast pressure might act on the structure simultaneously. This depends on the distance between explosion center and the structure and the properties of the ground [4]. But in most scenarios, the ground shock excites the structure before the air blast pressure and can damage the pile significantly. The failure of pile foundation could result in subsequent damages, such as partial settlement and tilting of the superstructure, leading to cracking and weakening of those structures. Additionally, severe ground shock could cause blast-induced liquefaction. Therefore, it is important to examine adverse effects on foundation caused by ground shocks prior to any reconstruction or rehabilitation procedures. Detailed investigation of foundation response to blast induced ground shocks is rare in the literature. This research will therefore fulfill the gap by treating the effect of ground shock on pile structures due to surface explosions.

II. Previous Research and Issues

As it mentioned before, terrorists usually target structures, particularly high occupancy iconic and public buildings in order to claim a maximum number of lives and cause extensive damage to public property. Thus, much research has been carried out on blast resistant building design to predict the bomb blast effects on the building. Ngo et al. [5] reported blast loading and blast loading effects on structures. They have given an explanation of the nature of explosions and the mechanism of blast waves in free air. They have also introduced different methods to estimate blast loads and structural response.

In a study carried out by Lan et al. [6], design techniques for protecting reinforced concrete columns from the effects of close in detonation of a suitcase bomb have been considered. LS-DYNA software was used for detailed analysis. It was shown that the tie spacing plays an important role in the post-blast residual load capacity of the columns.

Bao and Li [7] used numerical simulations with LS-DYNA to study the dynamic response and residual axial strength of reinforced concrete columns subjected to short standoff blast conditions. The model was verified through correlated experimental studies. A formula was proposed for estimating the residual axial capacity based on the mid height displacement.

Jayasooriya et al. [8] proposed a method to assess vulnerability, damage and residual strength capacity of building frames and component elements when subjected to near field blast events. However, those previous studies mainly investigated loads induced on structure components by air propagated blast shock waves. Relatively less attention has been paid on the blast loading on and response of foundation.

The evolution of centrifuge tests had led to some studies on the dynamic response of underground structures to blast loading [9, 10]. Shim [11] used centrifuge models to study the response of piles in saturated soil under blast loading. Shim carried out a series of 70-g centrifuge tests to investigate the blast wave propagation and response of piles embedded in saturated sand. Several tests have been carried out on Aluminum piles with hollow circular section at different standoff distances.

To this date large number of computer programs have been developed to study the response of underground structures subjected to blast load. These programs use finite element methods, finite difference methods, or some combination of the two with implementation of various constitutive models, integration techniques and soil-structure interaction interface.

Yang et al. [12] discussed blast resistant analysis for Shanghai metro tunnel using explicit dynamic nonlinear finite element software LS-DYNA. The overall analysis evaluated the safety of the tunnel lining based on the failure criterion. Since there have not been any established common standards governing the design of such a structure, a series of parametric studies have been carried out in order to evaluate the significance of several parameters, such as shear modulus and bulk modulus of soil, on the lining thrust.

Nagy et al. [13] investigated the response of a buried concrete structure to various factors affecting structural performance by carrying out a parametric study using the FE model. Depths of the structure and charge were considered as parameters. It was shown that buried explosions result in significant effects on the buried structure than surface explosions under the same conditions (of charge weight, properties of structure and soil).

III. Proposed Research

This research aims to investigate the effect of blast loads generated as a result of explosive charges on pile foundations of a typical building. Response of the pile will be investigated for ground shock caused by both surface and underground explosions. The validation of the numerical techniques is first presented in this paper.

The response of pile foundation under buried blast is numerically studied through the commercial software package LS-DYNA [14]. The results from the experiments described in Shim's [11] study are considered for the validation of the numerical models. Although Shim [11] carried out tests on scaled down centrifuge models, finite element models were developed for the corresponding prototype dimensions in present study. Similitude principles and scaling laws presented by Granier et al. [15] were used to extrapolate model dimensions to prototype dimensions.

FE modeling includes two parts; first geometry was completed using MSC PATRAN which has been designed based on LS-DYNA solver. In the second part, simulation was completed using LS-DYNA solver. LS-DYNA uses explicit time integration algorithm for solving problems. It was originally developed to solve problems in wave propagation and impact engineering. In an explicit FEM, the solution can be achieved without forming a global stiffness matrix. It solves on the basis of element by element, and updates the stiffness matrix at the end of each increment of load (or displacement) based on changes in geometry and material. As a result, the explicit FEM can treat large three-dimensional models with comparatively modest computer storage requirement.

The overall the geometric model is divided into different regions representing the soil, air, pile and explosive materials as shown in Fig. 3. By making use of symmetry, only a quarter of the system was modeled. Eulerian meshes were generated for the explosive, air and for a part of soil that are close to the explosive. This is to eliminate the distortion of the mesh under high deformations. 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. Eight-node solid elements (brick elements) were used for all parts. The materials of the explosive, air and near field soil are specified as multi material. Multi-material option means that up to three different materials can be modeled within same mesh [16]. Thus, using this technique, the meshes are fixed in space and the explosive product is able to expand into the initial soil mesh or air mesh. Similarly the soil can move into the initial air mesh.

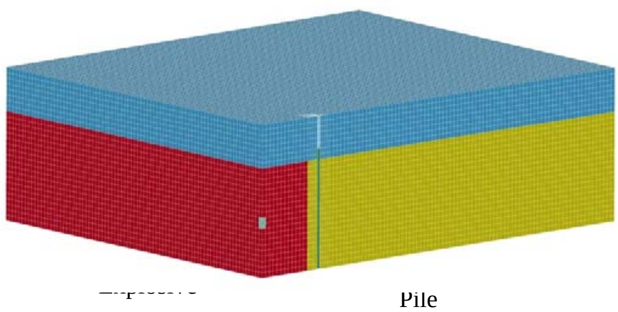

Fig. 3 Finite element model

The present study adopts the fully coupled numerical simulation approach. Explosive was modeled using high explosive burn material model with JWL equation of state to generate blast pressure in the model by expansion of the detonation product [14].

To form the symmetry in the FE model, the translational displacements of nodes normal to symmetry planes were constrained. The nodes along the interfaces between the air and soil were merged. Bottom of the mesh was considered as fixed in all directions. Fixed boundary conditions were assigned to for the top and bottom nodes of the pile.

IV. Results and Discussions

By comparing the numerical and experimental results [11], it was found that the developed numerical models correctly predict the experimental results. The results were compared in two parts. First, stresses in the soil were compared and then pile deformation was compared. The results from the simulations are presented, compared and discussed in the following sections.

A. *Free Field Stress in Soil*

Saturated soil was modeled using FHWA soil material model in LS-DYNA. This material model was chosen because it includes strain softening, kinematic hardening, strain rate effects, element deletion and excess pore water effects. Since, in saturated soils, voids between soil skeleton are fully filled by water, it is important to consider excess pore water effects. FHWA soil model incorporates this in the calculations.

Shim [11] obtained free field stresses in the soil at 7.1, 10.7, 14.3, 17.9, 24.3, 28.6, and 35.7cm measured horizontally from the charge. These results correspond to the results from numerical model at 5, 7.5, 10, 12.5, 17, 20 and 25m, respectively. Fig. 4 shows the comparison of the peak stresses in the soil obtained from shim’s [11] experiment and present numerical model. It can be observed that the correlation is quite good between the two sets of results.

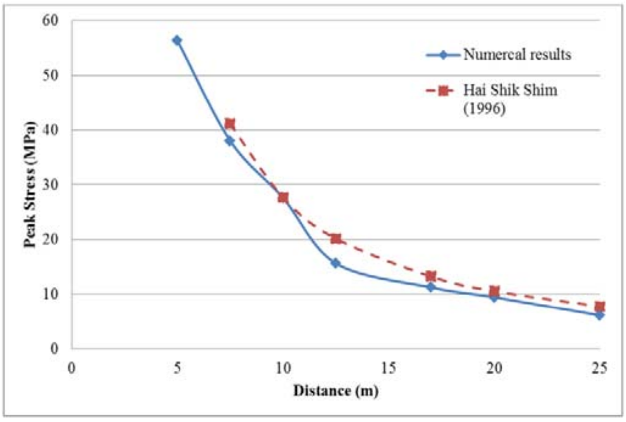

Fig. 4 Comparison of peak stresses

B. *Response of Pile*

10 m high pile having a circular hollow section, with 400mm outer diameter and 335mm inner diameter, was modeled using piecewise linear plasticity material model in LS-DYNA to model the elasto-plastic response with strain rate dependency. Properties of Aluminum alloy 3003 H14 were considered to define the material parameters. In the numerical analyses, three standoff distances, i.e. 7.5m, 12.5m and 17m, are considered to analyze the pile response to underground explosion.

The horizontal deformation of the pile was obtained at different heights on the pile from the pile tip (base). Fig. 5 shows the comparison of the horizontal deformations of the pile for different standoff distances. It is evident that the pile has suffered permanent deformation and its response decays significantly with the standoff distance.

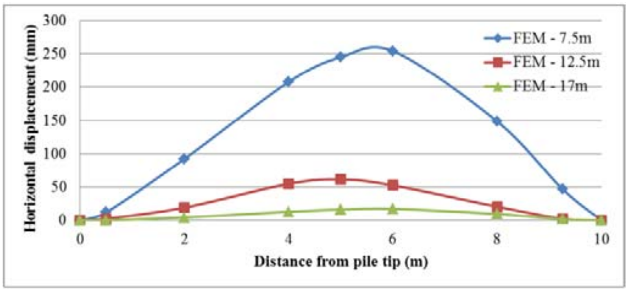

Fig. 5 Horizontal pile deformation at 7.5m, 12.5m and 17m standoff distances

Fig. 6 shows the comparisons of the pile deformations obtained from the numerical models and experiment tests and it is evident that the two sets of results compare well. These observations provide adequate confidence in the present modeling techniques.

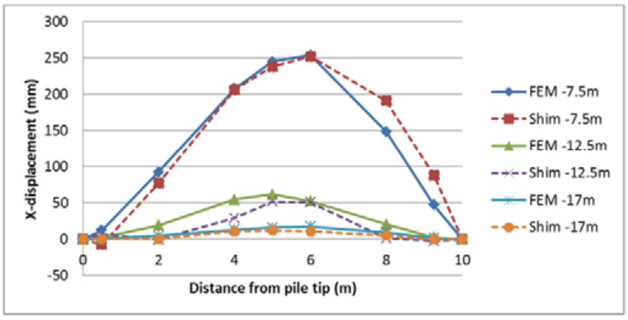

Fig. 6 Comparison of horizontal pile deformation

Furthermore, the analysis also focused on the maximum Von Mises stress in the pile, which determines the yield and damage of the pile. Fig. 7 shows the effective stress response of the pile for a standoff distance of 7.5m at 0.75s. From the figure one can clearly see that the pile is severely damaged, especially, at the ends and the middle region of the pile.

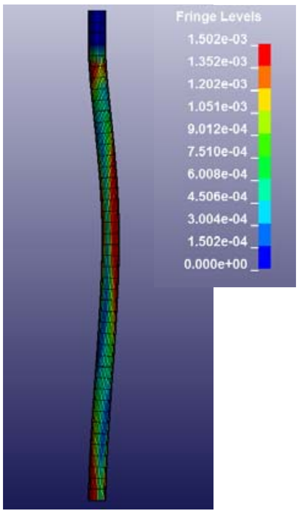

Fig. 7 Effective stress on the pile at 0.75s

V. Parametric Study

In order to study the effect of explosive shape on the pile response, analyses were carried out using the same finite element model and material parameters. Cylindrical, spherical and cubic shapes of H6 explosives having same weight situated at the mid depth of the soil were considered to investigate the pile response. Distance between pile and charge was considered as 7.5m for all the cases.

Fig. 8 shows the residual horizontal deformations of the pile caused by explosion with different explosive shapes. The pile was found to have a maximum lateral residual deflection of 254mm for the blast loads induced by cylindrical charge. The corresponding maximum lateral deflections were 219mm and 170mm for the spherical and cubic shape charges occurring at approximately 6m and 5m heights of the pile respectively.

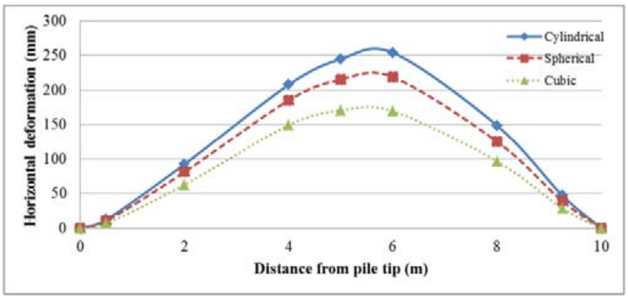

Fig. 8 Comparison of horizontal pile deformation for different explosive shapes

From the above results, the shape of the explosive material can influence the response of the pile under same conditions. Cylindrical shape has the maximum effect on the response of the pile. Thus consideration of the shape of the explosive will be important in the study of the blast response of pile or any underground structure.

VI. Conclusion

The dynamic response of pile foundation to ground shocks induced by a buried explosion has been evaluated using the commercial computer program LS-DYNA. The numerical results have provided good agreement with the experimental results in reference [11]. This provides adequate confidence in the modeling techniques used in this study. Furthermore, response of pile has been investigated for different explosive shapes, and it was found that cylindrical shape explosive has the maximum effect on the pile behavior.

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