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PILE FOUNDATION RESPONSE TO GROUND VIBRATION FROM ROCK BLASTING

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ABSTRACT

Ground vibrations from blasting are undesirable and they are very short in duration with high principal frequencies and high amplitude. Structural response to that kind of excitations may differ significantly from that generated by lower-frequency earthquake vibrations. In practice, the damage to nearby structures to generated ground vibrations has been controlled by various codes and regulations available. However, the existing vibrations limits are not always applicable, as they depend on the geological conditions of the site and the dynamic characteristics of the structure. This paper investigated the influence of the rock-soil interface on the response of pile foundation to ground-borne vibration from rock blasting, through numerical simulations using finite element software LS-DYNA. It is found that the slope of the rock-soil interface greatly influences the location of damage and the extent of damage on the pile. The bottom of the pile is subjected to a larger blast pressure and stresses are highly concentrated at the pile bottom. Thus, the pile bottom can fail in shear before it reaches its plastic moment capacity.

Keywords: rock blasting, numerical simulation, pile foundation

INTRODUCTION

Drilling and blasting is the widely accepted method to large-scale rock breaking activities in civil engineering constructions due to its cost effectiveness, higher efficiency and ability to break hard rock. However, ground vibrations from blasting are undesirable and it can cause damage to nearby structures. In practice, the damage to nearby structures to generated ground vibrations has been controlled by various codes and regulations available. The existing vibration limits are not always applicable, as they depend on the geological conditions of the site and dynamic characteristics of the structure.

Pile foundations are commonly used as foundations of high-rise buildings and bridges to transfer the heavy loads from the superstructure above through weak compressible soil strata into deeper, competent soil layers which have adequate capacity to carry these loads. In engineering practice, many piles are normally designed to carry mainly vertical loads and very little lateral loads, as typically the vertical loads (the gravity) are significantly larger than the horizontal loads such as wind loading. However, in recent years, there have been a number of reported case studies of translational soil movements that have induced stresses and bending moments that have damaged pile foundations and in some cases resulted in collapse of the superstructure. Typical lateral load include nearby construction activities such as an excavation for a basement or slope, the construction of a road embankment or a tunnel, as well as earthquakes (Abdoun 1997; Goh et al. 1997; 2003; Chen et al. 1999; Dobry et al. 2003; Boulanger et al. 2007; Black et al. 2007).

Short duration, high frequency, high amplitude loads such as rock blasting may also have an impact on the pile foundation system. The ground vibration can induce lateral and bending stresses in the piles and cause significant damage, resulting in differential settlement and tilting of the superstructure, leading to weakening of the structure. Thus, the lateral response of piled foundation is important in the designing of structures that may be subjected to lateral loads. The performance of pile foundations subjected to dynamic lateral loads is a complex research area, as the laterally loaded pile is a threedimensional problem, and the soil-pile interaction (SPI) is extremely complex as non-linear and dynamic conditions exist simultaneously and also it plays a significant role in the pile response to ground vibrations (Wu and Finn 1997)

Unfortunately, studies and discussions on the damage and failures of piles under blasting vibration are limited in the literature. Thus, it is necessary to study the performance of piles under blast loading, because of the wide application of blasting and to highlight their impact on the surrounding piled foundation structures.

PROBLEM DESCRIPTION

The present study aims to assess the damage on a pile foundation system subjected to ground vibrations from rock blasting. A pile group of two 600 mm diameter circular reinforced concrete (RC) piles of 8 m length is considered in this study. The distance between the leading pile of the pile group and the blast hole is 7.5 m and blast responses of piles are studied when fully coupled charges are detonated. Moreover, a sloping soil-rock interface is considered in the present study as shown in Fig. 1. Three different slope angles (α) are considered for the purpose of comparison as shown in Table 1.

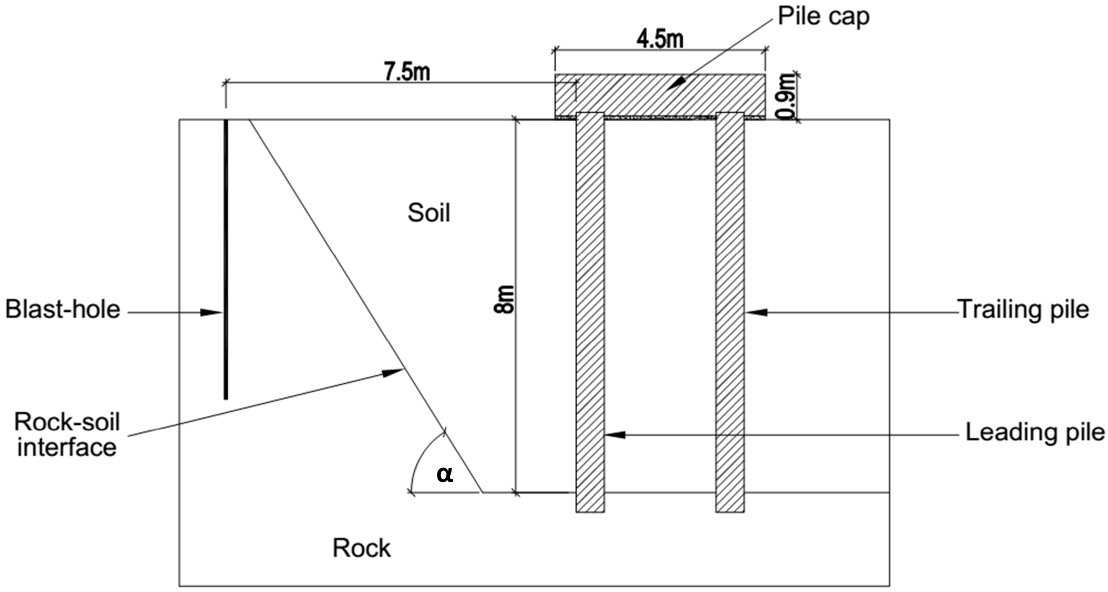


Fig. 1. Cross-section of pile group

Table 1. Analysis cases

Analysis case	Slope angle (α)
1	60°
2	75°
3	90°

NUMERICAL SIMULATION

Currently, a number of Finite element (FE) codes are available that are capable of analyzing challenging engineering problems, but selection of the appropriate numerical technique is dependent on the type of problem and its computational cost. The commercial software package LS-DYNA (LSTC, 2007) which is a non-linear, dynamic analysis software, suitable for modeling large strain problems including blasts and impact was used in this study. The software allows different numerical simulation techniques such as Lagrangian, Eulerian, Arbitrary Lagrangian-Eulerian (ALE) and

Smooth particle hydrodynamics (SPH). This paper uses coupled SPH-FEM technique in LS-DYNA to investigate the response of a pile group of 2 piles subjected to ground vibration from rock blasting.

By making use of the symmetry of the model, only a half symmetry-geometrical FE model was developed to minimise the computational time. Fig. 2 shows the developed 3D FE model to study the the response of piles subjected to ground vibration from rock blasting. The explosive charge, stemming materials and the part of the rock experiencing large deformations were modelled with SPH particles while the rest of the model (rock and soil) was based on Lagrange FEM element. The symmetry face is fixed against translational displacements normal to the symmetry plane. Non-reflecting boundaries are applied to the other surfaces, except the top surface which has the free boundary condition.

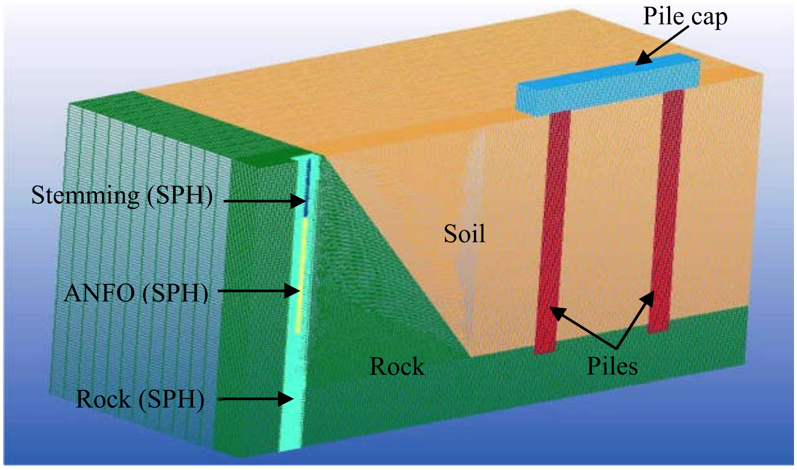


Fig. 2. A half symmetrical model

The 3D FE model was developed for the 8 m long reinforced concrete (RC) piles with 600 mm diameter circular cross section. Both the leading and tailing piles are socketed 1 m into the rock. The piles were reinforced with 8 numbers of 16 mm diameter bars, providing a vertical reinforcement ratio of 0.6% and spiral reinforcement of 10 mm bars at spacing of 200 mm. Except for the reinforcing cage, eight-node solid elements were used for the 3D explicit analysis. Both the vertical reinforcements and the ties were modelled with 25mm long beam elements having 2x2 Gauss integration. The vertical reinforcements were defined as Hughes-Liu beam elements with cross-integration and ties were defined as truss elements. The ANFO explosive, stemming material and part of rock close to the explosive were modelled with SPH particles while Lagrangian meshes were used to model the pile, soil and the rock region away from the explosive charge. The simulations used automatic node to surface contact conditions for the coupling interaction between the SPH particles and Lagrange FEM elements.

Nonlinear effects near the explosive source were considered to accurately model the physical behaviour. There are several material models for rock implemented in LS-DYNA. The plastic kinematic model was used to simulate the constitutive characteristics of rock under blast loading. The physical and mechanical parameters of the Bukit Timah granite are described in Jayasinghe et al. (2017) and were used in the simulations. The constitutive behaviour of the soil model is also an important aspect in wave propagations in soil and SPI analysis. Generally, there are two types of soil models that are used in finite element analyses of soils such as elastic models and elastic-plastic models. Elastic-plastic constitutive models such as Mohr-Coulomb and Drucker-Prager can provide a reasonable representation of a typical wave propagation problem. In this study, the Mohr-Coulomb model in LS-DYNA was used to simulate the soil. This material model requires the main parameters of mass density, elastic shear modulus, Poisson’s ratio, friction angle and cohesion. The corresponding parameters for the rock and soil are described in Table 2 and 3, respectively.

Table 2. Material parameters for rock

Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio	Yield stress (MPa)	Tangent modulus (GPa)	Hardening Parameter (β)
2650	61.41	0.27	154.57	24.56	1

Table 3. Material parameters for soil

Density (kg/m^3)	Elastic shear modulus (MPa)	Poisson's ratio	Friction angle	Cohesion (kPa)
1960	140	0.3	30°	22

Concrete_damage_rel3 material model was used to simulate the concrete behaviour. It is a plasticity-based model with three shear failure surfaces and includes damage and strain rate effects (Malvar et al. 1997). The literature has shown that material concrete_damage_rel3 model can successfully incorporate non-linear concrete properties (Thilakarathna et al. 2010; Jayasinghe et al. 2014). The advantage of this model is that unconfined compressive strength and density of concrete are the only two parameters required in the calibration process. In this study, the concrete density and the compressive strength of concrete were assumed as 2300 kg/m^3 and 35 MPa, respectively. In order to account for the increase in strength under high strain rates, a coefficient called the dynamic increased factor (DIF) is employed in this analysis. The plastic kinematic model was used to model the vertical and lateral reinforcement. It is an elastic-plastic material model with strain rate effect. A strain rate effect is accounted for using the Cowper-Symonds model which scales the yield stress by a strain rate dependent factor. The parameters of concrete and steel used in this study can be found in Jayasinghe et al. (2017) and are listed in Table 4.

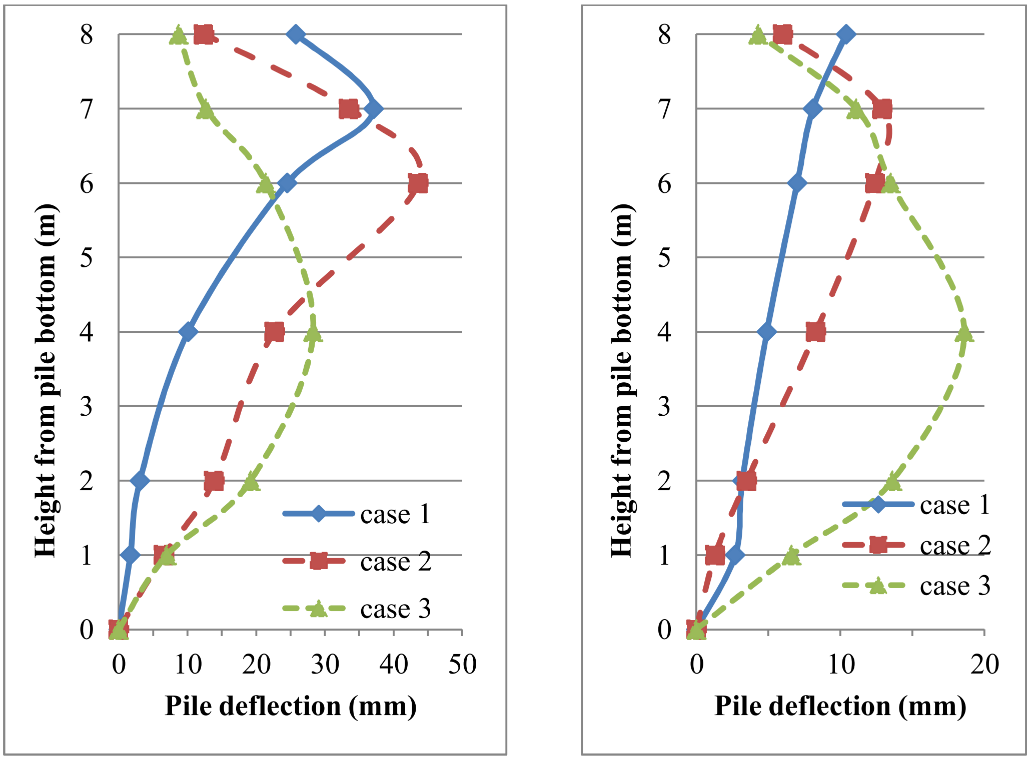
Table 4. Material parameters for steel

	Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio	Yield stress (MPa)	Tangent modulus (GPa)	Hardening Parameter (β)	C	P
Vertical R/F	7850	210	0.3	460	2	0	40	5
Ties	7850	210	0.3	250	2	0	40	5

RESULTS AND DISCUSSION

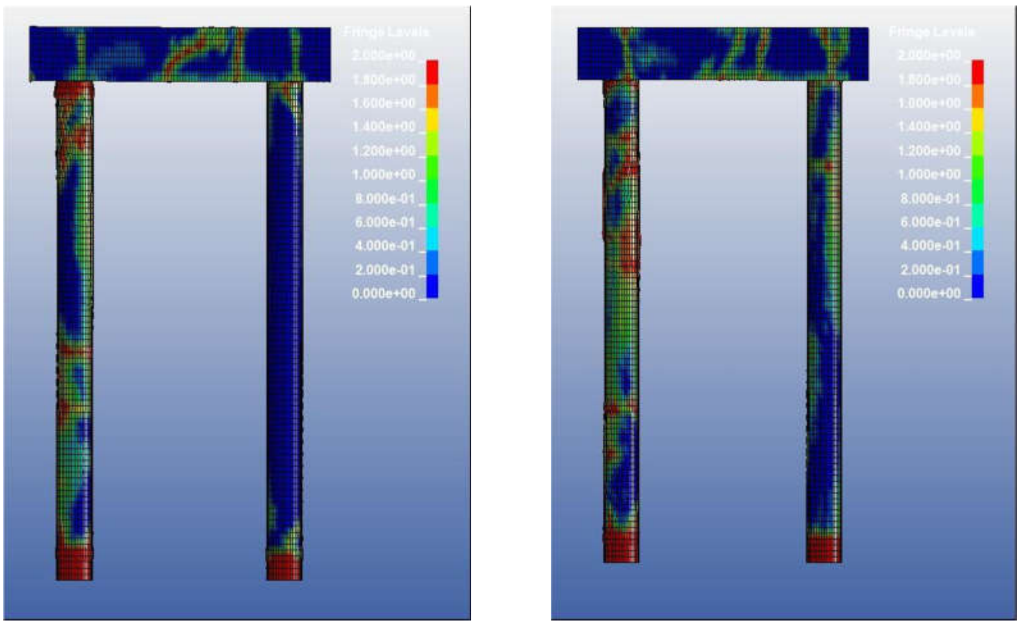
The horizontal deformations of the pile were obtained at 7 monitoring points along the pile at different heights from the pile bottom: 0 m, 1 m , 2 m, 4 m, 6 m, 7 m and 8 m, in each case. Horizontal deforamtions of the piles obtained in each case are compared as shown in Fig. 3. Figure 3(a) shows the horizontal deformation of the leading piles in the pile groups. It is clearly seen that the pile is subjected to a maximum deformation of 37 mm at a height of 7 m above the pile bottom in case 1. However, it was found that the leading pile is subjected to a maximum deformation of 44 mm at a height of 6 m above the pile bottom and 29 mm at the mid-height, in cases 2 and 3, respectively. Figure 3(b) shows that the horizontal deformation of the trailing piles in the pile groups. It can be clearly seen that leading piles of the 2-pile groups are subjected to larger deformation than the trailing piles. They have pile head displacements of 26 mm, 12.5 mm and 8.7 mm in cases, 1, 2 and 3, respectively.

To further study the behavior of each pile, blast damage in each pile in the pile groups were examined using the effective plastic strain diagrams. Fig. 4 depicts the concrete effective plastic strain variation of each individual pile in the pile groups. The effective plastic strain in the concrete_damage_rel3 material model is the damage parameter which ranges between 0 and 2, with fringe levels 0 and 2 indicating no yielding and maximum yielding of the concrete, respectively.

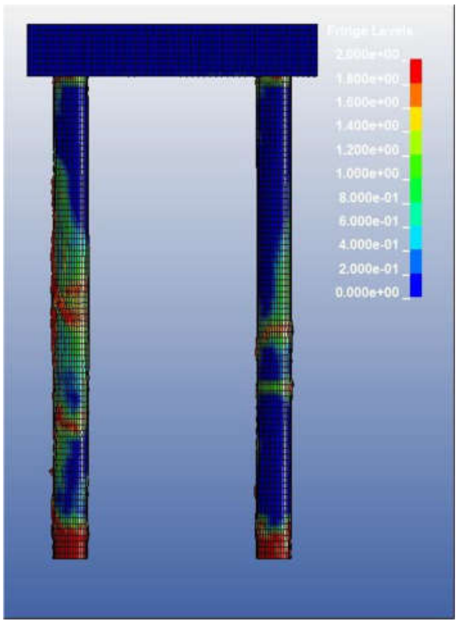


(a) (b)

Fig. 3. Comparison of pile deformations obtained in cases 1 to 3 (a) leading pile of pile groups (b) trailing pile of pile groups



(a) (b)



(c)

Fig. 4. Results for effective plastic strain diagram of concrete in (a) case 1 (b) case 2 (c) case 3

As can be seen in Fig. 4, a significant portion of each pile has suffered damage and local failure, as the effective plastic strains are greater than 0. It is also clear that the bottom of the piles were significantly damaged in all cases. This is because of the bottom of the pile is subjected to a larger blast pressure and stresses are highly concentrated at the pile bottom. Because of this, the pile bottom can fail in shear before it reaches its plastic moment capacity. Also as expected, the trailing pile has less damage and deformations due to shielding effect from the leading pile.

The formed shapes of the piles are different in each case. It can be noted that the top of the pile suffered the most damage in the analysis case 1 compared to the other two cases while concrete in the middle of the pile suffered most damage in the analysis case 3. Therefore, it is clear that the slope of the rock-soil interface greatly influences the location of damage and the extent of damage on the pile.

CONCLUSION

This paper investigated the influence of the slope angle of the rock-soil interface on the dynamic response of a reinforced concrete pile foundation system to ground-borne vibration from rock blasting using the commercial computer program LS-DYNA. A downslope soil-rock interface was considered in the present simulation. Through the comparison of numerical simulation results, it was demonstrated that the rock-soil interface affects the ground wave propagation significantly and hence the location of damage and the extent of damage on the pile are greatly influenced by the slope of the rock-soil interface. In addition to that, because the wave attanuation in the rock is slower than in soil, the bottom of the pile is subjected to a larger blast pressure and stresses are highly concentrated at the pile bottom. Because of this, the pile bottom can fail in shear before it reaches its plastic moment capacity.

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