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A field study on pile response to blast-induced ground motion

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ABSTRACT

A series of field tests using controlled blasting was conducted at a location in the North Western part of Singapore to assess the behaviour of pile foundations subjected to ground excitation. The field tests involved three piles with different pile head fixity conditions. The piles were instrumented with strain gauges to evaluate the bending moments and axial force along the piles. For the fixed-head piles, the maximum bending moment occurred at the pile head level. For free-head pile exhibited higher bending moments close to the mid-height of the pile and zero bending moment at the pile head due to the absence of restraints at the top. For all cases, the axial force was maximum at the pile head.

1. Introduction

In a construction blasting operation, the main function of explosives is to break the rocks through the release of large amounts of energy. However, only a portion of the energy is consumed in breaking the rocks and the remaining energy is dissipated in the form of seismic waves expanding rapidly outward from the blast as ground vibrations and air blast. Ground vibrations from rock blasting are a particular concern as the vibration which has a high amplitude and short duration can cause damage to nearby structures in one or several ways. For example, blasting induced ground vibration may compact the foundation soil on which the structure is built, resulting in distress to the structure. When the natural frequency of the structural member(s) coincides with the frequency of the impinging ground vibrations, resonant vibrations are produced and cause substantial damage to the structure. In addition, ground vibrations which have high frequency and high amplitude may also have an impact on the various components of the structure so that the strength of the member or material is exceeded. Moreover, soil can be liquefied beneath or adjacent to the structure as a result of blasting, resulting in substantial damage to foundations and consequently to the superstructure.

Generally, for the safer performance of any structure, the foundation should have sufficient strength and stability. Nowadays, high-rise buildings, bridges and other smart infrastructures depend largely on the pile foundation for transferring 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 designed only for carrying vertical loading, as typically the vertical loads (from the gravity weight of the structure) are significantly larger than the horizontal loads such as wind loading. Short duration, high frequency and high amplitude loads such as ground vibrations from rock blasting may also have an impact on the pile foundation system. They 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 [1]. A small magnitude of a blast, if it occurs in close proximity of a pile, it may cause the pile to fail which can subsequently lead to progressive failure of the whole structure [2,3]. It is therefore important when designing structures that may be subjected to the ground vibrations from rock blasting to assess the stability and vulnerability of a pile foundation system against ground-borne vibrations.

The influences of ground vibration on pile foundations have been studied by researchers using small-scale experiments and numerical simulations. Abdoun et al. [4] and Wilson et al. [5] carried out small-scale centrifuge tests to study the dynamic response of pile foundations in liquefying sand during seismic loading. Shim [6] also has carried out a series of 70-g centrifuge tests to investigate the blast wave propagation and response of piles embedded in saturated sand. Aluminium piles with hollow circular section at different standoff distances from buried the explosive charge were used in the test. Kamijo et al. [7] conducted vibration tests at a large-scale mining site to investigate liquefaction phenomena and dynamic responses of pile foundations. Ground

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motions from large-scale blasting operations were used for the vibration tests. It is found that bending moments were maximum at the pile heads, regardless of input motion levels. However, the moment distribution shapes differed with the degree of the liquefaction in the test pit Ashford et al. [8] conducted full-scale tests to assess the dynamic response of a single pile, a four-pile group, and a nine-group subjected to lateral spreading. The steel pipes were 11.5 m long with an outer diameter of 318 mm and thickness of 10.5 mm. The test results indicated that the pile head displacement and moment in the single pile were significantly higher than those observed in the pile groups. It is also found that the degree of fixity at the pile tips had a great influence on the moments of individual piles in the group. Large bending moments are developed in the pile when the larger degree of fixity into the dense soil layer. Durante et al. [9] performed 1-g shaking table tests to investigate the dynamic response of a single pile and a pile group subjected to both horizontal and vertical dynamic shaking. The studies have shown that the kinematic interaction may be significant near the pile head if rotations are prevented and close by the interface between soil layers with different stiffness [10–12].

A number of researchers have developed numerical methods to analyse the performance of pile foundations subjected to dynamic lateral loads [13–17]. Hao et al. [18] presented a numerical method to calculate the elastic and inelastic single pile responses to blast loads. The pile-soil system was modelled as beam-column elements supported by both vertical soil springs of Winkler foundation. However, this method cannot incorporate the radial and three-dimensional components of interaction. The shear stress which is acting along the side of the pile is ignored by this method. Since a 3D FE analysis requires a considerable amount of computational cost for generating input and interpretation results, it has not been used frequently until recently for the soil-pile interaction analyses. Huang et al. [19] studied the dynamic response of pile-soil-structure interaction (PSSI) system under blasting load. Solid elements were used to simulate piles, soil and pile cap, while beam elements were used to simulate columns and beams of the superstructure. In this study, they applied a velocity-time history curve of blasting seismic wave on the tip of the pile. The authors have concluded that because of the maximum shear stress at the top of the pile, the connection of piles and pile cap are easily damaged and pile-soil contact pressure increases at the pile ends. Jayasinghe et al. [20] developed a fully coupled method to treat the blast response of a pile foundation in saturated soil and the effects of end restraint of pile head and the number and spacing of piles within a group were investigated later [21].

The objective of the present study is to investigate the impact of rock blasting on pile foundations. Thus, a series of field tests was conducted at a location in the north western part of Singapore to study the pile response and possible damage when subjected to ground excitation of various intensities. In this paper, a brief description of the test set-up and the pile instrumentation is presented first. Then, the measured results and the calculated bending moments and axial forces are presented and discussed.

2. Test set-up

In Singapore, bored cast-in-situ concrete piles are commonly used as the foundation for high-rise buildings. Chang and Broms [22] reported that approximately 200,000–400,000 m length of large diameter bored piles are installed in Singapore each year, because of the high capacity, relatively low costs, easy length adjustment, and low noise and vibration levels during construction. The diameters of these piles vary from 600 mm to 1500 mm depending on the design load on the pile. The piles can be end-bearing piles, friction piles or a combination of end bearing and friction piles. Socketed piles are widely used in the Singapore construction industry as well as all over the world. Socketed piles are usually end-bearing piles which are socketed into a weathered/soft rock. Socketing piles into a soft or weathered rock will improve the

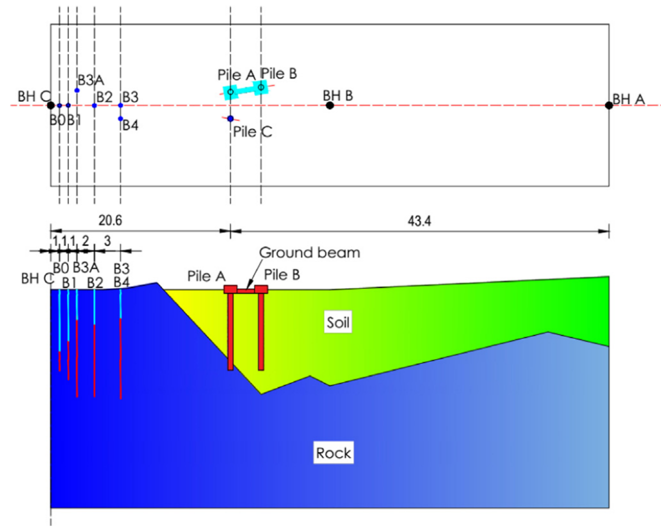

Fig. 1. Plan and section view of the piles and blast holes locations (units of meters).

axial and lateral load capacities of piles when the surrounding soil above the rock is weak.

Before the field blast tests, soil investigation works were carried out to establish the subsurface ground conditions. The layout of the test site is shown in Fig. 1. The test site consisted of medium-grained granite bedrock, overlain by residual soils [23]. The rock-cores retrieved from the boreholes, indicated the occurrence of Bukit Timah Granite rocks [24]. The slightly weathered granite G (II), was encountered at depths of between 0.6 m and 11 m below the ground level.

In the field test, three instrumented bored cast-in-situ concrete piles (1 single pile and a pile group of 2 piles) were used to investigate the response of piles subjected to rock blasting induced ground vibration. All the piles were 600 mm in diameter, and an average length of 8 m. Two piles (pile A and C) were socketed into rock while the other one (pile B) was embedded in soil. Moreover, two piles (pile A and B) had pile caps to prevent the rotation at pile head and the other pile (pile C) had a free end at the pile head level. The dimensions of the pile caps were 1.5 m (width) x 1.5 m (length) x 0.9 m (height). A ground beam which has cross section of 0.5 m x 0.5 m was used to connect the pile A and B.

The compressive strength of the concrete was 53.7 N/mm^2 at 28 days and all the piles were nominally reinforced with 8 numbers of 16 mm diameter of high strength deformed bars (characteristics strength of 460 N/mm^2) for the main vertical bars and 10 mm diameter of high strength deformed bars (characteristics strength of 460 N/mm^2) at 200 mm centre to centre spacing for the stirrups as shown in Fig. 2.

In total, six numbers of blast tests were carried out as summarised in Table 1. The first 2 blast tests (B0 and B1) were carried out to check and test the data logger's settings, and the remaining four blast tests (B2, B3, B3A and B4) were conducted to study the pile response under blast-induced ground vibration. The sequence of the tests was B0, B1, B2, B3, B3A and B4, respectively. Each blast hole was 76 mm in diameter and the explosives used in the tests were Ammonium Nitrate-Fuel Oil (ANFO). The detonator used in the test was an electronic detonator. Also shown in Fig. 2 are the locations of the blast holes (denoted by the notations B0, B1 etc.). All the distances are measured from the reference borehole C (BH C), which was used in the soil investigation works.

The other important concern in this test was pile instrumentation. The main objective of pile instrumentation was to obtain the pile response along the pile shaft. The instrumentation consisted of installing strain gauges and force transducers at selected levels of the pile. The pile deformation and blast pressures on the pile were measured using