Computers and Geotechnics 82 (2017) 1–15

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Pile response subjected to rock blasting induced ground vibration near soil-rock interface

L.B. Jayasinghe, H.Y. Zhou, A.T.C. Goh *, Z.Y. Zhao, Y.L. Gui

School of Civil and Environmental Engineering, Nanyang Technological University, Singapore 639798, Singapore

ARTICLE INFO

Article history:
Received 10 June 2016
Received in revised form 22 September 2016
Accepted 30 September 2016

Keywords:
Rock blasting
Numerical simulation
Pile foundation
Wave propagation
Smooth particle hydrodynamics

ABSTRACT

Blasting has been widely used in mining and construction industries for rock breaking. Ground vibration induced by blasting is an inevitable side effect that may cause damage to nearby structures, if not properly controlled. In this study, response and possible damage of rock-socketed pile near soil-rock interface subjected to ground shock excitations are investigated and quantified with coupled SPH-FEM method. Results indicate that the base of the pile is relatively vulnerable and that the soil properties significantly influence on response of pile subjected to a specific blast load. Furthermore, based on the numerical results, ground vibration attenuation equation is proposed.

1. Introduction

Blasting is the widely accepted method to rock breaking in mining industry, and in civil engineering constructions such as constructing underground structures and tunnels. In addition to that, rock blasting method is one of the most practical technique to use for land development projects in land-scarce countries like Singapore to create additional spaces 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.

Many studies on blast-resistant designs have been carried out by the military services, and the relevant documents are restricted only for official use. However, a considerable amount of research on the dynamic response and damage of nearby structures to blast ground motion can be found in the literature [1–5]. Structural responses and damage to blast induced vibration have been extensively studied in the past several decades and those studies concentrated on establishing allowable ground vibration levels in terms of peak particle velocity (PPV) together with the frequency of the ground vibration to limit the structural damage. However, safe vibration limits given by different researchers differ because of those limits were usually obtained based on field observations of low-rise residential buildings. Recently, with the development of technology, numerical simulations have become popular in investigating the dynamic response and damage of structures subjected to blast-induced ground vibration. Chen and Zhang [6] proposed an orthotropic dynamic damage constitutive model to simulate the dynamic responses of typical masonry structures under blasting vibration. The authors have found that the blasting vibration duration influences structural responses and taller structures experience less damage than do smaller structures under the same blasting vibration. Dhakal and Pan [7] performed nonlinear finite element (FE) analyses on a two-storey reinforced concrete (RC) frame to investigate the effects of blasting on structural response. Wu et al. [8] performed a three-dimensional (3D) dynamic response and damage analysis of masonry and masonry infilled RC frame structures to blast ground motions. The authors have concluded that the damage to the structure under blasting vibration is governed by the force-stress rather than the ductility or the interstorey drift. It is also found that the out-of-plane damage of the masonry walls is more severe than the in-plane damage.

In practice, the damage to nearby structures to generated ground vibrations has been controlled by various rules 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. The scope of the present study is limited to assess the stability and vulnerability of the pile foundation system against ground vibration caused by typical blast loads from nearby rock blasting.

* Corresponding author.
E-mail address: CTCGOH@ntu.edu.sg (A.T.C. Goh).

http://dx.doi.org/10.1016/j.compgeo.2016.09.015
0266-352X/

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. Vertical piles are normally designed to carry mainly vertical loads and very little lateral loads. Short duration, high frequency, high amplitude loads such as 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. Thus, the lateral response of piled foundation is important in the designing of structures that may be subjected to lateral loads. The lateral response of a pile, however, is a complicated soil-structure interaction problem; because pile deflection depends on the soil resistance and in turn the soil reaction depends on the pile deflection [9].

The performance of pile foundations subjected to dynamic lateral loads is a critical research area, as the foundation plays an important role in the overall structure response. A foundation system can fail even if the piles are not failed by the short-term dynamic load like blast loads, simply due to the combination of secondary action effects such as reduction of effective capacity of the pile due to blast damage, amplification of moments induced by displacements, and amplification of buckling effects [10]. In contrast to an axially loaded pile, the laterally loaded pile is a three-dimensional problem, and soil-pile interaction (SPI) is extremely complex when non-linear conditions and dynamic conditions exist simultaneously and also it plays a significant role in the pile response to ground vibrations [11].

Since a pile foundation is usually buried beneath the ground surface, it can also be considered as an underground structure in some aspects. Thus, it is also relevant to briefly review related experimental and numerical studies on blast response of underground structures. The influences of blasting vibration on underground structures have been studied by researchers using field experiments and numerical simulations. Kutter et al. [12] carried out a series of 1-g to 97-g centrifuge tests to investigate the blast response of shallow tunnels in dry sand. The authors found that the distance from the tunnel to the crater is a more significant factor than the distance from the tunnel to the charge in causing damage to flexible tunnels. Liu and Nezili [13] used a centrifuge test to study the response of transit tunnels in saturated soils under internal blast loading. The test was carried out with a centrifugal acceleration of 50-g on a thin wall Aluminium tube. The study showed that the model tunnel was significantly damaged by the internal blasting and that the large lining deformation that occurred was mainly concentrated in the area close to the explosive. The authors have also concluded that surrounding soil liquefaction is possible for a tunnel in saturated soil subjected to internal blasting.

Finite element method (FEM) is a useful tool in the analysis of soil-structure interaction problems. In certain situations, FEM provides a relatively simpler tool for the analysis. Yang et al. [14] discussed blast resistant analysis for Shanghai metro tunnel using explicit dynamic nonlinear FE software LS-DYNA [15]. The arbitrary Lagrangian-Eulerian (ALE) method was employed in their model and 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. [16] investigated the response of a buried concrete structure to various factors affecting structural performance by carrying out a parametric study using a 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. De [17] used fully coupled numerical model to study the effects of a surface explosion on an underground tunnel. The model was validated using the centrifuge test results. Koneshwaran et al. [18] investigated the performance of buried tunnels subjected to surface blasts. The authors found that the response of the tunnel buried in saturated sand is more severe than that in dry soil for a given blast event. Moreover, some researchers have tried to investigate the response of tunnels subjected to internal blasting with different numerical methods. Liu [19] carried out extensive numerical simulation to investigate the soil-structure interaction and failure of cast-iron tunnels in saturated soil subjected to internal blast loading and found that the ground-tunnel interaction was one of the governing factors determining the damage of tunnel lining. It also found that lining damage was mainly caused by the tensile hoop stress because of large inertia and dynamic forces in the radial direction of the tunnel. Khan et al. [20] performed FE analysis of underground tunnels with cast-iron lining embedded both in soil and rock subjected to an internal explosion at the center of the tunnel. It was found that the thickness of tunnel lining, peak blast pressure in the tunnel, and the elastic moduli of soil and rock affect the blast response of tunnel more significantly.

Unfortunately, only a few studies can be found in the literature and discuss the damage and failures of piles under blasting vibration. Thus, it is necessary to study SPI under blasting load, because of the wide application of blasting and to highlight their impact on the surrounding structures. Kamijo et al. [21] conducted vibration tests at a large-scale mining site to investigate liquefaction phenomena and dynamic responses of pile foundations. The test structure included RC top slab and pile cap, 4 steel tubular piles and 4 steel H-section columns. Ground vibrations from large-scale blasting operations were used as excitation forces for the vibration tests. Nonlinear responses of the soil-pile system at different levels were obtained for various levels of liquefaction in the test pit. 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. [22] conducted full-scale experiments using controlled blasting to assess the dynamic responses of piles during lateral spreading. The test piles included a single pile, a 4-pile group and a 9-pile group. The single pile had the free end condition while the pile groups had RC pile caps, and steel pipes were used for all the piles. 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 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.

With the rapid development of explosion theory and computer technology, numerical simulation has become a promising approach to analyzing the SPI problems. Hao et al. [23] 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 recent for the SPI analyses. Huang et al. [24] 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