Development of coupled centrifuge-numerical modelling: investigation of global tunnel-building interaction

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ABSTRACT: There is an increasing demand for underground space in urban areas for infrastructure development. This has resulted in tunnel construction taking place in close proximity to buried infrastructure and building foundations. Various studies have considered the effect of tunnel construction on buildings; however the global tunnel-ground building interaction problem is still not well understood. This is due partially to the fact that the available modelling tools do not accurately replicate the global behaviour of soil-structure domains. This research aims to enhance physical modelling capabilities by coupling centrifuge and numerical techniques. The research focuses on tunnelling beneath buildings which are founded on piled foundations. In this paper, the proposed method and the developed equipment are presented. The expected outcomes of this research will provide a better understanding of complex tunnel-ground-building interactions which will help to improve the design approach of tunnels beneath buildings.

KEYWORDS: centrifuge, numerical, modelling, coupled, tunnel, soil, structure, interaction, pile

1 INTRODUCTION

In urban areas, the excavation of tunnels for the development of infrastructure and services is becoming increasingly important. Due to the limited availability of underground space, tunnels are generally excavated close to existing surface and buried structures. This scenario is particularly important when constructing tunnels beneath buildings founded on piled foundations. In order to prevent possible damage to structures, engineers need to accurately assess the soil-structure interaction induced by the tunnelling. Although tunnel-soil-structure interaction has recently received considerable attention, a comprehensive understanding of the problem has not yet been achieved. This is due in part to the complexity and non-linear response of the global system (Standing and Potts 2008). To investigate the effect of global interactions, this research aims to develop a new method for modelling the problem of tunnelling beneath framed structures on piled foundations.

In previous studies, the tunnel-piled foundation interaction problem has been analysed using field trials, physical modelling, and numerical simulations (Mroueh and Shahrour 2002, Jacobsz et al. 2004, Kaalberg et al. 2005). However both current physical and numerical modelling methods cannot give an accurate representation of the global tunnel-ground-building interactions. A geotechnical centrifuge allows testing of small scale models within a controlled laboratory environment by increasing the self-weight of the model and thereby reproducing full-scale prototype stresses. Thus soil behaviour and soil-structure interactions are properly modelled within the centrifuge model. Nevertheless, centrifuge methods tend to assume constant loads from the structure to reduce the complexity of the experimental set up. In this way, the superstructure contribution to the foundation response is not modelled and the effect of the modified behaviour of the foundation on the behaviour of the soil is not accounted for. The use of numerical methods is common in structural and geotechnical engineering. Nevertheless, they generally provide poor predictions of tunnelling-induced ground movements unless unrealistic material parameters or sophisticated constitutive models are used (Franzius et al. 2005).

2 METHODOLOGY

The proposed global tunnel-structure analysis method is illustrated in Figure 1. The method couples experimental and numerical modelling tools to benefit from their respective strengths: the numerical model allows accurate simulation of the structure, the tunnel-ground-foundation system is modelled with the centrifuge to accurately reproduce soil and soil-structure interaction behaviour and the coupling is achieved by means of a real-time data acquisition and load-control interface.

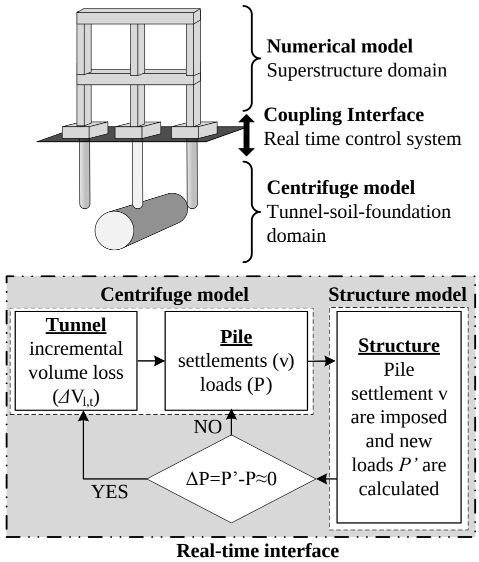

Figure 1. Proposed coupled numerical-centrifuge method

This method can be summarized in the following steps. 1) In the centrifuge, the model piles are driven within sandy ground and loaded using independent actuators to replicate serviceability building loads P_0. After the pile installation, 2) an incremental tunnel volume loss, $\Delta V_{l,t}$, is induced in the model tunnel by using an external volume control system. This volume loss causes ground movements and consequently settlement of the pile group, v. 3) The pile displacements, v, are measured and fed into a real time control system where the numerical simulation is carried out. 4) The incremental pile displacements, v, are passed to the structural numerical model to calculate the new pile loads, *P'*, accounting for the structure. 5) The modified loads, *P'*, are then fed back into the centrifuge model to adjust the pile loads to the demand values. The cycle, 3) to 5), continues until the coupled system reaches convergence. It is possible afterwards to apply further incremental tunnel volume loss. In order to obtain an accurate coupling of the centrifuge and numerical domain, it is necessary to minimize the incremental volume loss and the load convergence time (i.e. number of required cycles).

The vertical loads and settlements are the main parameters affecting tunnelling beneath piled foundations. Therefore, to minimize the experimental set up complexity, the proposed tests will only consider the vertical pile loads in the centrifuge. The numerical model is designed with this assumption.

3 EXPERIMENTAL EQUIPMENT, REAL-TIME DATA INTERFACE, AND NUMERICAL MODEL

3.1 Centrifuge equipment

The experimental facilities will be tested using the University of Nottingham (UoN) geotechnical centrifuge. The following components are part of the equipment (Figure 2).

- Centrifuge package previously developed for tunnelling in greenfield condition (Zhou et al. 2014), including a strong box, a 90 mm diameter model tunnel, a tunnel volume control system, and tunnel pressure measurement.
- Model pile foundation, consisting of a transverse row of full section model piles. The piles are jacked into the ground in-flight prior to tunnel volume loss to properly model the installation of displacement piles. The model piles consist of an 8 mm diameter aluminium alloy round bar over a length of 175mm. The tip is a 4 mm cylinder, with enlarged conical tip, fixed within the round bar. The model piles are instrumented for measurement of axial loads and head settlements. Seven full bridge strain gauges, protected with a 2mm epoxy coating, are placed along the pile shaft at 20mm spacing. An additional half-bridge strain gauge is located at the pile tip, allowing reliable measurement of the base load.
- Loading system. Each pile is independently loaded through a lever system by 5 kN capacity ballscrew actuators with 100 mm stroke. A load cell is installed in-line with the pile head to have a reliable measurement of the head load, which is a critical measurement for the coupling system. In this way the measurement is not influenced by the loading system.
- Foundation settlement measurement system. Each pile settlement is measured with a Linear Variable Displacement Transducer (LVDT) mounted on the instrumentation beam

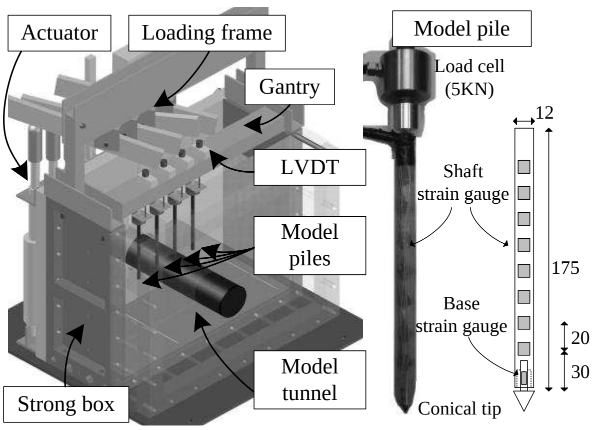

Figure 2. Drawing of the centrifuge equipment (on the left). The model pile (on the right).

3.2 Real-time interface and control system

The interface system between the centrifuge and numerical models is designed to allow real-time communication of data between the centrifuge and the numerical models.

The real-time interface is developed in the LabVIEW environment and run on a National Instruments real time embedded controller and motion controller mounted on the centrifuge. The system is designed to 1) retrieve pile settlements and load data from pile LVDTs and load cells, to 2) communicate with the numerical process, to 3) control tunnel volume loss, and to 4) control pile loads.

3.3 Numerical model

The numerical model is developed to 1) accept an input of foundation displacements, 2) efficiently perform the structural analysis in less than five milliseconds and 3) output the new pile loads based on the derived solution.

The accurate simulation of prototype framed structures can be performed using the finite element method. At this stage of the research, the global interaction is assessed for the case of linear elastic frames. The effect of various geometries and non-linear plastic behaviour will be considered in future work.

4 CONCLUSION

The paper presents a novel method to study soil-structure interaction through a real-time coupling of numerical and centrifuge modelling. The research aims to investigate the effects of tunnelling beneath buildings founded on piled foundations. The accurate simulation of the global interaction will allow for a more accurate assessment of the behaviour of piled foundations which accounts for the effect of the superstructure.

This research provides a direct link between ground and structural engineering, enhancing centrifuge modelling potential in studying global interaction problems. In general, the outcomes are expected to provide useful data for tunnel design engineers in case of construction of tunnels in urban areas. The method may also be used to study specific and current construction related problems, such as the effect of Crossrail tunnels on buildings in London.

5 ACKNOWLEDGEMENTS

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