# Development of a coupled centrifuge-numerical model to study soil-structure interaction problems

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ABSTRACT: There is increasing demand for infrastructure development that requires a better understanding of complex soil-structure interaction problems. Accurate centrifuge modelling of soil-structure interaction problems is notoriously difficult to achieve because of the complexity of including realistic reduced scale models of the structures (accounting for the configuration and the structural load distribution). To overcome these limitations, the real-time substructure testing approach may be extended to centrifuge modelling. This paper presents a novel method to study complex soil-structure interaction problems through the real-time coupling of numerical and centrifuge modelling to enhance centrifuge modelling capabilities. In this paper, the coupled centrifuge and numerical modelling technique is used to achieve a better representation of the global behaviour of a tunnel-soil-building system. The case of tunnelling beneath a piled building was considered: tunnelling induces differential pile settlements that result in the redistribution of loads among piles because of the effect of the superstructure. The proposed method uses a finite element model to simulate a generic framed structure whereas the tunnel-ground-foundation system and the structural loads are modelled within the centrifuge. The coupling between the numerical and centrifuge models is achieved by means of a real-time data acquisition and load-control interface. The paper provides a detailed description of the developed equipment and load-control systems. Preliminary results from four centrifuge tests are presented to illustrate the capability of the developed equipment and coupling methodology.

## 1 INTRODUCTION

Accurate centrifuge modelling of soil-structure interaction problems is notoriously difficult to achieve because of the difficulty of including realistic reduced scale models of the structures. Conventional physical modelling methods tend to assume simplified/equivalent superstructures (i.e. rigid connections or beams) or constant loads from the superstructure. However, in this way, the superstructure contribution to the foundation response is not modelled properly and the effect of the modified response of the foundation on the behaviour of the soil is not accounted for.

To overcome these limitations, the real-time substructure testing approach described by Blakeborough et al. (2001) can be extended to centrifuge modelling. Real-time substructure testing consists of performing a full or large scale physical test on key elements of the domain (where non-linear or complex behaviour is expected), and coupling this experimental data in real time to a numerical model of the remaining domain. The coupling is based on the transfer of information (loads and displacements) at a shared boundary. Gaudin et al. (2012) successfully developed a hybrid centrifuge-numerical model to study the jack-up-footprint interaction problem. Real-time distributed substructure testing involving centrifuge facilities has also been applied in distributed grid testing networks, where testing is performed through experimental and numerical models (simulating the substructures) located at different test facilities (Madabhushi et al. 2010).

This paper presents a method to study soil-structure interaction through the real-time coupling of centrifuge and numerical modelling. The equipment and methodology were developed at the University of Nottingham and tested on the Nottingham Centre for Geomechanics 2 m radius geotechnical centrifuge (Ellis et al. 2006). This paper provides a description of the design philosophy and the implementation of the system. The current test development will be applied to investigate the effects of tunnelling beneath piled structures. For demonstration purposes, three applications were carried out: pile loading, tunnelling beneath piles with constant loads, and tunnelling beneath framed buildings (where the building characteristics affect the redistribution of loads on piles). Test results are presented to confirm the expected performance of the newly developed coupled centrifuge-numerical modelling (CCNM) system.

## 2 BACKGROUND ON TUNNELLING BENEATH PILED STRUCTURES

Tunnelling inevitably affects existing surface and buried structures if protective measures are not adopted. In the case of piled buildings, it is necessary to assess the structural distortions caused by tunnelling. Despite its practical importance, tunnelling beneath piled buildings has not been adequately investigated.

Previous works on tunnel-structure interaction in the case of shallow foundations recognised the importance of the building stiffness which tends to decrease structural distortions and the risk of damage (Farrell et al. 2014, Franzius et al., 2006). The interaction problem between a tunnel and a single pile or pile group has been analysed using field trials as well as physical and numerical modelling; however few studies have been conducted to understand the global tunnel-pile-structure interaction. Neglecting the building influence on the global interaction may be overly conservative, as illustrated by the case study reported by Goh & Mair (2014).

## 3 METHODOLOGY

The proposed global tunnel-structure analysis methodology 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, whereas the tunnel-ground-foundation system is modelled with the centrifuge to accurately reproduce soil and soil-structure interaction behaviour. The coupling is achieved by means of a real-time data acquisition and load-control interface.

This method can be summarised in the following steps. [1] In the centrifuge, using independent actuators, the model piles are driven or loaded to replicate an installation procedure and serviceability loads $P_0$. After the initial pile loading, [2] the numerical model is run in parallel with the centrifuge model. Centrifuge and numerical models are coupled in real-time by the interface system that continuously a) adjusts the pile loads in the centrifuge, $P$, to the demand values $P'$ ($\Delta P = P' - P$), and b) retrieves the target loads $P'$ from the numerical model. To compute the numerical demand value $P'$, i) the incremental pile displacements, $v$, are measured in the centrifuge and passed to the numerical model; ii) the structural simulation is carried out to calculate the new pile loads, $P'$; iii) the modified loads, $P'$, are passed back to the interface and the demand load for the centrifuge model is updated. The actions a) and b) are run independently by the interface at the maximum rate to achieve convergence of the CCNM (i.e. to match the boundary conditions at the interface). Note that the time necessary for the physical motion of the actuators and loading system inevitably results in a time lag for the convergence of the physical and numerical models. [3] An incremental tunnel volume loss, $\Delta V_{l,t}$, is induced in the model tunnel using an external volume control system. This volume loss causes settlement of the pile group, $v$. If the convergence of the coupled system is satisfied by the real-time interface through the process in step [2], it is possible to apply further $\Delta V_{l,t}$. To obtain an accurate coupling it is necessary to minimise: $\Delta V_{l,t}$, the computational time of the numerical analysis, and the load convergence time between $P$ and $P'$. The vertical loads and settlements are the main parameters affecting tunnelling beneath piled foundations. Therefore, to minimise experimental complexity, the proposed tests only consider the vertical pile loads in the centrifuge.

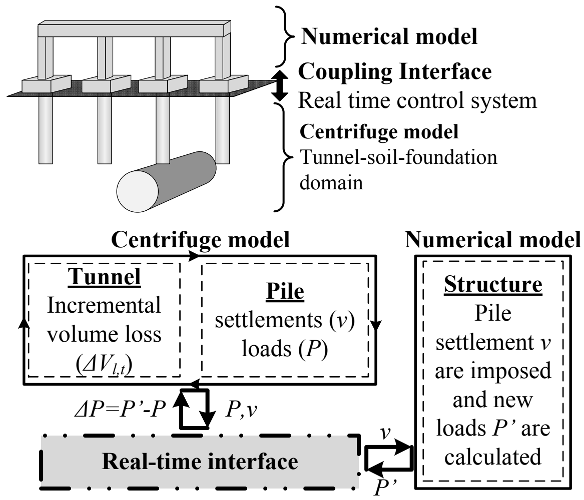


Figure 1. Proposed coupled numerical-centrifuge method.

## 4 EXPERIMENTAL EQUIPMENT, REAL-TIME INTERFACE, AND NUMERICAL MODEL

### 4.1 *Centrifuge equipment*

The tests were performed at 60 g ($N = 60$); model dimensions and results are reported in model scale. The experiment prototype, illustrated in Figure 2b, was simulated with the physical model (Figure 2a) which comprised the following components:

- Tunnel: plane strain tunnel model (Zhou et al. 2014) with 90 mm diameter tunnel and tunnel volume control system. It was buried at 225 mm depth (to tunnel axis). Dry silica sand (Leighton Buzzard Fraction E) with $d_{50}$ = 0.122 mm was used.
- Model foundation (one transverse pile row): 12 or 16 mm diameter aluminium alloy round bar with a length of 185 mm. Piles have fully rough interface obtained by bonding sand to the outer surface. Final

embedment depth was ~150 mm. Piles can be jacked into the ground in-flight to model the installation of displacement piles.

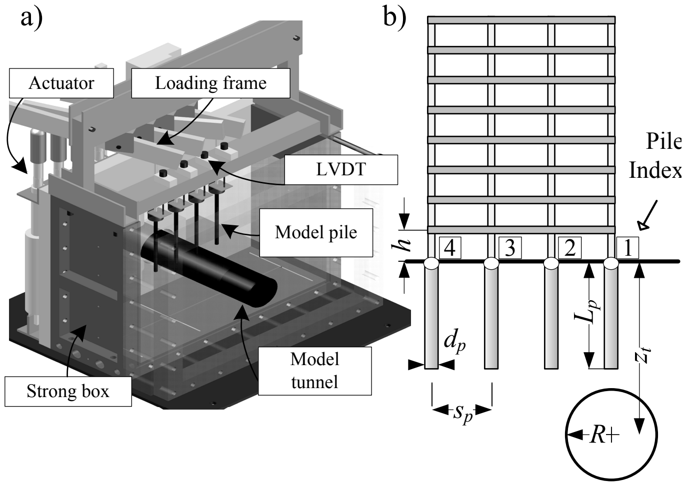


Figure 2. a) View of the experimental equipment; b) layout of the experiment prototype.

- Loading system: four-axis servo actuator apparatus capable of applying independent vertical loads. Each pile is loaded via a lever system by 5 kN / 100 mm stroke ball screw actuator. In-line load cell used to measure pile head load.
- Pile settlement measurement: Linear Variable Differential Transformers (LVDT) mounted on each of the piles.

### 4.2 *Real-time interfacing with control system*

Coupling the output of the numerical models to the actuators requires the use of flexible and scalable hardware and reliable software integration. Actuator control and data acquisition tasks must be performed synchronously with the real-time numerical computations. Microcontrollers and embedded controllers have been used previously to achieve actuator control and data acquisition tasks. However, these systems do not provide a high level of flexibility, are difficult to integrate with other high-end acquisition systems, and require lengthy development (Monmasson et al. 2011). They are also not easy to reconfigure and are usually deployed after an extensive development process (Ullmann et al. 2004). An alternative implementation utilises Field Programmable Gate Array (FPGA) technology that consists of reconfigurable elements that give the end user/developer full control of the controller at the hardware level (Monmasson et al. 2011). Their inherent ability to execute parallel programs makes them ideal for applications such as the real-time CCNM program that require a low response time.

The real-time system is comprised of an FPGA controller (NI-9149) for scalable hardware integration, interchangeable modules, and a local PC that runs LabVIEW. The modules are required for acquisition (NI-9205); relay triggering (NI-9474); motor control (NI-9505); and limit switch sensing (NI-9403). Sensor signals are acquired and processed in the FPGA then transferred to a LabVIEW program on the local PC. The FPGA controller and its hardware components were mounted on the centrifuge platform adjacent to the centrifuge strongbox to minimise the level of noise in the signals. The hardware has been tested up to ~100 g without showing any performance issues.

The main processes that couple the two models are contained within two loops that are run independently and at different frequencies. One loop is executed in LabVIEW on the local PC and the other is run on the FPGA controller. The LabVIEW program on the PC loops at a fixed interval $\Delta t = 60$ ms. This loop a) monitors changes to the user interface; b) gets new information from the FPGA on the centrifuge sensors; c) feeds the incremental pile settlements $v$ to the numerical model which runs in a MATLAB script within LabVIEW; d) executes the structural analysis that computes new target loads; and e) transfers the new target loads to the FPGA. The local PC program also logs data and sends a signal to the FPGA at a given interval to indicate continued safe program operation.

The FPGA program, which loops at real-time frequency (~2 ms), a) acquires data from the centrifuge instrumentation (4 load cells, 5 LVDTs and 12 limit switch sensors) and b) adjusts the pile loads in the centrifuge to the target values. The FPGA program carries out action (b) by controlling the actuators based on communication with the PC and performing automatic load-control using a Proportional, Integral, Derivative (PID) algorithm. The program also transfers the system state to the local PC LabVIEW program and continuously maintains system safety by monitoring the limit switches and the "safe operation" signal from the PC.

The LabVIEW user interface provides the user with information about the sensors and adequate control of the actuators. Manual actuator extension or retraction can be executed by the FPGA motor controller when the user modifies manual controls. Alternatively, automatic load-control can be activated which initiates the PID force controller on the FPGA. Load targets for the automatic load-control can be specified by 1) the user on the LabVIEW control interface, or 2) set equal to the force targets obtained from the numerical model. These force targets are realised by the PID control algorithm. Manual tuning methods were used to determine gain settings for the PID control algorithm at 1g but were later fine-tuned for elevated gravity operations. The control system is illustrated in Figure 3 and Figure 4.

A watchdog timer in the FPGA was implemented as one safety precaution. Loss of communication with the PC for a time duration t > 500 ms causes the watchdog to stop power to the motors. This prevents catastrophic actuator motion in case of PC failure. Limit switches were also employed to prevent excessive actuator movement. Software limiting was adopted to halt unwanted motion and hardware limiting was implemented as an additional failsafe. A third level of safety was employed using data from the LVDTs to warn the user if any of the 4 actuators exceeds a pre-set movement threshold.

It was important to adopt effective signal filtering since scatter within measurements from the centrifuge model is amplified by the scale factors in the data passed to the numerical model (working at the prototype scale). In particular, filtering LVDTs was critical to avoid unrealistic target load fluctuations *P*' in the centrifuge model. For a given prototype structure of stiffness *K*, according to the centrifuge scaling laws, the target load at the model scale are $P' = K\,[N\,(U^r + U^e)]\,/\,N^2$, where $U^r$ and $U^e$ are, respectively, the model pile settlements and the error in the LVDT measurements due to the signal noise (both at the model scale). Target load fluctuations due to LDVT signal noise are $P^{e\,\prime} = K\,U^e\,/\,N$. Note that the stiffer the superstructure the more critical is this aspect.

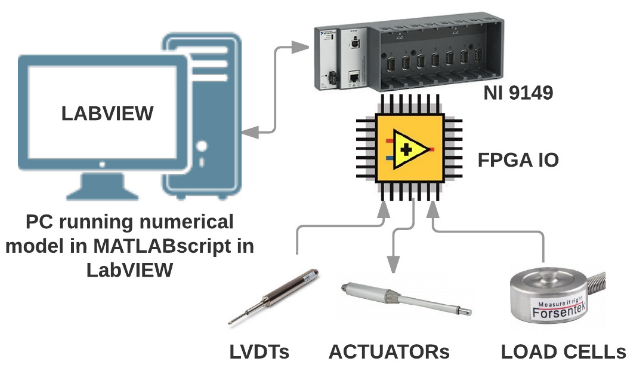


Figure 3. Components of Real-time control system

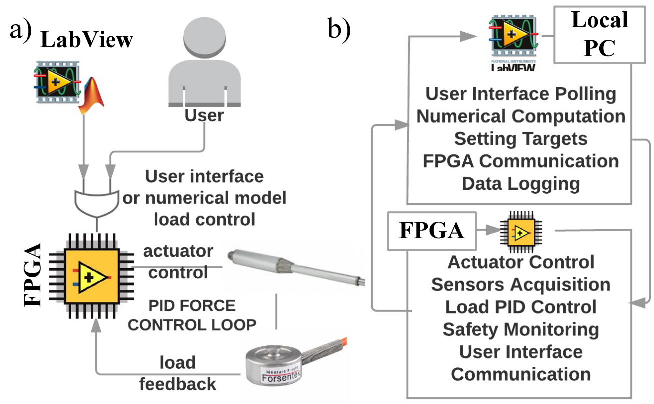


Figure 4. a) Load-control loop from user command and numerical model demand; b) order of operations for LabVIEW on local PC and FPGA setups.

The measurement system had peak-to-peak noise of 5 mV which meant ±0.0125 mm noise on the 50 mm LVDTs at the model scale. This would be equivalent to ±0.75 mm at prototype scale for a scale factor $N = 60$, which is not compatible with the structural analysis of realistic buildings. Signal filtering reduced this peak-to-peak noise to 0.3 mV using a 4$^{th}$ order Butterworth low-pass filter with 30 Hz cut-off frequency implemented in the FPGA after the acquisition step. This resulted in the input for the numerical model being subjected to an acceptable fluctuation (±0.05 mm at prototype scale). Clearly, minimisation of noise from the LVDTs has a beneficial effect on the CCNM performance; the minimum achievable range is determined by the hardware and adopted filtering. Definition of an acceptable noise level depends on the scaling factor *N* and the characteristics of the scenario and superstructure being studied, hence a general criteria cannot be defined.

Minimal signal filtering was used for the load-control since high-frequency updates to the PID controller was required (f =1 kHz). As such, a low-pass filter with 1 kHz cut-off frequency was applied to the load signals.

### 4.3 *Numerical model system*

In this paper, a matrix structural analysis was adopted to calculate the pile load distribution, *P*', based on the pile head displacements, *v*. The simulation of the prototype framed structures was performed using the finite element method, which was implemented in MATLAB. The stiffness matrix of the rigidly connected elastic frame structure (fixed pillar-beam connections) was obtained using Euler-Bernoulli beam theory. The numerical model was designed with the assumption of hinged pile-superstructure connections to replicate the conditions in the centrifuge model (Fig. 2b). At this stage of the research, the global interaction is assessed for the case of linear elastic frames.

The numerical model was implemented within the real-time interface as a component of the LabVIEW program using the MathScript node. Note that the time cost for calling and executing the function in the MathScript node was 35 ms. Additional time (~20 ms) was also required to complete the other tasks in the LabVIEW program. Therefore, the execution of the LabVIEW program, set to loop every $\Delta t = 60$ ms, ensures a deterministic response of the CCNM. This frequency rate is considered satisfactory for the proposed tunnelling application.

## 5 APPLICATIONS

### 5.1 *Pile axial loading*

This experiment was performed using two model piles to verify the accuracy and the convergence time of the load-control system. Piles were located in positions 2 and 4 from Figure 2b and had, respectively, a diameter of 12 and 16 mm to investigate the performance of the CCNM in the case of varying stiffness of the soil-pile system. Load was applied in steps of 50 N, with minimum and maximum loads being 400 N and 800 N.

The demand loads, $P'$, and the centrifuge load measured at the pile head, $P$, are shown against time in Figure 5a (large time interval) and 5b (detailed interval). The data show that the load-control system maintains the target load within 10 N. For the specified load demand variation of 50 N, the system reaches convergence ($\Delta P = P' - P < 10$ N) within 100 - 200 ms. For the tunnelling application, $P'$ varies in steps considerably smaller than 50 N due to the small increments of $V_{l,t}$; practical convergence time will, therefore, be less.

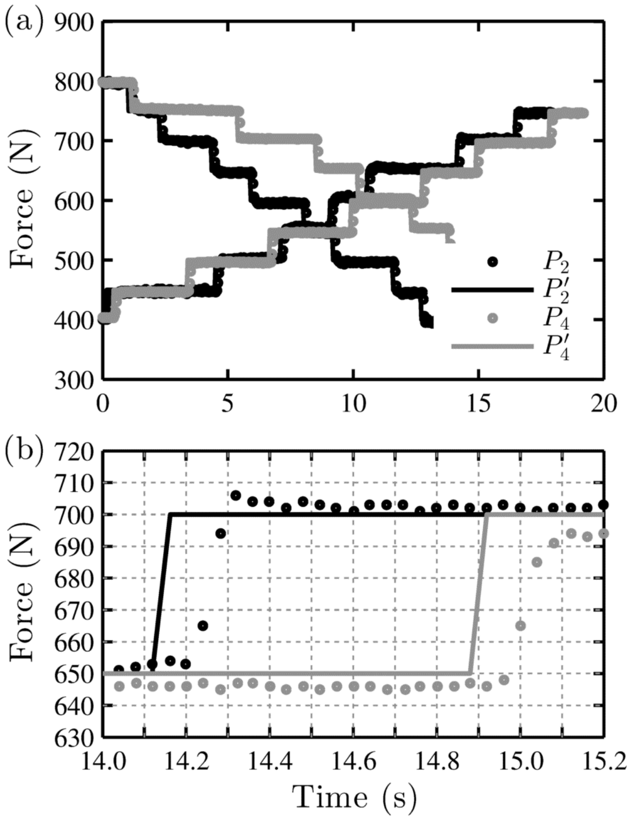


Figure 5. Comparison of centrifuge and demand loads.

## 5.2 *Tunnelling beneath piles*

In the experiment, if the actuator position is not adjusted, pile settlements result in a decrease of pile loads. An experiment was performed for the case of tunnelling beneath piles with constant load demand to verify load-control capability. This testing procedure is equivalent to performing a more conventional centrifuge test where piles are loaded using independent masses.

Two model piles with a diameter of 12 mm were located in positions 2 and 4 and a constant load demand, $P'$, of 600 N was specified after centrifuge spin-up. Thereafter, although CCNM tests of tunnelling beneath piles should be performed with discrete values of $\Delta V_{l,t}$, during this "performance" test a constant rate $\Delta V_{l,t}$ / s ≈ 0.15 % was induced to investigate the capability of the system under more extreme conditions.

Figure 6 shows pile head settlements ($U$), vertical loads ($P$) and target forces ($P'$) for the two piles. Note that as pile 2 undergoes a considerable rate of settlement ($U_2$ / s ≈ 0.9 mm) for $V_{l,t}$ = 0.6 - 1.9 %, the load-control system is able to maintain, within an acceptable tolerance, the target load. After $V_{l,t} \sim$ 1.9 %, the system becomes unstable due to complete failure of pile 2. Overall, the results of this test illustrate the good performance of the load-control system.

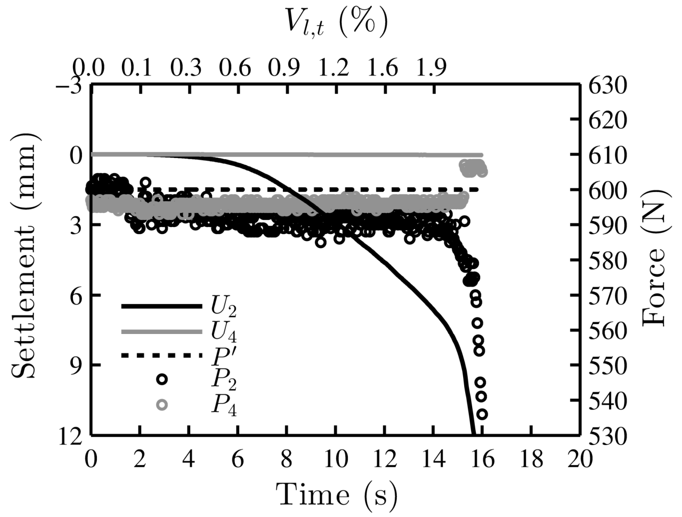


Figure 6. Pile head settlements and load cell measurements during tunnelling beneath piles with a constant load demand.

## 5.3 *Tunnelling beneath piled frames*

Two tests (A and B) were performed for the case of tunnelling beneath piled framed buildings to verify the performance of the developed CCNM technique and to illustrate its potential. The flexibility of the framed building was varied: test A included a semi-flexible frame, whereas test B included a rigid frame. Frame B represents an upper limit of practical stiffness of a framed building. Modelling of rigid buildings represents a challenge in these tests because of the LVDT signal noise amplification at the prototype scale, which for rigid buildings results in larger fluctuations of the target forces.

During both tests, four model piles with a diameter of 12 mm were located in positions 1 to 4. A structural serviceability load demand, $P_0'$, of 500 N was specified after centrifuge spin-up. Thereafter, to simulate tunnelling, discrete $\Delta V_{l,t}$ were induced in the centrifuge model. The resulting demand load is equal to the sum of the serviceability load, $P_0'$, and the superstructure reactions, $\Delta P'$, due to incremental pile settlements $v$ (i.e. $P' = P_0' + \Delta P'$). The geometry of the prototype frames is displayed in Figure 2b. The 8 storey concrete buildings ($E$ = 30 GPa) had a storey height, $h$, and a span length, $s_p$, of 3 and 4.5 m, respectively. The beams and columns of frame A had square cross-sections of 0.3 × 0.3 m, whereas frame B had structural elements with square cross-sections of 0.7 × 0.7 m.

The variation of head settlements ($U$) and model pile vertical loads ($P$) with $V_{l,t}$ during tests A and B are shown in Figure 7. The different response of the piled buildings to tunnelling in the two tests is evident, as illustrated by a qualitatively different distribution of loads and settlements in Figure 7a, b. The fluctuation of model pile loads is greater in test B than test A due to signal noise amplification of LVDT measurements with the scale factor $N$ which, as previously discussed, has a greater impact on the CCNM performance for more rigid structures.

Overall, the performance of the CCNM technique was very satisfactory and gives confidence that the methodology can be used for a wide spectrum of building typologies and stiffnesses. In general, the results of these two tests highlight the importance of accounting for the superstructure in the assessment of building/foundation response to underground excavations.

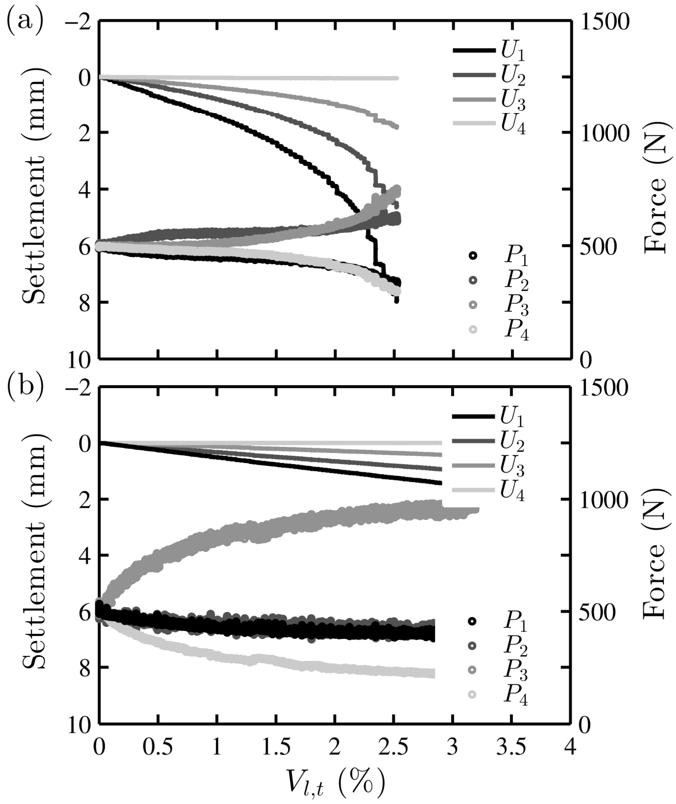


Figure 7. Pile head settlements and pile loads in case of tunnelling beneath a) semi-flexible building in test A, and b) rigid building in test B.

## 6 SUMMARY

The paper presented a method to study soil-structure interaction through a real-time load-controlled coupling of numerical and centrifuge modelling. A robust and versatile load-control system, which is based on a real-time interface able to actuate in the centrifuge (in-flight) user-defined load demands, has been developed at the University of Nottingham to efficiently solve complex problems of motion control and load sequences in the centrifuge. The results of four preliminary tests illustrated system performance. This research provides a direct link between ground and structural engineering, enhancing centrifuge modelling potential in studying global soil-structure interaction problems.

In particular, using this innovative modelling technique and loading apparatus, this research aims to investigate the effects of tunnelling beneath piled buildings. Various and complex construction scenarios (e.g. piled beams and frames) will be studied using the unique experimental equipment. Future outcomes of this research aim to contribute to the understating of global tunnel-ground-building interactions and to illustrate the importance of modelling the superstructure configuration, self-weight and stiffness distribution. The method may also be used to study specific and current tunnelling construction related problems. Further developments and application (e.g. deep excavations) will also be explored.

## 7 ACKNOWLEDGEMENTS


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REFERENCES


Blakeborough, A. Williams, M.S. Darby, A.P. & Williams, D.M. 2001. The development of real–time substructure testing. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.*, 359(1786): 1869-1891.

Ellis, E.A. Cox, C. & Yu, H. S. Ainsworth, A. & Baker, N. 2006. A new geotechnical centrifuge at the University of Nottingham, UK. In C.W.W. Ng et al (ed.), *Pro. 6th Int. Conf. Phys. Model. Geotech.*: 129–133. Hong Kong.

Gaudin, C. Kong, V. & Cassidy, M.J. 2012. An Overview of Spudcan Reinstallation Near a Footprint. In: *Offshore Technology Conf.*.

Goh, K.H. & Mair, R.J. 2014. Response of framed buildings to excavation-induced movements. *Soils & Found.*, 54(3): 250-268.

Farrell, R. Mair, R. Sciotti, A. & Pigorini, A. 2014. Building response to tunnelling. *Soils & Found.*, 54(3): 269-279.

Franzius, J.N. Potts, D.M. & Burland, J.B. 2006. The response of surface structures to tunnel construction. *Proc. Inst. Civ. Eng. Geotech. Eng.*, 159(1): 3-17.

Madabhushi, S.P.G., Haigh, S.K. et al. 2010. Distributed testing of soil-structure systems using web-based applications. In: *Proc. 7th Int. Conf. Phys. Model. Geotech.*: 355-360.

Monmasson, E. Idkhajine, L. Cirstea, M.N. Bahri, I. Tisan, A. & Naouar, M.W. 2011. FPGAs in industrial control applications. Industrial Informatics, *IEEE Trans. Ind. Inf.*, 7(2): 224-243.

Ullmann, M. Hübner, M. Grimm, B. & Becker, J. 2004. An FPGA run-time system for dynamical on-demand reconfiguration. In: *Proc. Int. Parall. Distrib. Process. Symp. IPDPS 2004*: 1841-1848. IEEE.

Zhou, B. Marshall, A.M. & Yu, H.S. 2014. Effect of relative density on settlements above tunnels in sands. In: *Proc. 2014 GeoShanghai Int. Congress*: 96-105.