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Response of framed buildings on separate footings to tunnelling: a hybrid modelling study

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ABSTRACT: Within the framework of hybrid geotechnical modelling, the coupled centrifuge-numerical modelling (CCNM) technique, developed at the University of Nottingham Centre for Geomechanics (NCG), is becoming a well-established approach to study the interaction between tunnel excavation, related soil movements, and induced response of affected structures. The CCNM technique involves a centrifuge model that includes the tunnel, soil, and foundation system, and a parallel finite element numerical model schematising the structure. Displacement and loading data at the structure-foundation interface are shared between the centrifuge and numerical domains in “real-time”, such that a global evaluation of the interactions occurring can be captured for buildings that require a higher level of detail to be fully described. This study focused on the application of CCNM technology to the analysis of a 2D bare frame with separate strip footings running parallel to the tunnel axis. The frame geometry is consistent with previous “conventional” centrifuge tests (i.e. not hybrid), involving a small-scale physical model of the building. As such, the presented CCNM test aims to provide benchmark data to validate the hybrid modelling method before considering frame configurations with infills. The findings are presented for a case in which the foundation rests on the soil surface.

1 INTRODUCTION

Understanding how tunnels interact with framed structures is crucial for the assessment of potential risks and impacts on these buildings, development of specific construction and mitigation techniques, and definition of guidelines and regulations to assist future urban and infrastructure planning and improvement.

Geotechnical centrifuge and numerical modelling approaches are essential to evaluate the induced displacements on the buildings and predict possible damage. Centrifuge modelling directly simulates interaction phenomena using, but being limited by, scaled-down simplified physical models in controlled experiments. For example, Xu et al. (2021) carried out centrifuge tests to study the response to tunnelling of bare framed building models on shallow foundations with a variable number of bays and storeys, element thickness, tunnel-building eccentricity, and variable structure weights. In terms of numerical modelling, non-linear constitutive laws and detailed structural layouts can be adopted to achieve simulations of soil and building responses in variable tunnelling andground conditions. Numerical investigations can be used to extend the applicability of centrifuge tests. For instance, Boldini et al. (2021a, 2021b) further developed the tunnel-frame scenarios from Xu et al. (2021) to consider more complex building configurations, including masonry infill panels. A hybrid modelling technique has been developed to bring together the advantages of both numerical modelling and centrifuge testing (Idinyang et al., 2019). Nottingham Centre for Geomechanics (NCG) developed a new ‘real-time’ coupled centrifuge-numerical modelling (CCNM) approach to test buildings on shallow foundations under plain strain conditions, including buildings characterised by a non-linear response to tunnelling (Tang et al. 2024). The tunnel, soil, and strip foundations are included in a centrifuge model, while the full-scale buildings are simulated in Abaqus. Key data (settlements and loads at the building-foundation interface) are transferred by a shared data exchange interface. In this way, the CCNM method can achieve more accurate predictions of the tunnel-building interaction processes if building characteristics cannot be properly modelled in the centrifuge.This paper presents results from a CCNM test for a 2-storey reinforced concrete framed building affected by tunnel excavation. The building rests on seven separate footings running parallel to the tunnel axis. The building was modelled in 2D in Abaqus, while the foundations were modelled in 3D in centrifuge. This study initially explores the possibility of extending the application of the CCNM method to 3D scenarios.

2 CCNM TESTING METHOD

The CCNM technique represents a sophisticated example of hybrid modelling applied to centrifuge testing for geotechnical engineering. The CCNM method was initially used to study the response of elastic framed buildings on piles affected by tunnelling for plane strain conditions (Idinyang et al., 2019). The methodology has recently been extended and further improved to test more complex building behaviours (with gravity effects and non-elastic materials) and continuous strip foundations perpendicular to the tunnel axis direction (representing a continuous interface between two domains) (Tang et al., 2024).

2.1 Problem layout

The layout and dimensions of the structure and tunnel at the prototype (full) scale are illustrated in Figure 1, basically consistent with Xu et al. (2021). The hybrid test was performed at 68 g. The tunnel, with a diameter D_t of 90 mm in model scale, was located at a depth z_t of 162 mm below the soil surface corresponding to a cover-to-tunnel diameter ratio C/D_t=1.3. Seven strip foundations (shown in red in Figure 1) were positioned with a spacing of 76.2 mm on the soil surface. The building was modelled prototype scale in Abaqus. The schematic red dashed line in Figure 1 represents the boundary between centrifuge and numerical model domains, which was controlled by a LabVIEW data exchange interface.

2.2 Centrifuge model

The centrifuge domain comprises soil, an eccentric rigid boundary mechanical model tunnel (developed by Song and Marshall (2020)), and seven separate strip foundations, as shown in Figure 2. The soil was a fine-grained dry silica sand (Leighton Buzzard Fraction E) with a relative density of $I_d = 90\%$, minimum and maximum void ratios of 0.61 and 1.01, and an average diameter of 0.14 mm (Lanzano et al., 2016). The minimum size of model elements directly contacting soil (i.e. 12 mm foundation width in Figure 3) is 86 times the soil average diameter, which exceeds 30 (the minimum structure-to-soil size ratio suggested by Fuglsang and Ovesen (1988)).

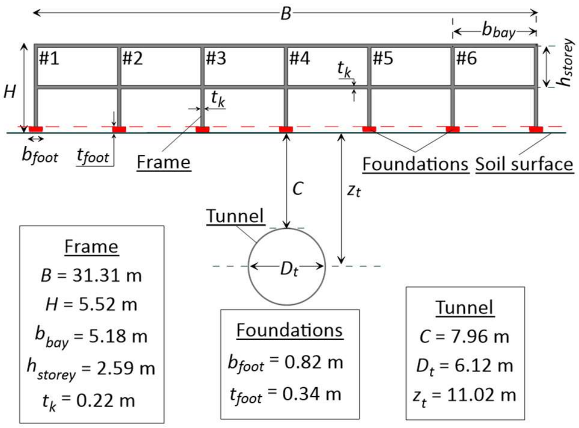

Figure 1. Frame-footing-tunnel layout in prototype scale.

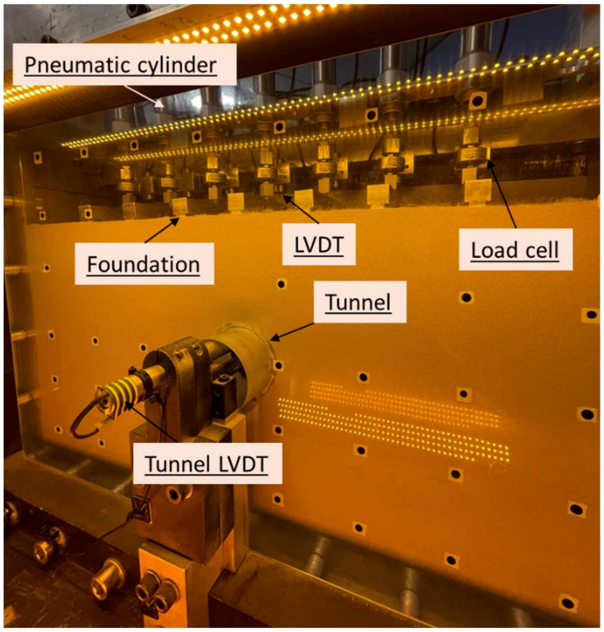

Figure 2. View of the centrifuge model.

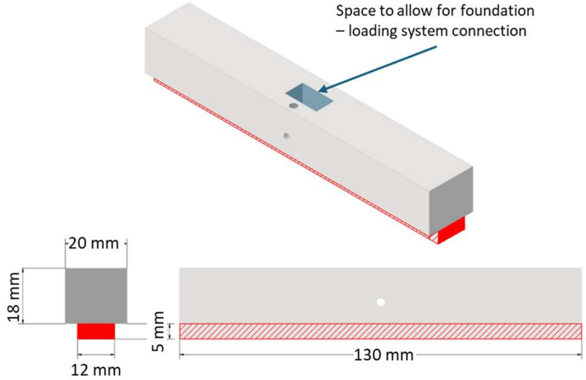

Figure 3. Foundation layout in model scale (in red the actual footing).

The model container, which has been used for similar studies (e.g. Song and Marshall, 2020), has inner dimensions of 500 mm height, 700 mm length (sufficiently long that settlements tend to zero at length boundaries), and 150 mm width (boundary effects were evaluated and judged to be acceptable for these types of tests in Marshall et al., 2012). The soil within the container was prepared by air pluviation using the NCG automatic sand pourer. The foundation and soil movements were recorded using two Dalsa Genie Nano-M4020 cameras through the front transparent acrylic wall of the container for digital image analysis. The model tunnel can achieve a maximum tunnel volume loss $V_{l,t}$ of 3.5% with increments of ≈ 0.1%.

The foundation (highlighted in red in Figure 3) is a simplified scheme of separate footings resting at the ground surface that runs continuously along the tunnel axis direction for 130 mm (model scale). The foundation has a width of 12 mm and a thickness of 5 mm. The foundations were made of aluminium with Young's modulus similar to that of reinforced concrete in terms of order of magnitude (70 GPa vs 30-50 GPa). The upper part (18 mm × 20 mm) of the model foundations has a larger bending stiffness in the tunnel axis direction and provides space to connect to the loading elements at its centre. In fact, the model foundation was deemed to undergo negligible bending due to the application of concentrated loads within tests, with a maximum deflection of 0.05 mm under a concentrated vertical force of 500 N in a 3-point bending test simulated in numerical analysis.

The loading system includes seven C85 series double-acting pneumatic cylinders, a manifold, and eight compact pneumatic regulators (ITV0050-3ML-Q). Each cylinder has upper and lower chambers; all upper chambers shared a common pressure from a manifold, and the pressure of compressed air (not exceeding 1 MPa) within the lower chambers was controlled independently by regulators for each cylinder to achieve the desired load. The cylinder rod, 500 N load cell, and rod end joint were connected in line with the centre of the upper part of the foundation models, where a small central pocket (12 mm × 6 mm) accommodated the rod-end joint through a steel rod with a diameter of 3 mm and length 20 mm. Linear variable differential transformer (LVDT) sensors with 10 mm stroke were used to measure the vertical displacement at the foundation top.

2.3 Numerical model

The 2D frame was modelled in the finite element code Abaqus using CPE8R elements. A homogenous solid section with a thickness of 8.772 m along the tunnel axis direction (equal to half of the physical frame model reported by Xu et al. (2021)) was considered. The frame was described through an isotropic linear elastic constitutive law, adopting the following parameters: unit weight $\gamma = 27$ kN/m^3, Young's modulus $E = 53.8$ GPa, and Poisson's ratio $\nu = 0.334$ (Boldini et al., 2021b, Spaggiari et al., 2023).

Two stages were simulated in Abaqus: first, the vertical displacements were restrained at the building base nodes and gravitational loading was imposed on the building before centrifuge spin-up; second, at 68 g, the vertical displacements of the foundations (after scaling) were imposed to the base of the building columns (in the form of user-defined boundary conditions) by connection to the data exchange interface using a Fortran subroutine. Rotation and horizontal displacement within the plane were free.

2.4 Centrifuge-numerical interface

A LabVIEW data exchange interface controls data transfer and processing between the centrifuge (top of the foundations) and numerical domains (nodes at the base of building columns). During each tunnel volume loss increment, the foundation settlements are recorded, scaled, transferred, and applied to the base of the Abaqus frame model. Revised loads at the building base are then computed in Abaqus, which are then applied back to the foundation.

A number of "load control and transfer" protocols were defined within the data exchange interface that ensure smooth operation of the tests and make necessary scaling/corrections to data being transferred. For example, load increments of less than 3 N were directly applied to each foundation model; for load increments over this threshold, the load increment was applied in several stages as a means of damping the change and, if settlements caused by the load changes were sufficiently large, the Abaqus analysis step was re-run with the current displacements. This process was found to prevent fluctuations in the model states during the convergence process.

Another example of a data transfer protocol relates to the maximum uplift force on the foundation. The model-scaled weight of each foundation is 14 N at 68 g (red portions in Figures 1 and 3), while the model foundations have a weight reading (in-flight) of 99 N in the centrifuge, including the full block and rod-end joint connection; thus a demand load of –99 N (where negative is upwards) would lift the foundation off the soil surface. As the considered dry soil cannot sustain tension, this value (i.e –99 N) should represent the limit of negative force to be applied. Therefore, a threshold of upwards load of –95 N was specified, where a nominal load of 99–95=4 N is maintained between foundation and soil, to avoid potential foundation misalignment (which is established at 1 g before centrifuge spinning) and impact load on the soil surface upon gap re-closure and re-loading of the foundation. Although preventing gap opening, this nominal load still represents the effects of the condition of soil-foundation separation sufficiently well (i.e. very low stresses beneath the foundation). The complete and detailed description of all CCNM data transfer principles and protocols is presented in Tang et al. (2024).

2.5 Testing procedure

In the description below, the conversion between model scale and full (prototype) scale parameters followed well-established scaling laws for centrifuge testing (Taylor et al., 1995).

The seven foundations were lowered and positioned in contact with the soil surface at 1 g, with a small load of 8 N applied to each foundation to ensure full contact between the bottom of the foundations and the soil surface. Then, the centrifuge was spun up to 68 g and two subsequent stabilisation cycles consisting of spinning up and down from 10 g to 68 g were carried out to improve soil homogeneity.

The following testing procedure was performed at the target level of 68 g (summarised steps in Figure 4):

- Step 1: the initial static loads $L_{c,g}$ (in model scale; including the fixed load above each footing of 85 N), determined by the gravity activation on the frame, were applied to the foundation in increments of 25%. The foundation/surface settlement was set to zero, and the data exchange interface was activated.
- Step 2: a small tunnel volume loss increment ($\Delta V_{l,t} \approx 0.1$-$0.2\%$) was conducted, inducing ground movements.
- Step 3: the vertical displacements S_c on each footing were recorded by the LVDT and transferred to the data exchange interface.
- Step 4: the foundation settlements S_c, after scaling up to prototype scale S_f, were applied to the nodes at the frame column base in Abaqus. Each column base included five nodes, which experienced the same vertical displacement.
- Step 5: based on the input settlements S_f, frame distortion and load redistribution were calculated in Abaqus.
- Step 6: the vertical force of frame base nodes was transferred to the data exchange interface; the prototype scale column base force L_f was calculated by summing up the node force at each column base, after scaling down to model scale and subtracting the additional load given by each footing, and then the target load L_c was applied back to the foundations.

Steps 3-6 were repeated until a balanced and stable condition was reached; then a subsequent new tunnel volume loss increment was initiated (i.e. step 2).

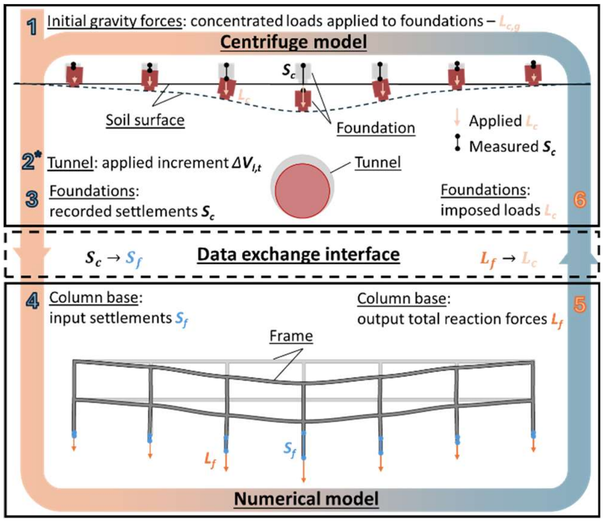

Figure 4. Scheme of CCNM procedure for a framed building on separate strip foundations (step 2 is activated when the testing system is balanced and stable, otherwise ignored).*

3 HYBRID TESTING RESULTS

Figure 5 shows the exchanged vertical loads L_c (in model scale) at the column base for selected $V_{l,t}$ values. The CCNM approach can clearly capture the load redistribution within the frame building induced by tunnel excavation: the four outer foundations were progressively loaded as a result of the unloading of the three inner foundations. In particular, the enforced limit condition on the maximum upward tensile force (i.e. –95 N) of the central foundation was reached at $V_{l,t} = 2.5\%$.

Figure 6 shows the base vertical u_v and horizontal displacements u_h (in prototype scale) of the frame column at $V_{l,t} = 2.0\%$ from Abaqus part, along with

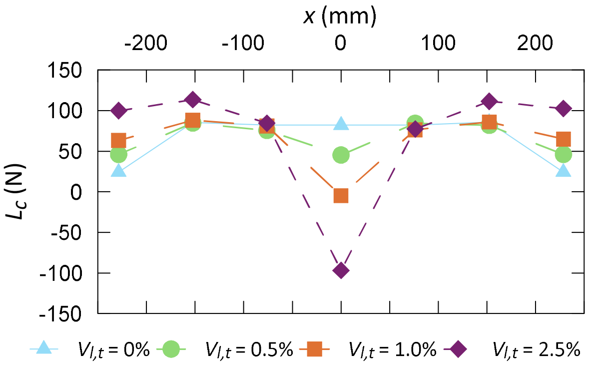

Figure 5. Frame base loads (model scale) at $V_{l,t}$ of 0, 0.5, 1.0, and 2.5 %.

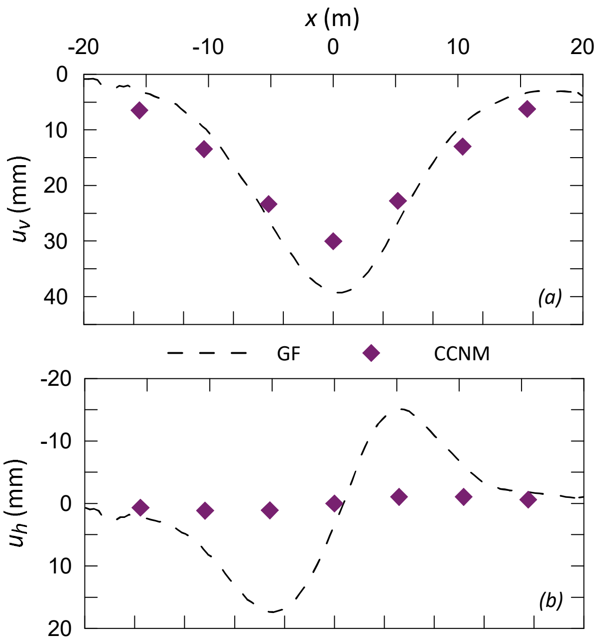

Figure 6. Results in (a) vertical u_v and (b) horizontal u_h displacements (prototype scale) of frame base in CCNM and surface in greenfield (GF) at $V_{l,t}$ = 2%.

greenfield (GF) test results at 70 g (using the same centrifuge model; from dataset by Tang et al. (2024)) for comparison. The CCNM test outcome of foundation response is in contrast with the greenfield displacements; the structural stiffening action of the frame results in lower differential settlements at the base of the columns (and the foundations) compared to the corresponding greenfield.Figure 7 presents the deformed shapes of the frame structure at $V_{l,t}$ = 1.0% and 2.0%, together with the angular distortion β for bays (Son and Cording, 2005) and the categories of damage (Boscardin and Cording, 1989). The results in terms displacements are also used to evaluate the induced building distortion and damage (Ritter et al., 2020).

At $V_{l,t}$ = 1.0%, the tunnel excavation causes, in most of the bays, an angular distortion corresponding to a slight level of damage (i.e. category 2), while for a $V_{l,t}$ = 2.0%, most lower panels experience greater distortion with moderate damage (i.e. category 3). The upper bays adjacent to the central two bays (bays #2 and #5) are roughly located above the inflection point of the surface settlement curves (at approximately ± 6 m in prototype scale, see Figure 6(a)), undergoing moderate damage levels (category 3) at $V_{l,t}$ = 2.0%.

Overall similar damage categories were obtained with respect to previous conventional centrifuge testing (Xu et al., 2021), despite the different tunnel model adopted and building stiffness. In fact, the rigid boundary tunnel causes slightly greater maximum settlements than the flexible membrane tunnel used in conventional tunnelling (Song and Marshall, 2020), and the adopted model considered only half of framed structure with implication in terms of building weight and stiffness.

A preliminary results in terms of maximum and average angular distortion β of the upper bays with tunnel volume loss $V_{l,t}$ is presented in Figure 8. It can be observed that the average β increases with $V_{l,t}$ and reaches a maximum damage of category 3 (moderate). The maximum β (at bays #2 and #5) presents a similar trend but with greater damage. In particular slight and moderate damage are obtained for $V_{l,t}$ greater than 0.75% and 1.4%.

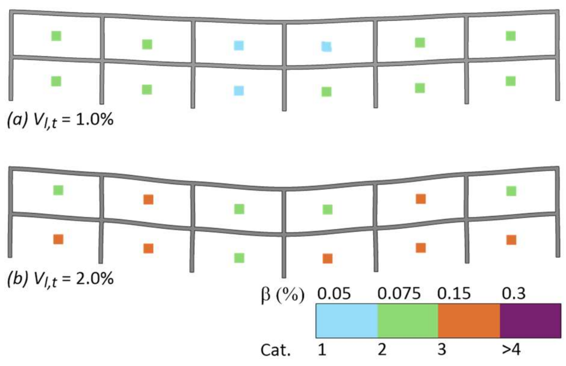

Figure 7. Building deformed shapes (scale factor =50) and bay damage categories at (a) $V_{l,t}$ = 1.0% and (b) 2.0%.

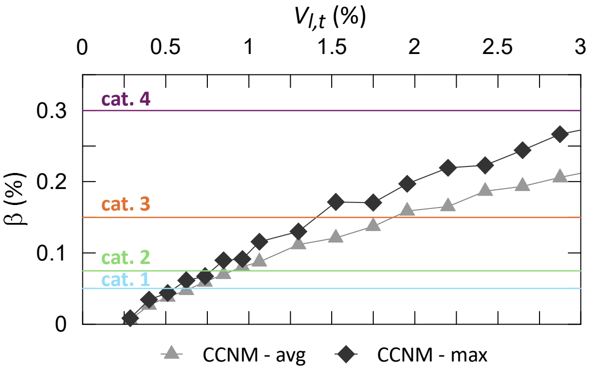

Figure 8. Comparison between average and maximum angular distortion β values calculated from CCNM test against tunnel volume loss $V_{l,t}$.

4 CONCLUSIONS

This paper presented results from a new application scenario of the NCG coupled centrifuge-numerical modelling (CCNM) testing method. In particular, a framed building with separate strip foundations resting on the soil surface and subjected to tunnel excavation was analysed.

In the CCNM approach, only vertical displacements and related resultant forces of the foundation models can be acquired and controlled; horizontal displacements and rotations of foundation models are ignored, which might be of influence for a separate foundation building configuration. The most significant factors in the framed building load redistribution are expected to be the structure stiffness and weight, the connection between the beams and columns, and the applied constitutive model (contribution of plasticity). These aspects have been considered for subsequent investigation.

Finally, it was demonstrated that the CCNM methodology is effective in capturing the induced displacements, that are useful to evaluate the tunnelling related damage of the frame structure, and the load redistribution within the building, that is typically neglected by conventional centrifuge testing.

Additionally, work is underway to extend the CCNM tests described here to consider a 3D building including non-linear constitutive behaviour of structural components (i.e. a 3D frame with masonry infill walls). This will enable a more comprehensive exploration of the innovative potential of this advanced testing method towards building configurations more representative of a proper framed structure.

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