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Experimental challenges of modelling structure response to tunnelling

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ABSTRACT: This paper discusses centrifuge modelling challenges when exploring the response of surface structures to tunnelling in sand. The model tunnel employed consists of an interior brass cylinder surrounded by water inside a sealed flexible latex lining. Prior to extracting water to simulate tunnelling volume loss, soil displacements obtained during centrifuge acceleration indicate that this flexible tunnel can lead to differential settlements during spin-up. These ground movements are triggered by a change of the tunnel shape due to a stress imbalance between the tunnel and the surrounding soil. Additionally, it was found that surface structures interact with the model tunnel during the spin-up, and thus can change the amount of differential surface settlements, depending on the structure location. As a consequence, some differential settlements may be imposed on the structures as the g-level increases. Results indicate the necessity to consider these effects when interpreting the results of the subsequent tunnelling simulation.

1 INTRODUCTION

A key aspect of urban tunnelling is the protection of adjacent structures. While tunnelling-induced settlements at a greenfield site have been widely discussed, there remains uncertainty over the response of surface structures to tunnel construction. Geotechnical centrifuge model tests of such urban tunnelling scenarios demonstrated significant potential to study the mechanisms of tunnelling on surface structures (Taylor & Yip 2001, Caporaletti et al. 2005, Farrell & Mair 2012). However, much of the research up to now has been restricted to unrealistically simple structural models. More complex building models with non-linear material properties, similar to masonry, can be created using 3D printing. These building models result in improved centrifuge model tests, which could provide effective means to better predict tunnelling effects on surface structures. However, in these centrifuge tests, it is essential to evaluate modelling limitations, and potential undesired effects that occurred to the artificial tunnelling simulation procedure.

The focus of this work is to address experimental challenges when modelling the behaviour of surface structures subjected to tunnelling in sand. In particular, potential differential surface displacements during centrifuge acceleration. After describing the setup of the centrifuge model and the test procedure, the impact of spin-up phenomena on the structure model are quantified and compared to the structure response during the tunnel excavation phase.

2 CENTRIFUGE MODEL

A series of centrifuge tests was performed on the University of Cambridge beam centrifuge in order to study the effects of tunnel construction in sand on surface structures. A model scale of 1/75 was used, with a centrifuge acceleration level of 75g. Figure 1 schematically presents the dimensions of the centrifuge model. Leighton Buzzard Fraction E silica sand with a grain size D_{50} of 0.14 mm, a specific gravity of 2.65, a critical state friction angle of 32° and minimum and maximum void ratio values of 0.613 and 1.014 (Haigh & Madabhushi 2002) was used throughout this centrifuge test series.
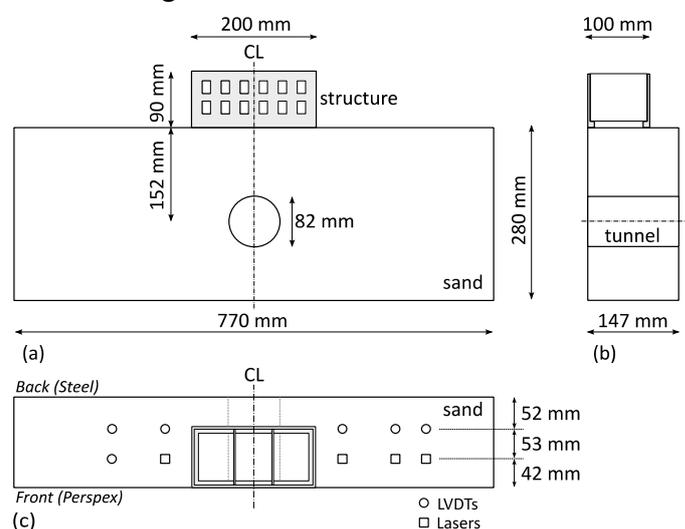

Figure 1: Centrifuge model: (a) front view, (b) cross-section through tunnel centreline and (c) planview.

Ground and structure displacements were obtained through an image based deformation measurement technique (i.e. geoPIV, White et al. 2003). In addition, laser displacement sensors (Baumer OADM 12I6430/S35A) and linear variable differential transformers (LVDTs, supplied from Solartron) were used to monitor the settlements of the soil surface (Fig. 1). In the subsections that follow, the key experimental equipment will be described.

2.1 Tunnel excavation simulation technique

Figure 2 shows the main parts of the model tunnel, which is a rigid brass cylinder surrounded by a flexible latex membrane. The annulus between the tunnel lining and the brass cylinder is filled with water. The brass cylinder is placed eccentric to the tunnel lining (Fig. 2b). This design considers radial and oval shaped tunnel deformation patterns which is similar to tunnelling practice. The model tunnel is fixed with fitting rings to the sidewalls of the centrifuge model.
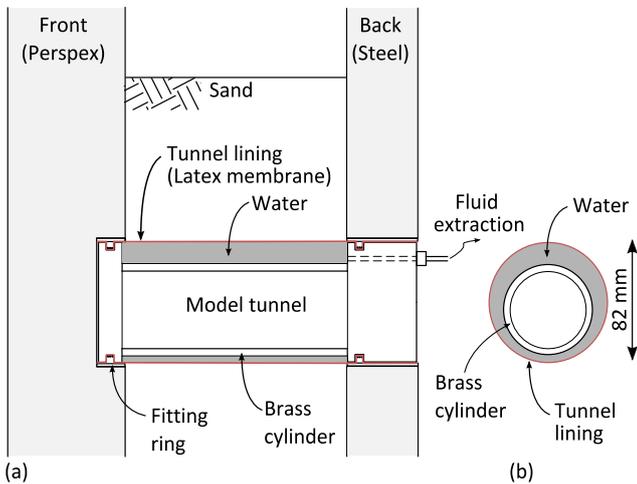

Figure 2: Model tunnel: (a) cross-section through centrifuge model and (b) cross-section through model tunnel.

Two-dimensional tunnelling (plane strain conditions) is replicated by withdrawing water from the model tunnel. A certain volume of extracted water relates to a known tunnel volume loss, and thus a range of volume losses can be simulated in a single centrifuge test. In the past 15 years, a number of researchers applied this fluid extraction approach, and produced valuable data to study ground movements caused by tunnelling (e.g. Longanathan et al. 2000, Vorster 2002, Farrell & Mair 2012, Marshall et al. 2012, Zhou et al. 2014).

During centrifuge acceleration the model tunnel is connected via a solenoid valve to a constant water head standpipe, as shown in Figure 3. This setup balances the pressure within the tunnel and the greenfield vertical soil stress at tunnel axis throughout the spin-up phase. However, due to differences in the density of sand and water, the tunnel pressure above and below the tunnel axis cannot match the soil stress profile. This is in particular true for tunnels in sand

where the soil stresses considerably vary with orientation. Although this technique minimizes the impact of the model tunnel on the initial stress conditions of the soil surrounding the tunnel, the stress conditions in the model tunnel cannot replicate the theoretical earth pressure at rest (König 2012). As a consequence, this tunnelling simulation method properly replicates ground movements away from the tunnel, but is less suitable to observe stress changes surrounding a tunnel. In section 3.2, the impact of this tunnel excavation modelling technique on the soil will be discussed in detail.
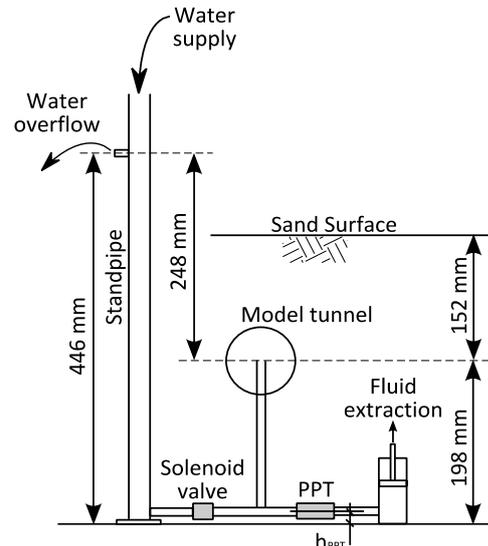

Figure 3: Tunnel pressure and volume loss control system.

2.2 Building model

In order to analyse tunnelling effects on surface structures, building models with brittle material properties were 3D printed. The building models were built by a *Visijet PXLCore* powder and *Visijet PXLClear* binder using the *Zprinter350* 3D printer. Figure 1 gives an overview of a typical building model and indicates that realistic building characteristics such as foundation type, façade openings and intermediate walls were taken into account. Dead load bars were placed on top of the structure models to achieve a bearing pressure of 100kPa beneath the façade walls perpendicular to the tunnel axis. Moreover, an artificial texture was created on the front façade of the building models in order to track displacements with geoPIV.

2.3 Model preparation

To obtain a uniform soil model, in particular surrounding the model tunnel, the sand was poured with the model lying on the Perspex face. The achieved relative density was 90% (±2%). After the sand pouring was finished, the back steel plate (Fig. 2) was installed and the model was moved to its vertical position. Subsequently, the building model was placed on the sand surface. Particular care was taken to place

the building flush with the sand surface and the Perspex face. Finally, the lasers and LDVTs were installed.

2.4 Testing procedure

For the centrifuge test series presented in this paper a standardized testing procedure was followed. Firstly, the centrifuge model was accelerated in 10g increments up to 70g and then the 75g level was reached in a final increment. As mentioned above, during the spin-up the pressure in the model tunnel is supplied by the standpipe (Fig. 3). Secondly, the solenoid valve (Fig. 3) was closed and the tunnel excavation was modelled by draining the tunnel until a final tunnel volume loss of about 26% was achieved. Finally, the test was stopped and the spin-down was carried out. Throughout the test, images were captured at defined acceleration levels and defined increments of tunnel volume loss.

Within this paper, results of four centrifuge tests are presented, as shown in Figure 4. Throughout this test series, the properties of the soil model were kept constant but different building models were investigated. Test (a) examined a surface structure with dimensions of 200 mm by 100 mm by 90 mm and 20% of facade openings in the theoretical sagging region of the greenfield settlement trough (Figs 1, 4a) while test (b) investigated an equivalent building model in the hogging region (Fig. 4b). Figure 4c presents a building model with dimensions of 260 mm by 100 mm by 90 mm and 20% of openings in the transition region (i.e. test c). In contrast to test (c), the structure in test (d) had 40% of window openings (Fig. 4d). Throughout this paper it is referred to the centrifuge tests (a), (b), (c) and (d).
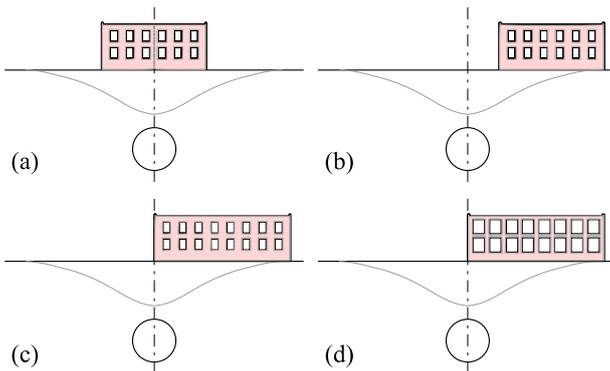

Figure 4: Tunnelling scenarios investigated: (a) structure with 200 mm by 100 mm by 90 mm and 20% openings (reference structure) in sagging, (b) reference structure in hogging, (c) enlarged structure (length of 260 mm) with 20% openings in transition region and (d) enlarged structure with 40% of openings in transition region.

3 SPIN-UP PHENOMENA

As was pointed out in the introduction of this paper, it is essential to evaluate possible impacts of the spin-up phase on the centrifuge model. During spin-up the soil model theoretically experiences uniform one-dimensional compression caused by an increase of the self-weight of the soil. It is common practice, to take the final state of the spin-up as the initial condition of the subsequent tunnel excavation simulation. However, an investigation of the spin-up phase of the conducted centrifuge tests revealed an interaction between the soil, the tunnel and the building. A number of issues were identified which are discussed below.

3.1 Tunnel pressure control

To assess the performance of the model tunnel during spin-up of the centrifuge tests, it is essential to discuss the pressure within the tunnel pressure system (Fig. 3). Figure 5 presents this pressure monitored by the pore pressure transducer (PPT, Fig. 3). As the legend in Figure 5 indicates, the presented data is related to the water head in the standpipe and is not the tunnel pressure. It can be seen from Figure 5 that the pressure increased with spin-up duration as g-level increases. The data shows close agreement with the expected pressure at 75g. The differences between the tests are likely to be related to a minor variation of the height of the PPT (h_{PPT}, Fig. 3) between the centrifuge tests. Nevertheless, the data indicates that the tunnel pressure control system performed successfully, and stress imbalances between the model tunnel and the surrounding soil during spin-up were minimized.
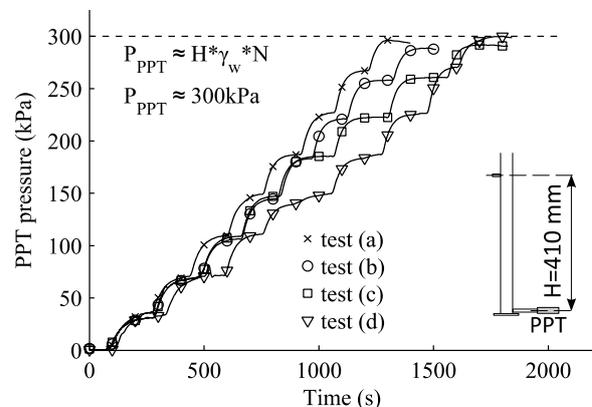

Figure 5: Pressure in the tunnel pressure and volume loss control system during spin-up.

3.2 Impact of tunnel excavation simulation technique

Vorster (2002) described two main reasons for a non-uniform ground displacement during centrifuge acceleration: the flexible tunnel lining and the rigid connection of the tunnel to the sidewalls of the centrifuge model (Fig. 2). Results of geoPIV reveal these mechanisms, as shown in Figure 6. A perfectly rigid tunnel fixed to the sidewalls would reduced the vertical soil displacements directly above the tunnel crown (Vorster 2002). The flexible model tunnel, however, minimizes the soil movements above the tunnel due to an

imbalance between the tunnel pressure and the vertical soil stresses above the mid height of the tunnel (Fig. 6, left). As noted above, this stress imbalance is caused by the different density of sand and water. The horizontal displacements (Fig. 6, right) depict a horizontal outward movement of the tunnel lining which can be attributed to differences between the horizontal soil stresses and the significantly greater tunnel pressure. The combination of these two effects results in an ovalisation of the model tunnel as g-level increases.

In addition to these previously reported modelling limitations, it was found that the building models also altered the tunnel behaviour and the ground movements. In test (a) the structure was placed symmetrically to the tunnel centreline, which caused symmetric settlements and a symmetric deformation of the tunnel (Fig. 6a). By contrast, the building models placed in the hogging and transition region (tests b, c and d) resulted in asymmetric ground movements (Figs 6b, c, d). In all these cases, the vertical displacements increased underneath the influence area of the structure (right hand side of model tunnel). This surcharge resulted in higher soil stresses to the right of the model tunnel and thus restrained the outwards movement of the tunnel lining in this region. As a consequence, the flexible tunnel membrane moved more to the left tunnel shoulder (Figs 6b, c, d, right) compared to the test (a) with a symmetrically located building (Fig. 6 a, right). Together these results affected the near surface soil displacements and the structure displacements as discussed below.

3.3 *Near surface soil and structure vertical displacements*

Figure 7 provides the near surface soil and structure vertical displacements during spin-up. It is apparent from these graphs that settlements above the regions affected by the outwards movement of the model tunnel showed reduced soil settlements. This trend is particularly clear for the left hand side of the asymmetric tests (Figs 7b, c, d), and can be explained by an increase of the soil stress near the left tunnel springline due to tunnel ovalisation (Vorster 2002). On the contrary, the mechanism on the right hand side of the model tunnel is governed by the building load, and causes the maximum soil settlements during spin-up (Figs 7b, c, d).

Interestingly, in all cases the obtained vertical structure displacements exceed the settlements of the underlying soil. These results are in line with those of Farrell (2010) who argued that the building models cannot be placed perfectly flush on the soil surface. In addition to this embedment effect proposed by Farrell (2010), parts of these higher structure displacements can be a phenomenon of geoPIV, which allows one to track the soil and structure displacements only at a certain distance from the soil-structure interface.
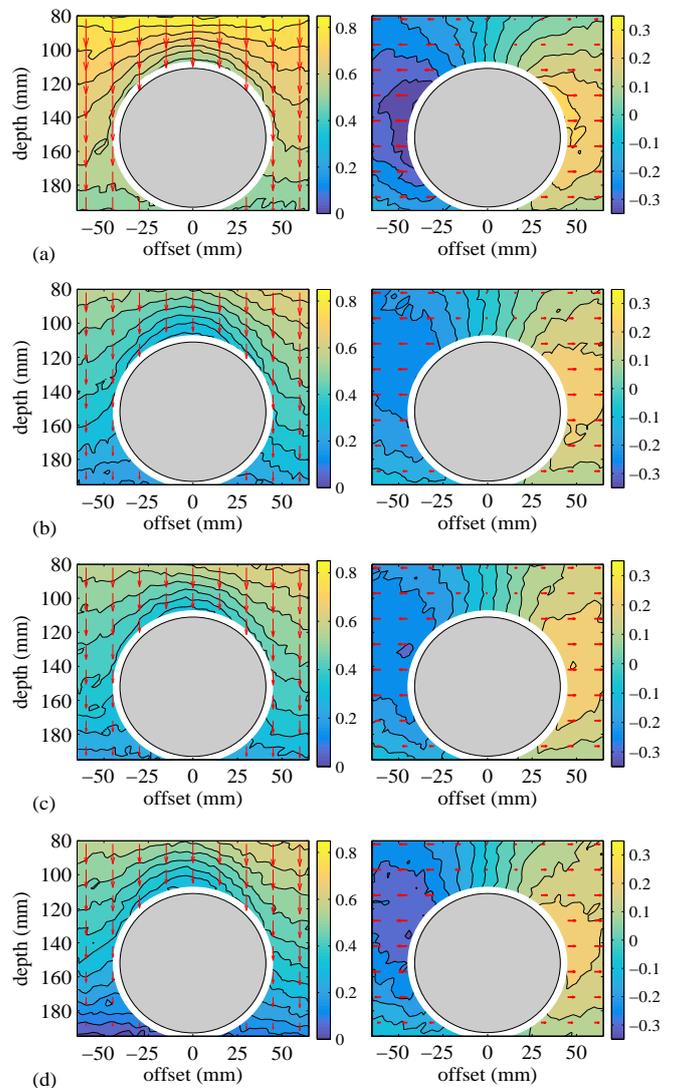

Figure 6: Vertical (left) and horizontal (right) soil displacements (in mm) adjacent to the model tunnel for centrifuge tests (a), (b), (c) and (d) (settlements are positive, left horizontal displacements are negative while right horizontal displacements are positive, displacement vectors are times 20).

The soil settlements are thus presented at a depth of 4 mm and are expected to be slightly smaller than the surface soil settlements. This explanation can be supported by the readings of the lasers and LVDTs, indicating generally greater soil compression than obtained with geoPIV (Fig. 7). However, as Marshall et al. (2012) stated, this difference can also be attributed to boundary effects caused by the friction between the sand and the Perspex. Another reason for this unexpected result might be that the structure is not perfectly flush with the Perspex face throughout the spin-up phase. As a result, the soil next to the Perspex might not experience the entire building load and thus reduced soil settlements are measured by geoPIV.

The results in Figure 7 indicate that the building models experienced distinct displacements during centrifuge acceleration. The next section is concerned with how these spin-up displacements affected the building models, and compares the response of the building models during spin-up and tunnel excavation.
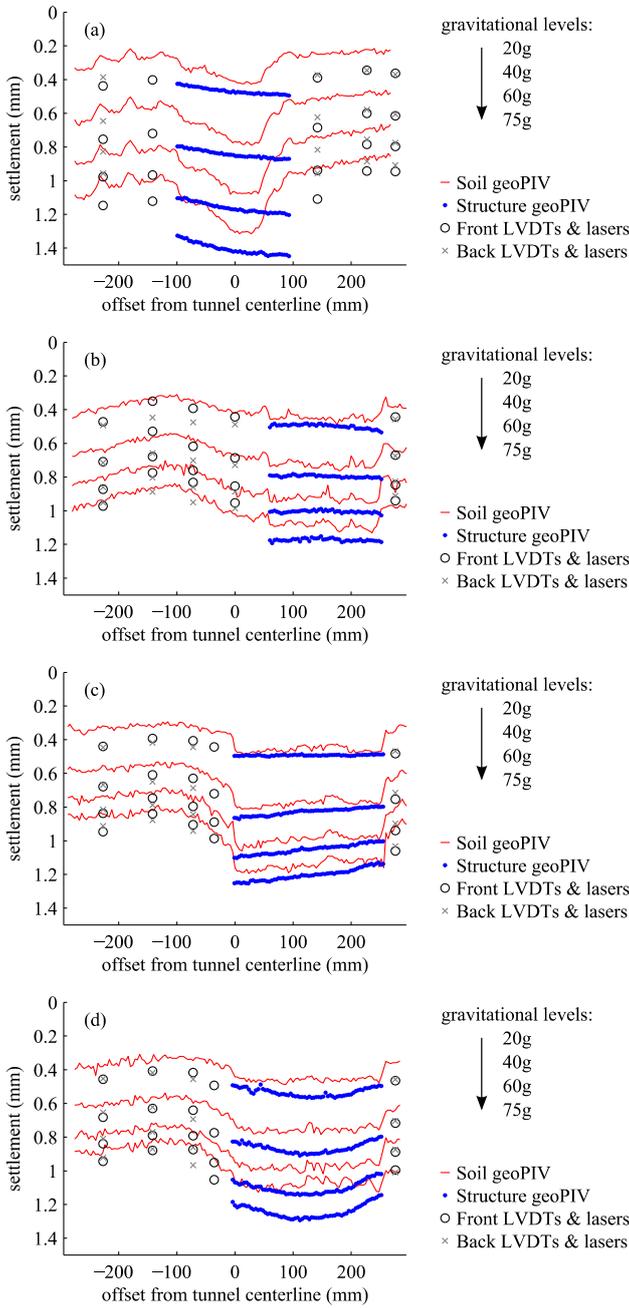
Figure 7: Near surface soil and structure vertical displacements at final g-level for centrifuge tests (a), (b), (c) and (d).

4 COMPARISON TO TUNNEL EXCAVATION SIMULATION

Widely applied methods to estimate the risk of building damage caused by tunnel excavation make use of foundation movement parameters (e.g. Burland 1995). Within this study, the structure response is evaluated using the horizontal building strains (ε_a), the deflection ratio (DR) and the slope (s). ε_a is the average horizontal strain at the base of the structure and was estimated from the slope of a linear function fitted to the horizontal building displacements. The definition of *DR* and *s* is given below, and illustrated in Figure 8.

$$DR = \frac{\Delta_{max}}{L} \tag{1}$$

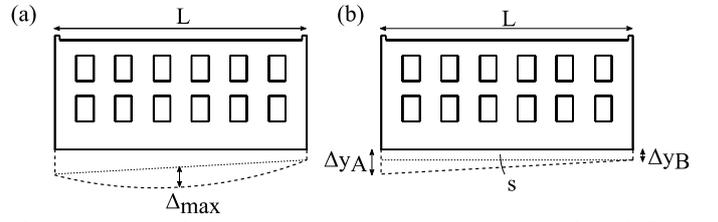$$s = \frac{\Delta y_A - \Delta y_B}{L} \tag{2}$$

Figure 8: Foundation movement parameters. Negative deflection ratios (DR) indicate convex deflected shapes (hogging) while concave deflected shapes (sagging) are positive. A clockwise rotation gives a negative slope while a counter clockwise rotation is presented by a positive slope.

Figure 9 and compare the structure response at the final g-level and a tunnel volume loss of 2.0%. As mentioned above, the final spin-up state was used as the initial condition for the tunnel excavation simulation. The deflection ratios during spin-up were significant, though they were less than the tunnel excavation stage, except for the test (b) which was the most rigid structure. By contrast, the measured slope depended on the position of the structure to the tunnel. While the structure located symmetrically about the tunnel centreline (i.e. test a) experienced a higher slope during spin-up (Fig. 9a), the asymmetric cases (i.e. test b, c and d) encountered a considerable higher slope during tunnel excavation (Figs 9b, c, d). These results can be attributed to the structures tilting towards the tunnel as tunnel volume loss progresses. Rigid body tilting has little effect on damage, and is thus of lower importance for damage prediction.

Surprisingly, the average base horizontal building strains were found to be consistently higher during the spin-up compared to the tunnel excavation phase (Fig. 9). This result might be explained by the lateral component of the centrifugal acceleration, which tends to drag the building model from the centre of the centrifuge model as g-levels increase. However, the monitored strains were at least an order of magnitude smaller than the strain to failure of the 3D printed material (i.e. $\varepsilon_f = 0.31\%$). It is also important to point out that during the tunnel excavation phase negligible horizontal strains were induced to the buildings which confirms recent research of Farrell & Mair 2012.

Table 1: Comparison of building damage indicators after spin-up (su) and 2.0% of tunnel volume loss (te) for the tests (a), (b), (c) and (d).

	DR (%)		Slope (%)		ε_a (%)	
	su	te	su	te	su	te
a	0.018	0.025	-0.063	-0.024	0.011	0.001
b	-0.015	-0.015	-0.006	0.125	-0.003	-0.002
c	0.009	-0.040	0.045	0.198	-0.015	0.013
d	0.031	-0.047	0.020	0.216	-0.036	-0.003

Overall, no building damage was observed during the centrifuge acceleration. However, according to this data one can infer that more vulnerable structure models might experience building damage as the g-level increases. In that case, and depending on the
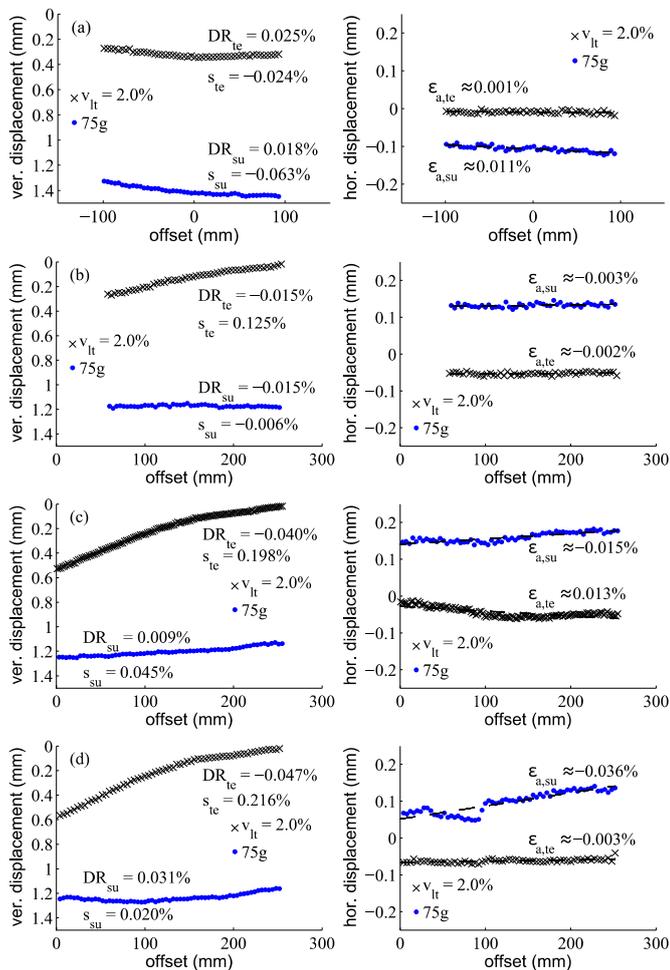
Figure 9: Vertical (left) and horizontal (right) base structure displacements for test (a), (b), (c) and (d). Deflection ratio (DR), slope (s) and average horizontal base strain (ε_a, compressive strains are positive) are given for the final spin-up level (su) and a tunnel volume loss of 2.0% (te).

combination of spin-up and tunnelling-induced damage mechanisms, the final structural response could change (Giardina et al. 2015). This finding indicates that there is a need to incorporate the structure behaviour during the spin-up phase when studying tunnelling-induced settlement building damage in a geotechnical centrifuge.

5 CONCLUSIONS

This paper identified experimental challenges when modelling the response of surface structures to tunnelling in sand. Non-uniform ground displacements during centrifuge acceleration were monitored as a result of the adopted tunnel excavation simulation technique and the position of the building model relative to the tunnel. A comparison between the structure response during spin-up and the tunnel excavation highlighted that notable building distortions can be observed as the g-level increases. The deflection ratio prior to tunnel excavation may be significant, and should not be ignored when evaluating the volume loss at which cracking occurs in centrifuge tests. In addition, the horizontal strain induced by spin-up can be larger than those induced by tunnel excavation.

These findings underline the need to consider the spin-up phase when studying the mechanisms of tunnelling on realistic surface structures, and provide a base for further centrifuge modelling researchers dealing with the effects of tunnel construction on buildings.

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