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Tunnel-framed building interaction: comparison between raft and separate footing foundations

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Abstract:	This paper investigates the influence of the foundation configuration (raft or separate footings) on tunnel-soil-framed building interaction using geotechnical centrifuge testing. Tunnelling-induced soil movements and deformation fields, framed building displacements, and structure shear distortions (with associated modification factors) are illustrated. Framed building stiffness and footing bearing capacity are also evaluated experimentally. Results show that the foundation configuration plays an important role in determining the ground response to tunnelling, affecting soil displacement fields as well as the distribution of soil shear and volumetric strains. In particular, foundation settlements and differential horizontal displacements are larger for separate footings compared to raft foundations. The effects of building width, weight, and eccentricity (with respect to the tunnel) on foundation settlements and structural distortions is quantified for separate footings and contrasted against results for raft foundations. The modification factor of the maximum building shear distortion is linked to the relative soil-building shear stiffness; interestingly, for buildings with similar values of relative stiffness, the level of shear distortion within framed buildings is lower for separate footings than rafts.
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Author Comments:	Mr. Jingmin Xu PhD candidate Department of Civil Engineering University of Nottingham University Park Nottingham NG7 2RD UK tel: +44 (0)7596411964 email: jingmin.xu@nottingham.ac.uk Prof. David Potts Editor in Chief Géotechnique Re: Submission of technical paper: 'Tunnel-framed building interaction: comparison between raft and separate footing foundations' Dear Prof. Potts, Kindly consider the revised manuscript entitled 'Tunnel-framed building interaction: comparison between raft and separate footing foundations' by Jingmin Xu, A. Franza, A. M. Marshall, N. Losacco and D. Boldini for publication within the Journal of Géotechnique. Please feel free to contact me at the above given details if there is any further information required. Regards, Jingmin Xu

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Tunnel-framed building interaction: comparison between raft and separate footing foundations

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This paper investigates the influence of the foundation configuration (raft or separate footings) on tunnel-soil-framed building interaction using geotechnical centrifuge testing. Tunnelling-induced soil movements and deformation fields, framed building displacements, and structure shear distortions (with associated modification factors) are illustrated. Framed building stiffness and footing bearing capacity are also evaluated experimentally. Results show that the foundation configuration plays an important role in determining the ground response to tunnelling, affecting soil displacement fields as well as the distribution of soil shear and volumetric strains. In particular, foundation settlements and differential horizontal displacements are larger for separate footings compared to raft foundations. The effects of building width, weight, and eccentricity (with respect to the tunnel) on foundation settlements and structural distortions is quantified for separate footings and contrasted against results for raft foundations. The modification factor of the maximum building shear distortion is linked to the relative soil-building shear stiffness; interestingly, for buildings with similar values of relative stiffness, the level of shear distortion within framed buildings is lower for separate footings than rafts.

KEYWORDS: Tunnels & tunnelling, foundation configuration, soil/structure interaction, frame, centrifuge modelling

INTRODUCTION

New tunnels are frequently excavated during the development and expansion of urban areas. To minimise the potential risk of tunnelling-induced ground movements on existing structures, it is important to be able to efficiently predict building distortions considering soil-structure interaction.

Although the structural characteristics of framed buildings need to be considered in tunnel-soil-structure modelling (Boldini *et al.*, 2018; Elkayam & Klar, 2019; Fu *et al.*, 2018; Franza & DeJong, 2019; Comodromos *et al.*, 2014) and risk assessments (Boone, 1996), equivalent beam or plate models with minimal shear flexibility are still often adopted (Franzius *et al.*, 2006; Haji *et al.*, 2018). However, Xu *et al.* (2020) recently provided experimental evidence that framed buildings on raft foundations primarily exhibit shear distortions when subjected to tunnelling-induced displacements and suggested, by contrasting framed building results with equivalent plate test results from Farrell *et al.* (2014), that the use of equivalent beams/plates with minimal shear flexibility may not be adequate for framed buildings.

With regard to foundation effects, while structural horizontal strains at the ground level are negligible for continuous foundations (Franzius *et al.*, 2006; Dimmock & Mair, 2008), discontinuous foundations can result in large differential horizontal displacements (Laefer *et al.*, 2009; Goh & Mair, 2014; Fu *et al.*, 2018), which have the potential to affect the deformation mechanisms of framed buildings (Franza & DeJong, 2019; Fu *et al.*, 2018). Experimental data related to tunnelling-induced ground displacements and deformations are limited to continuous foundations (i.e. strips and rafts) (Farrell *et al.*, 2014; Ritter *et al.*, 2017), whereas field data are sparse with limited insights into the subsurface soil behaviour (Dimmock & Mair, 2008; Goh & Mair, 2014). Because of the lack of a systematic experimental investigation of the effects of foundation configuration on both structural distortion and soil movements, the research community is limited in their capability to develop and verify reliable numerical and analytical tools.

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SCOPE

This paper investigates the influence of foundation configuration on the tunnel-soil-frame interaction. Here, two configurations are considered: a 'raft' foundation that is continuous beneath the entire building footprint, and a 'separate footing' foundation (strip footings parallel to the tunnel axis) that is discontinuous in the direction transverse to the tunnel axis (see Figure 1). The paper presents data obtained from plane-strain geotechnical centrifuge tests using dry sand: novel experiments including 10 tests simulating tunnelling beneath frames on separate footings and 3 tests characterising the individual footing bearing capacity; and published data from 2 greenfield tunnelling tests and 10 tests of tunnelling beneath frames on raft foundations from Xu *et al.* (2020). Greenfield and raft foundation test data are used here as a reference for comparison with the separate footing results. A parametric study considering building width, weight, eccentricity (i.e. lateral offset from the location of the tunnel), and soil density is presented.

CENTRIFUGE EXPERIMENTAL DETAILS

Tests were performed on the University of Nottingham Centre for Geomechanics 4 m diameter geotechnical centrifuge. The plane-strain experimental package developed by Zhou *et al.* (2014) was used, including a strongbox, a transparent acrylic front wall to allow acquisition of digital images of the subsurface, an aluminium back wall, a flexible membrane model tunnel (diameter D_t=90 mm) filled with water, and a tunnel volume loss control system. A fine-grained dry silica sand (Leighton Buzzard Fraction E), with minimum and maximum voids ratios of 0.65 and 1.01 was used (characterised by Zhao (2008) and Lanzano *et al.* (2016)).

In the experiments, the construction of a tunnel beneath a framed building with either a raft foundation or separate footings was simulated. Two model building widths were considered: a long building with width $B_l = 462$ mm and a short building with B_s=232 mm. The model tunnel had a cover, C, of 117 mm ($C/D_t = 1.3$) in all tests. Figure 1 shows the tunnel and building parameters in model scale. In particular, the width of the footing (b_{foot}) is 12 mm and the height of the footing column equals that of the storey height h_{storey} (38.1 mm). Building elements in all models are 3.2 mm thick, and the bay width b_{bay} of the model frame in the direction transverse to the tunnel is 76.2 mm. To achieve plane-strain conditions, all the building elements spanned the full extent (258 mm) of the framed building model in the tunnel longitudinal direction, leaving a 1 mm gap between the building model and front/back walls of the 260 mm wide centrifuge strongbox.

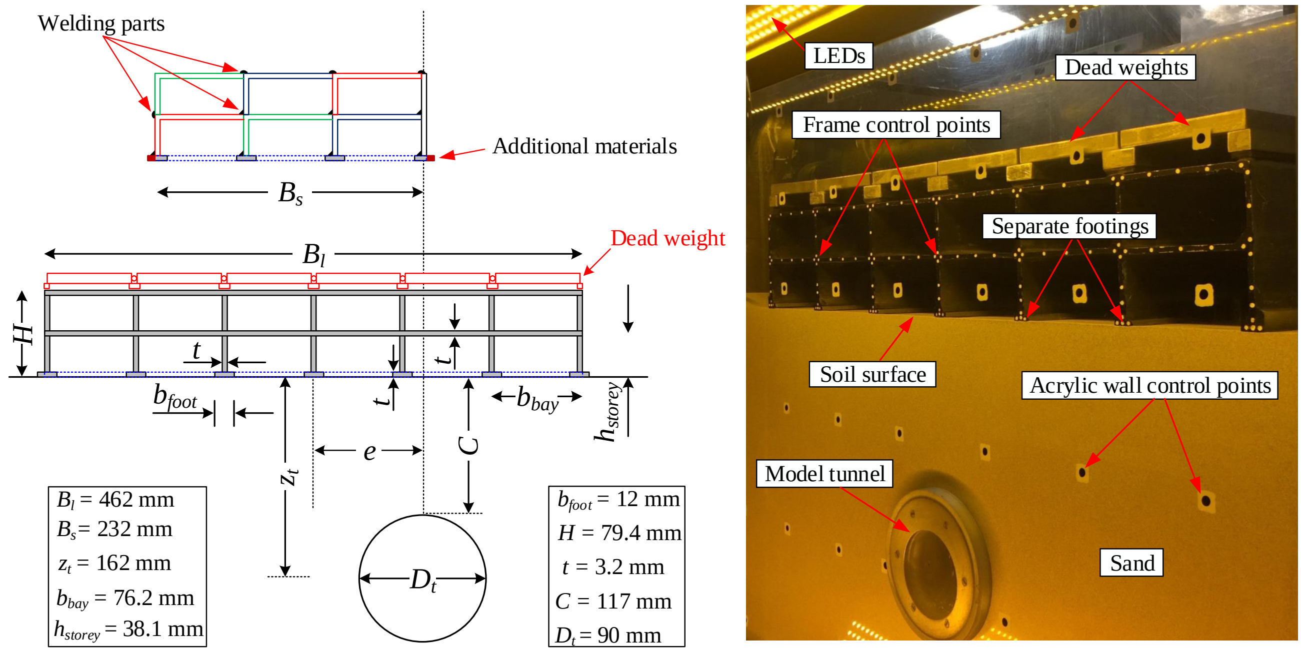

Fig. 1. Experimental set-up: (left) test layout in model scale dimensions, (right) view of the model.

The bare framed building models were manufactured by machining and welding two aluminium plates (one as the foundation plate and one side wall) and several angles, as illustrated in Figure 1 for the short frame model. Note that infill-walls were not physically modelled. For the connection between walls and slabs, 60% of the length (along the tunnel axis direction) was welded (Xu *et al.*, 2019). The frames with separate footings were made from the raft foundation models by machining out the aluminium plate at the base of the model (dotted lines in Figure 1); epoxy was added to the external footings to achieve the desired footing width of 12 mm.

To replicate a rough soil foundation interface, a thin layer of sand was bonded to the underside of the building foundations. The GeoPIV digital image analysis technique (White *et al.*, 2003) was used to measure both soil and structure displacements during tests. Structure displacements were obtained by tracking white dots painted on the front face of the building models (matt black background was painted prior to the white dots). A Dalsa Genie Nano-M4020 monochrome camera (with a 12.4-megapixel sensor and 8mm Tamron lens) and single wavelength light-emitting diodes were used (Xu *et al.*, 2020).

The tests were conducted at an elevated gravity level of 68 g, representing a prototype scenario with a D_t=6.1 m diameter tunnel beneath either a 31.4 m or a 15.8 m wide building. The structural element thickness of the prototype buildings is 0.22 m, the bay width is 5.2 m, and inter-storey height is 2.6 m. Considering that aluminium and concrete have a similar Young's modulus (which is not affected by the centrifuge scaling laws), the prototype cross-sectional stiffness of slabs and walls realistically replicates typical reinforced concrete structures.

Data from 25 centrifuge tests are presented in this paper, as shown in Table 1 and Figure 2: 2 greenfield tests, 20 tunnel-frame interaction tests, and 3 loading tests for isolated footings. For a given frame model, the relative density of the sand ($I_d = 30, 90\%$), the eccentricity (e) of the model building with respect to the tunnel, and the building self-weight (SW: standard self-weight; 2SW: double self-weight) were varied in the experiments. The standard self-weight SW is due to the weight of the aluminium used for the frame models (calculated for in-flight conditions considering the variation of gravity level across the height of the models). The double self-weight 2SW was achieved by adding simply supported (at wall locations) weights to the top of the frames; this system ensured that the additional weight did not increase the frame stiffness (see Figure 1). For the long frame, a total of 4 tests were performed for each foundation configuration: 2 tests involving a central tunnel in loose and dense soil for a standard weight SW building, 1 test with a central tunnel in dense sand and the 2SW frame, and 1 test for an eccentric tunnel case with $e/B = 0.2$ in loose sand and the SW frame. For the short building model, 6 tests were performed for each foundation configuration: for the loose sand, normalised eccentricity e/B of 0 and 0.5 was tested for the standard weight SW case only; for dense sand, both cases of e/B (0 and 0.5) and building weight (SW and 2SW) were tested.

Table 1. Centrifuge testing plan.

Total No.	Label	Foundation type	I_d (%)	e/B	Weight (pressure†, kPa)
2	Greenfield*	-	30 & 90	-	-
6	Short	Raft*	30	0 & 0.5	SW(19.4)
			90	0 & 0.5	SW(19.4) & 2SW(38.8)
6	Short	Separate footings	30	0 & 0.5	SW(94.4)
			90	0 & 0.5	SW(94.4) & 2SW(189)
4	Long	Raft*	30	0 & 0.2	SW(22.8)
			90	0	SW(22.8) & 2SW(45.6)
4	Long	Separate footings	30	0 & 0.2	SW(103)
			90	0	SW(103) & 2SW(206)
3	Loading	Separate footings	30 & 90	-	-

† Average value beneath the foundation at 68 g
* Data from Xu *et al.* (2020)

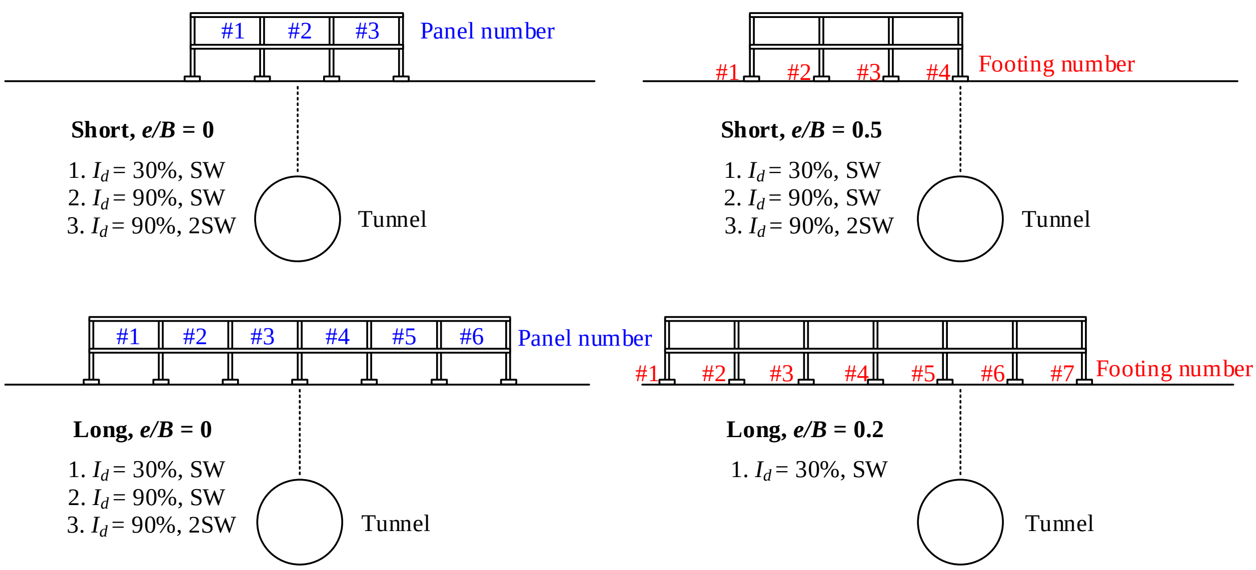

Fig. 2. Illustration of the centrifuge testing plan.

The preparation of the centrifuge models for dense (I_d=90%) and loose (I_d=30%) sand tests was different. The dense sand was poured into the container in-line with the model tunnel (consistent with Marshall *et al.* (2012); Farrell *et al.* (2014); Franza *et al.* (2019)) before moving the package onto the centrifuge cradle. The preparation of loose sand models was carried out with the experimental package on the centrifuge cradle (consistent with Xu *et al.* (2020); Franza & Marshall (2018)). After pouring the loose soil sample, the surface was levelled to ensure uniform contact at the soil-foundation interface. In the tunnel-frame interaction tests, the framed building model was carefully placed on the soil surface at 1 g, the model was then spun to 68 g, and two stabilisation cycles were carried out (going from 68 g to 15 g and back to 68 g); the stabilisation cycles are done to help obtain consistency between tests by reducing localised high-stress zones ('hung-up' particles), thereby achieving more uniformly stressed soil profiles. Tunnel volume loss $V_{l,t}$ was then simulated by extracting water from the model tunnel in increments of 0.1%, aiming to obtain a uniform displacement along the tunnel axis and achieve the intended plain strain boundary condition. At each increment of $V_{l,t}$, digital images of both the soil and the structure were taken.

The loading tests were conducted to evaluate the ultimate capacity of the footings; this information is used in the interpretation of results presented later and may be useful for others conducting numerical analysis of the problem. The loading tests were performed at two locations within the strongbox: position 1 at the centre of the strongbox, and position 2 at 225 mm from the centre and 95 mm away from the side wall. These locations correspond to the positions of the central and external footings, respectively, of the long frame with $e/B = 0$. Using a load controlled system, two loading conditions were implemented during the spin-up phase of the loading tests to achieve either a footing initially detached from the surface (null initial pressure q_0) or a footing loaded such that the average applied pressure was equivalent to the pressure beneath the model building footings (which varied during centrifuge spin-up; see Table 1 for pressures at 68 g). Upon reaching 68 g, a displacement controlled system was activated and the footing in position 1 was jacked at 0.02 mm/s and then unloaded. The footing in position 2 was then tested in the same way.

Finally, the implications of the 2D plane-strain conditions on the foundation schemes are discussed. While the 2D 'raft' foundation is representative of rafts or continuous strips oriented transverse to the tunnel axis, the 2D 'separate footing' foundation scheme applied here is an approximation of strips placed longitudinally in the direction of the tunnel axis or discrete pads. The adoption of the 2D condition does, of course, imply simplifications and approximations compared to more realistic 3D tunnelling scenarios, hence results presented here should be interpreted with this in mind.

OVERVIEW OF DEFORMATION PARAMETERS

Underground excavation-induced ground movements cause building shear distortions, the assessment of which is possible by several approaches (Cook, 1994; Mair *et al.*, 1996; Boone, 1996; Finno *et al.*, 2005; Elkayam & Klar, 2019). To quantify the shearing of a panel (geometrical area delimited by two columns and two slabs, as shown in Figure 3), it is possible to use the angular distortion β, which Son & Cording (2005) calculated by subtracting tilt θ from the slope s.

$$\beta = s - \theta = \frac{\Delta u_{tot}}{b_{bay}} - \left(\frac{\phi_2}{2} + \frac{\phi_1}{2}\right) \tag{1}$$

where $\Delta u_{tot} = U_{z,D} - U_{z,C}$ is the total differential settlement; $\phi_1 = \left(U_{x,C} - U_{x,A}\right) / \left(h_{storey}\right)$ and $\phi_2 = \left(U_{x,D} - U_{x,B}\right) / \left(h_{storey}\right)$ are left and right edge tilt, respectively; for $U_{i,j}$, $i = x; z$ is the displacement direction, and $j = A; B; C; D$ is the location of the panel corner. In this paper, only the shear distortions of panels confined by two columns and two slabs are considered. The lower panels for the footing foundation are not analysed because of uncertainties relating to footing differential horizontal displacements, as discussed later.

Alternatively, Cook (1994) proposed an approach to isolate tilt (Δu_{tilt}), bending (Δu_{bend}), and shear (Δu_{shear}) displacements from the total differential settlement Δu_{tot}. Based on this approach, Ritter *et al.* (2020) derived the shear distortion γ in Equation (2) using top and bottom corner displacements of the bay of interest (see Figure 3). Interestingly, shear distortion γ of the structure is equal to the angular distortion β estimated by Son & Cording (2005).

$$\gamma = \frac{\Delta u_{shear}}{b_{bay}} = \frac{\Delta u_{tot}}{b_{bay}} - \frac{\Delta u_{tilt}}{b_{bay}} - \frac{\Delta u_{bend}}{b_{bay}} = \frac{\Delta u_{tot}}{b_{bay}} - \phi_1 - \frac{\phi_2 - \phi_1}{2} = \frac{\Delta u_{tot}}{b_{bay}} - \left(\frac{\phi_2}{2} + \frac{\phi_1}{2}\right) \tag{2}$$

EVALUATION OF BUILDING STIFFNESS AT 1-G

Following the approach of Son & Cording (2007), Xu *et al.* (2020) presented results from a series of loading tests to evaluate the structure shear $GA_{s,exp}$ and bending EI_{exp} stiffness (computed using Timoshenko beam theory; refer to Xu *et al.* (2020)) of the frames with raft foundations. Similarly, two 3-point deflection tests were performed on the long frame with

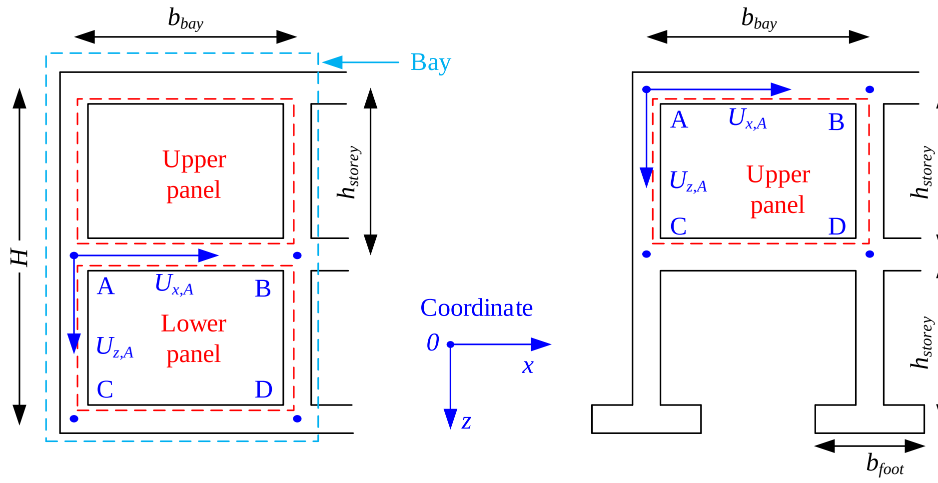

Fig. 3. Definition of building parameters definitions: (a) raft foundation; (b) separate footings.

separate footings with a free span length of either $6\,b_{bay}$ or $4\,b_{bay}$ to quantify the structure total stiffness $K = F/\delta$ (F is the force and δ is the total deflection) and, again using Timoshenko theory, estimate values of equivalent shear $GA_{s,exp}$ and bending EI_{exp} stiffness. In this paper, the term 'structure' refers to both the superstructure (above ground level) and the foundation elements (at the ground level). Figure 4 shows the deformed shapes of the frames in the loading tests, alongside the deformed shapes of the frames on raft foundations from Xu *et al.* (2020). Table 2 summarises the obtained experimental results of shear $GA_{s,exp}$ and bending EI_{exp} stiffness, along with the "pure" equivalent bending stiffness $EI_{EB,eq}$ (obtained using Euler-Bernoulli beam theory) and the values of δ_s/δ_b (the ratio between shear δ_s and bending δ_b deflections from the Timoshenko beam theory when using $GA_{s,exp}$ and EI_{exp}). The data show that all stiffness values of the frame on separate footings are smaller than for the raft foundation, as expected given the removal of the foundation slab. However, in both foundation cases, the deformed shape of the frame is dominated by shear deformation of the panels.

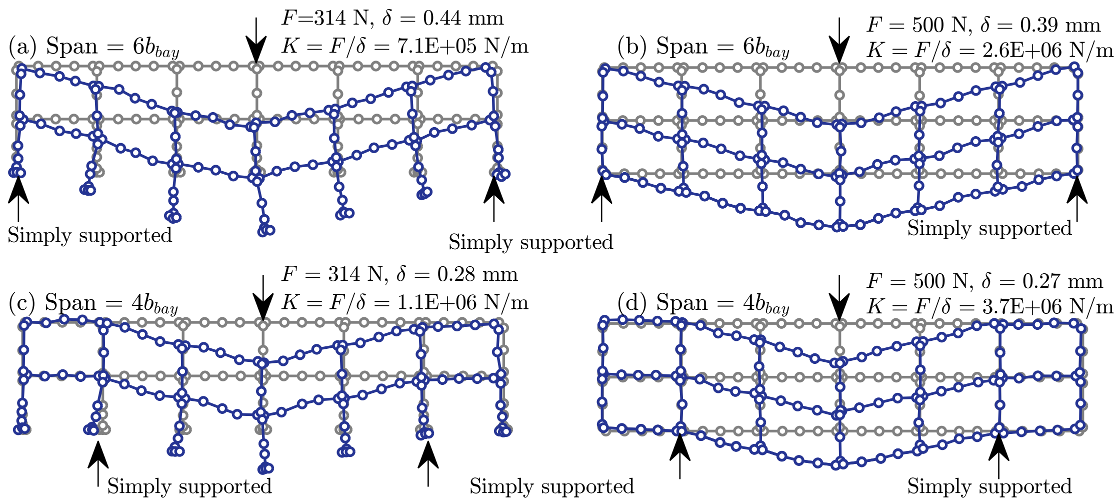

Fig. 4. Frame deformed shapes in the loading tests (scale factor=100): (a) separate footings with a span length of $6\,b_{bay}$; (b) raft with a span length of $6\,b_{bay}$; (c) separate footings with a span length of $4\,b_{bay}$; (d) raft with a span length of $4\,b_{bay}$.

Table 2. Experimental results of bending and shear stiffness of building models (model scale).

Foundation	EI_{exp}(Nm^2)	$GA_{s,exp}$(N)	$EI_{EB,eq}$(Nm^2)	δ_s/δ_b
Raft	5.0E+04	1.6E+05	2.6E+03	18
Separate footings	1.4E+04	9.2E+04	1.5E+03	8.6

The results of the loading tests highlighted an issue related to the manufacturing process of the model frame buildings, which in particular affected the separate footing model frames. In Figure 4, the central footing (Foot-4) is shown to rotate in an anticlockwise direction, whereas ideally no rotation should occur for this footing in the case of a perfectly symmetric scenario; for example, consider the deformed shape obtained from a finite element simulation of the frame loading in Figure S1. This experimental rotation occurred because the footing column is rigidly connected with the right-side beam/slab of the 1st storey (i.e. Bay-4 in Figure 1; this component is a single aluminium angle), whereas the column is welded to the left-side beam/slab of Bay-3. This result indicates that the welding of the connections between slabs and walls did not achieve a perfect fixed-fixed condition (only the top of the slab-column connection is welded) and, consequently, the ground-floor columns did not respond entirely as they should for fixed-fixed connections. This issue mainly affected the horizontal displacements of the separate footings and will be discussed in more detail later. As a result of this issue, the focus of analyses presented in this paper is on settlements of the foundations and distortions of the panels. Note that the left (Foot-1 to 3) and right (Foot-5 to 7) three footings moved outwards under loading due to the node rotation caused by the shear deformation; this behaviour is as expected (also observed in the finite element modelling in Figure S1), however each of these footings would also be affected by the issue discussed above.

CENTRIFUGE TEST RESULTS

Footing loading tests

The results of the separate footing loading tests, conducted in loose and dense sand to assess the pressure-settlement relationship, are shown in Figure 5, while Table 3 summarises the tested configurations and results. As mentioned earlier, the non-zero initial pressure q_0 in tests 1 and 2 was used to replicate the effect of the stress beneath the SW and 2SW separate footings of the model frames (refer to Table 1). Due to the limited capacity of the loading actuator used in test 2 for dense sand, the footing was unloaded prior to reaching a peak load (still providing data for initial and unloading stiffness). Table 3 also provides a summary of the main features of the pressure-displacement curves: the peak resistance of the footing q_p in the dense sand tests; the stress in the loose sand tests at which a significant change in the tangent stiffness occurred q_c; the settlement S_c corresponding to q_p and q_c; the initial loading stiffness and the unloading stiffness, taken as a tangent to the 'linear' portion of the initial loading and unloading curves (accepting that the curves are not perfectly linear).

The pressure-settlement curves are highly dependent on soil density, whereas the initial pressure q_0 and footing position have minor effects. The soil reaction pressure of the loose sand tests (test 1; positions 1 and 2) continuously increased with footing displacement with a distinct change in rate at $q_c = 460\,\text{kPa}$ but with no peak pressure, while the full pressure-settlement curves of the dense sand tests (test 3; positions 1 and 2) presents a peak resistance followed by a reduction at higher settlements (consistent with Vesic (1963); Lau & Bolton (2011)).

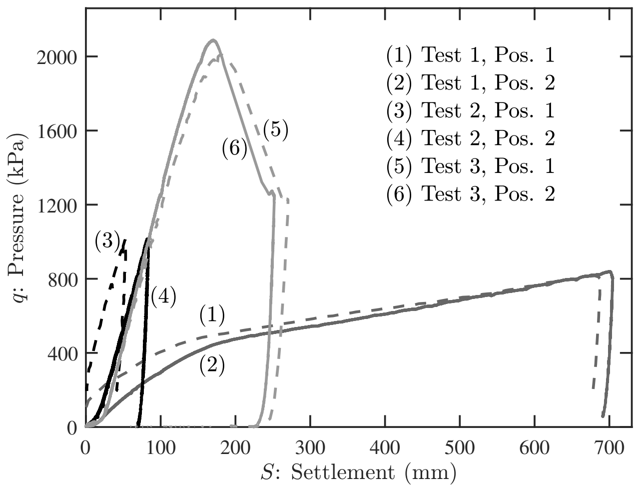

Fig. 5. The response of the footing models to vertical loading (Dimension in prototype)

Interestingly, when the initial pressure is $q_0 = 0$, the settlement S_c for both soil densities is within 170-185 mm, corresponding to 21-23% of the transverse width of the footing. In relation to the tunnel-frame interaction test results presented later (where $q_0 \neq 0$), the effect of applying q_0 =101-202 kPa was to decrease the value of S_c to 120-150 mm (estimated for dense soil from test 2, position 1 by projecting the trend to $q_p \approx 2000\,\text{kPa}$), corresponding to 15-18% of the transverse footing width. Using the values of q_p and q_c for the dense and loose sand cases, respectively, a safety factor with

Table 3. Footing loading test results (prototype scale).

No.	Test	I_d (%)	Pos.	q_0 (kPa)	q_p or q_c (kPa)	S_c (mm)	Initial loading stiffness (kPa/mm)	Unloading stiffness (kPa/mm)
(1)	1	30	1	101	460	120	2.7	64.8
(2)			2	0	460	170	2.8	78.3
(3)	2	90	1	202	-	-	15.1	76.0
(4)			2	0	-	-	14.8	100.1
(5)	3	90	1	0	2010	185	14.5	73.9
(6)			2	0	2086	180	16.1	111.2

respect to nominal average building pressure (see Table 1) can be computed as $SF \approx 20$ and 10 for the frame on dense soil with standard self-weight SW and double self-weight 2SW, respectively, while $SF \approx 4.5$ for the SW frame on loose soil.

Ground deformations

Figure 6 shows the prototype scale ground movements (horizontal U_x and vertical U_z), and strains (engineering shear γ and volumetric ϵ_v) contours for selected tests at a tunnel volume loss of $V_{l,t} = 2\%$. In Figure 6, positive horizontal and vertical displacements are oriented towards the right and downwards, respectively, while positive volumetric strains are contractive.

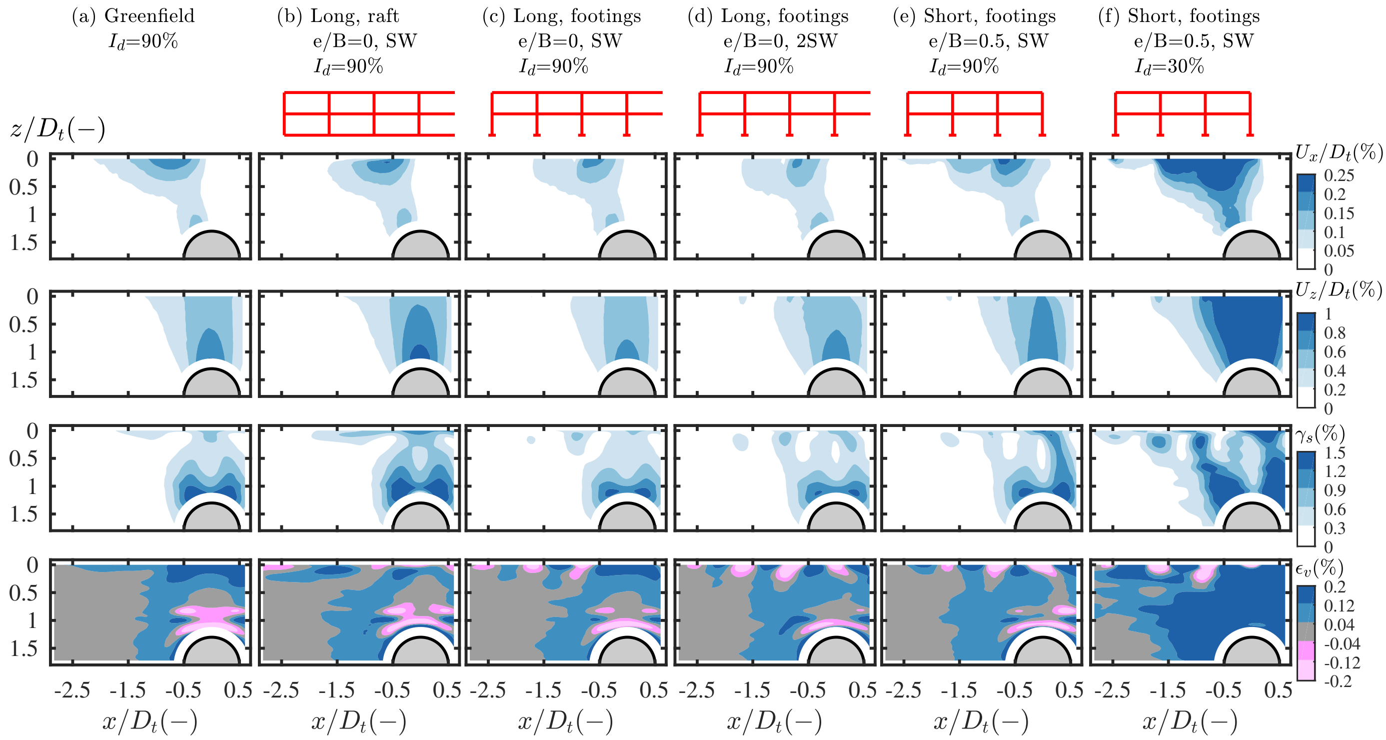

Fig. 6. Soil movements normalised by the tunnel diameter, engineering shear and volumetric strains (ϵ_v<0 indicates dilation) at $V_{l,t} = 2\%$ (data outside the contour thresholds were set equal to the closest limit value)

From Figure 6(a), the greenfield ground settlement shows a chimney-like pattern due to the low C/D_t value (Marshall *et al.*, 2012; Franza *et al.*, 2019), and large shear strains are observed at the tunnel shoulders. Soil directly above the tunnel crown experienced high levels of dilation, whereas the soil experienced intermediate levels of contraction within bands spanning from the tunnel springline to the surface. As discussed by Marshall *et al.* (2012), the zones of dilation and contraction correspond approximately to the areas of high and low shear strains, respectively. A zone of large contraction is noted centrally above the tunnel and near the surface; this zone is likely caused by the compressive action of the near-surface horizontal displacements on either side of the tunnel.

Firstly the effects, relative to the greenfield case, of the presence of framed buildings with raft foundations is considered. As shown in Figure 6(b), the horizontal displacements of the soil near the surface were largely restricted by the foundation roughness and building pressure towards the external part of the building, whereas the subsurface movements were marginally affected. Interestingly, the soil volumetric strain distribution near the surface was altered by the foundation axial action; this is consistent with the mechanism described by Ritter *et al.* (2017) that the foundation friction restricted the horizontal ground movements. The restriction of the horizontal soil movements resulted in a thin shear band at the soil-foundation interface with a decreased maximum contraction level and some areas of dilation now present. On the other hand, soil settlements increased throughout the ground, accommodated by a slight increase of shear strain at the tunnel shoulders.

For the central frames with standard weight SW on separate footings, as displayed in Figure 6(c), the footings restricted horizontal soil displacements with a distinct change in magnitude at the location of the footings (compared to a more uniform distribution for the raft foundation). The vertical displacement of the soil directly above the tunnel decreased compared with the greenfield case and the raft foundation, accompanied by a decrease of the shear strain. However, localised zones of high shear strain are noted at the footing positions, with dilative response directly beneath the footings and contraction within the soil between footings.

Next, the effect of the building weight is discussed for separate footings. Comparing Figure 6(c) and (d) shows that the increase of building weight slightly increased the settlement, shear and volumetric strains of the soil directly beneath the footings, but had a minor effect on the overall horizontal displacements.

The short eccentric frame with $e/B = 0.5$ in Figure 6(e) can be seen as half of the long frame in Figure 6(c). Therefore, data in these figures can be directly compared, with results showing that, because of the freedom to shift, the eccentric short frame in (e) increased the horizontal displacement of the soil near the surface compared with the long central frame in (c). At the same time, the action of the right-most footing (Foot-4) for $e/B = 0.5$ resulted in the soil chimney reaching the surface (i.e. larger soil settlements directly above the tunnel up to the surface), and the formation of a large shear band between Foot-4 and the right shoulder area of the tunnel (consistent with Ritter *et al.* (2017)).

Last, the effect of soil density is evaluated using data in Figure 6(e) for $I_d = 90\%$ and (f) for $I_d = 30\%$. The response of the loose soil in the $I_d = 30\%$ test is dominated by soil contraction (refer also to Figure 7). Consequently, the horizontal and vertical displacements, as well as the shear strain, were significantly increased compared to the $I_d = 90\%$ test. Furthermore, the soil around the tunnel for the $I_d = 30\%$ test was observed to be in contraction (in contrast to all the $I_d = 90\%$ tests where dilation occurred). Interestingly, areas of dilation occurred around the footings for the $I_d = 30\%$ test, likely due to the complex rotation/translation response of the footing and the soil shear/volumetric coupling.

Soil volume losses

In drained soils, because of their contractive/dilative response to shearing, the relationship between soil volume loss $V_{l,s}$ (given by the integration of the soil settlements at a given depth) and tunnel volume loss $V_{l,t}$ (the ground loss at the tunnel boundary) is not 1:1 (as would be the case in undrained soils), which could also have an impact on the tunnel-framed building interaction behaviour. Engineers tasked with designing excavations need to predict/assume reasonable values of soil volume losses given an expected level of tunnel volume loss $V_{l,t}$ for the applied tunnelling operations (Franza *et al.*, 2020).

First, the relationship between surface soil volume loss $V_{l,s}$ and tunnel volume loss $V_{l,t}$ is considered in Figure 7. Overall, soil relative density dominates the $V_{l,s} - V_{l,t}$ relationship. Similar to greenfield tunnelling data (Marshall *et al.*, 2012; Franza *et al.*, 2019), in the tunnel-structure interaction tests, the loose soil exhibits a contractive response, whereas the dense soil transitions from contractive at lower values of $V_{l,t} < 1\%$ towards dilative at higher tunnel volume losses. Regarding the influence of the building, all tests show relatively small effects at $V_{l,t} < 1\%$, whereas minor increases in $V_{l,s}$ can be seen at $V_{l,t} = 2 - 3\%$. Among the variation of building characteristics (weight, width, foundation type, e/B), only the building width played a notable role for eccentric structures.

To better quantify the impact of the structure on the ground volumetric behaviour, subsurface values of $V_{l,s}$ are shown in Figure 8 at $V_{l,t} = 1$ and 2% for central structures. Interestingly, the shift of the interaction curves, with respect to the greenfield data, towards greater $V_{l,s}$ values is relatively constant with depth. This shift, due to soil contractive strains, is greater in loose soil. This nearly uniform shift indicates that most of the change in the soil volumetric response (between greenfield and interaction tests) happened at $z/z_t \geq 0.7$, i.e. close to the tunnel. Also, note that the behaviour of the soil between the surface and the tunnel crown ($z/z_t = 0 - 0.7$) is overall contractive in both the loose and dense soils, with $V_{l,s}$ at $z/z_t = 0$ greater than $V_{l,t}$, hence the dilative response (when present) happened close to the tunnel.

Foundation and ground displacements

The settlement U_z and horizontal displacements U_x of the foundations (both raft and separate footings) and underlying soil are presented in this section at a tunnel volume loss $V_{l,t}$=2%. Figure 9 focuses on the effect of soil relative density whereas Figure 10 relates to building self-weight. To facilitate data interpretation, selected central structure tests with $e/B = 0$ are also directly compared in Figure 11. Note that measured soil settlements directly beneath the foundations were slightly less than those of the foundation in some areas; this inconsistency is mainly due to image analysis errors associated with

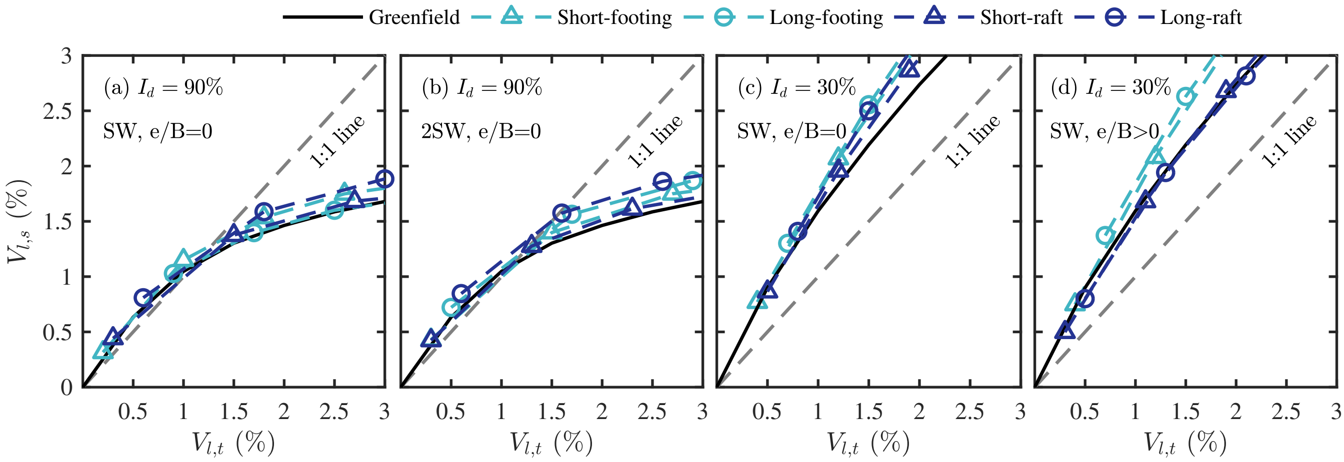

Fig. 7. Soil volume loss against tunnel volume loss: (a) central structures with self-weight SW in dense soil cases; (b) central structures with double self-weight 2SW in dense soil cases; (c) central structures with self-weight SW in loose soil cases; (d) eccentric structures with self-weight SW in loose soil cases.

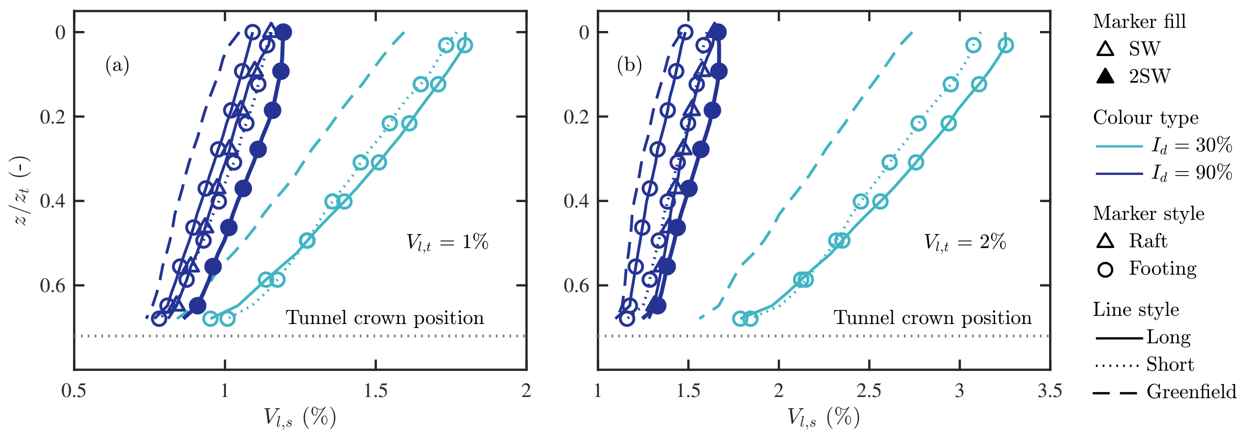

Fig. 8. Soil volume loss with varying depths for $e/B = 0$: (a) $V_{l,t}$=1%; (b) $V_{l,t}$=2%

the small gap between the model frame building and the acrylic wall. This issue also exists in results from other similar centrifuge tests (e.g. Farrell (2010); Ritter (2017)).

The greenfield settlement troughs, which are also provided in Figures 9-11, were characterised by fitting modified Gaussian curves (Vorster *et al.*, 2005) to surface settlement data. As shown in Table 4, the settlement trough width i is similar for both $V_{l,t} = 1$ and 2%. However, the maximum settlement $U_{z,max}$ in the loose soil is considerably larger than that in the dense soil, due to the ratio of $V_{l,s}/V_{l,t}$ presented in Figure 7.

Table 4. Greenfield settlement trough characteristics (prototype scale).

I_d (%)	$V_{l,t}$ (%)	$V_{l,s}$ (%)	$U_{z,max}$ (mm)	i (m)	trough width parameter = i/z_t (-)
30	1	1.6	31.7	3.8	0.34
90	1	1.1	19.9	3.8	0.34
30	2	2.8	60.3	3.4	0.31
90	2	1.5	29.7	3.4	0.31

To facilitate the description of soil-structure interaction, foundation settlements U_z are discussed first. Settlements in Figure 9(a)-(d) shows that the raft foundation frame has a smaller average settlement than the footings. This occurs because the building with a raft foundation is stiffer (see loading test results) and has a lower average soil-foundation contact pressure than the building with separate footings (the raft contact area is around 5 times larger than the footings; see pressures in Table 1). On one hand, for the eccentric configurations with $e/B = 0.5$ in Figure 9(d), all footings and the underlying soil settled more than the soil between the footings, particularly for loose soils. This embedment is probably caused by the coupled vertical-horizontal actions of the footings caused by tunnelling, as reported by Elkayam & Klar (2019). On the other hand, as shown in Figure 9(b) for $e/B = 0$, no embedment was measured for the central Foot-4 above the tunnel, which was uplifted by the frame action, while the external footings were embedded by the redistributed building weight (see Figure 2 for footing and bay numbering). Thus, the footing embedment is due to both an increase in vertical loads and/or shearing of the underlying soil. Finally, a gap is observed (where soil settlements are greater than foundation settlements) beneath the middle portion of the long raft in Figure 9(a), as well as beneath the central footing in Figure 9(b) for the loose soil case. In general, centrifuge results in Figure 9(a)-(d) confirm the outcomes of Elkayam & Klar (2019) that average footing settlements are greater than average greenfield settlements for semi-flexible buildings.

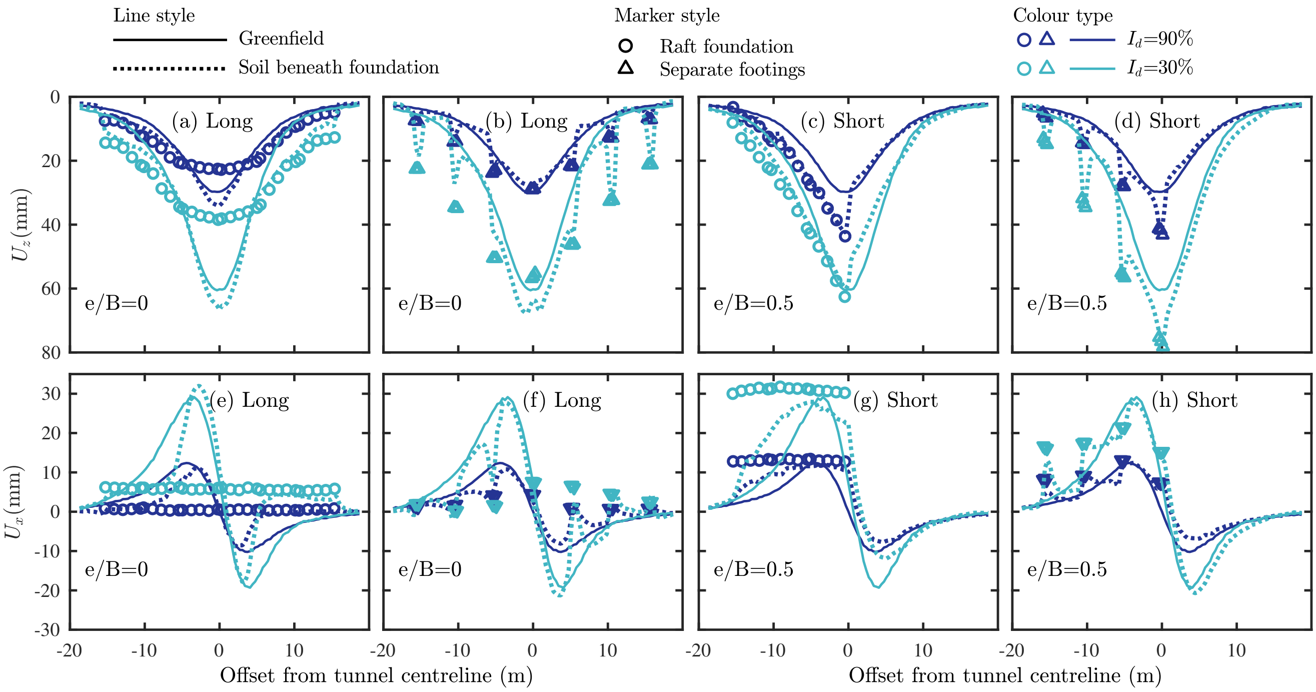

Fig. 9. Foundation and underlying soil displacements for loose and dense soil at $V_{l,t} = 2\%$

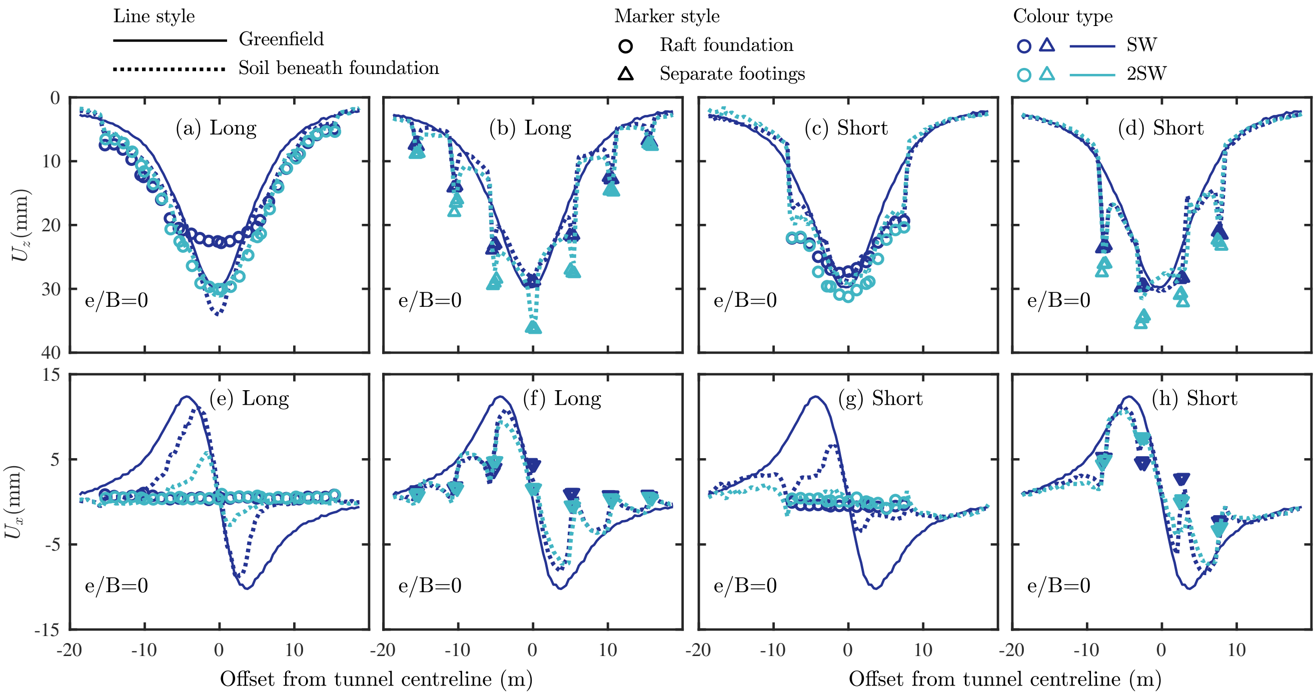

Fig. 10. Foundation and underlying soil displacements with different building weights for dense soil at $V_{l,t} = 2\%$

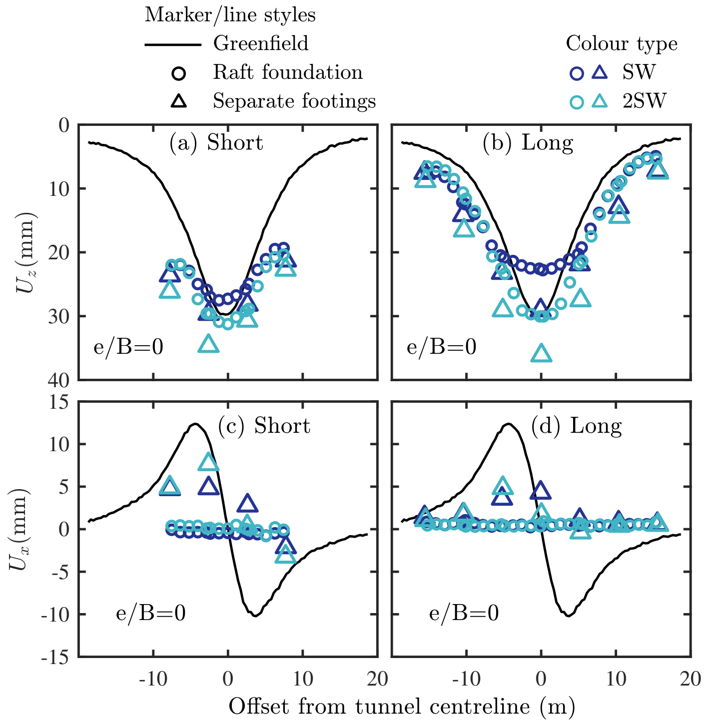

Fig. 11. Foundation displacements for central buildings founded on dense soil at $V_{l,t} = 2\%$.

Regarding horizontal displacements U_x, Figure 9(e)-(h) shows that raft foundations were axially rigid and effectively resisted horizontal ground movements, whereas separate footings underwent non-negligible differential horizontal displacements. Due to uncertainties caused by the model frame manufacturing process mentioned earlier, horizontal displacement data of the footings are only used to indicate general trends caused by a change in test parameter (i.e. those in Table 1). The soil was restricted horizontally where the foundation moved less than the greenfield, whereas movements increased where the foundation shifted more than the greenfield (the trend being continuous for the raft foundations and discontinuous for the separate footings). It is expected that this horizontal action of the foundation, which introduced further shearing within a narrow zone of the soil beneath the foundation (see surface shear band in Figure 6), would degrade the contact shear stiffness of the soil. This aspect could be important for the development of design charts and in evaluating horizontal strain modification factors, similar to Goh & Mair (2014).

Figure 10 shows the displacement data of the foundations and underlying soil for the central buildings with standard self-weight SW and double weight 2SW in the dense soil cases. The increase of building weight increased the maximum and differential settlements of the structures on both rafts (accompanied by a decrease of the size of gap in subplots (a) and (c)) and separate footings (associated with an increase of the embedment depth for the footings near the area of maximum soil settlement, for example Foot-3 to 5 in subplot (b) and Foot-2 and 3 in subplot (d)). A heavier building tends to have larger footing differential horizontal displacements (subplots (f) and (h)), especially for the short frame in (h), whereas the horizontal displacements of the raft foundations (subplots (e) and (g)) are negligible. The raft foundation provided a more significant restriction to the underlying soil horizontal displacement for the increased building weight (subplots (e) and (g)), whereas the effect was marginal for the separate footing cases (subplots (f) and (h)).

Next, the effect of the building width is considered using data presented in Figure 10. The decrease of building width increased the maximum settlement of the central structures with raft foundations (less true for the 2SW cases) and underlying soil (subplots (a) and (c)), whereas the change of building width had less of an effect on the settlement of the central frame with separate footings (subplots (b) and (d)). For the frames with separate footings, no gap formed regardless of frame width. On the other hand, the short frames with raft foundations embedded into the soil at their edges and showed no gap formation, in contrast to the long frames with raft foundations which showed little edge embedment and a considerable gap for the SW case (but not the 2SW case). For horizontal displacements, the shorter frame on the raft foundation had a more significant effect on restricting the underlying soil (subplots (e) and (g)). This is due to the difference in gap size beneath the foundations for the long and short frame tests, with a wide gap forming beneath the long frame and no gap forming beneath the short frame.

Finally, the effect of the relative tunnel-building location is discussed, referring to both Figures 9 and 10. For raft foundations, the increase of eccentricity from $e/B = 0$ to 0.5 of the short frame (dark colour in subplots (c) and (g)) decreased the flexural distortion of the building and increased horizontal soil displacements, whereas the central structure restricted them. Similarly, the eccentric short frame on separate footings also displayed lower flexural distortions (subplot (d)). However, the increase of eccentricity of the separate footing buildings changed the deformation mode of the bays at the ground level; for example, differential horizontal displacements of the footings of Bay-2 changed from compression in Figure 10(h) for the central frame to tension in Figure 9(h) for the eccentric frame.

Superstructure deformation parameters

The shear strain or angular distortion of frame bays/panels provides a more direct estimation of frame deformations than the deflection ratio (Boone, 1996; Xu *et al.*, 2020). Figure 12 presents the variation of maximum shear strain γ (from all panels for frames on a raft; from upper panels for frames on footings) against tunnel volume loss $V_{l,t}$ for all presented tests. Results are categorised into four groups based on soil density, building weight, and eccentricity.

General trends for data in Figure 12 relating to raft foundations were reported by Xu *et al.* (2020). The increase of building weight (subplots (a)-(b)) and the decrease of soil density (subplots (b)-(c)) increased building shear distortions for a given $V_{l,t}$, whereas the increase of building eccentricity (subplots (c)-(d)) decreased building distortions. On the other hand, there is little difference in shear distortion γ for separate footings compared to rafts (except for the eccentric long buildings in loose soil, for which the separate footings underwent larger settlements than the greenfield trough), despite the fact that the frames with a raft foundation have a greater structure stiffness than those with footings. This is likely due to the effect of two distinct phenomena affecting the two foundation types. For a given superstructure, the raft foundation contributed to increase the total stiffness of the frame, thereby reducing shear deformations, whereas for the separate footings (which do not contribute to the total frame stiffness), shear deformations were reduced by the effect of tunnelling-induced pressure redistribution beneath the footings, causing higher levels of shear strain within the soil around the footings and reducing the soil-foundation stiffness, resulting in greater structure embedment.

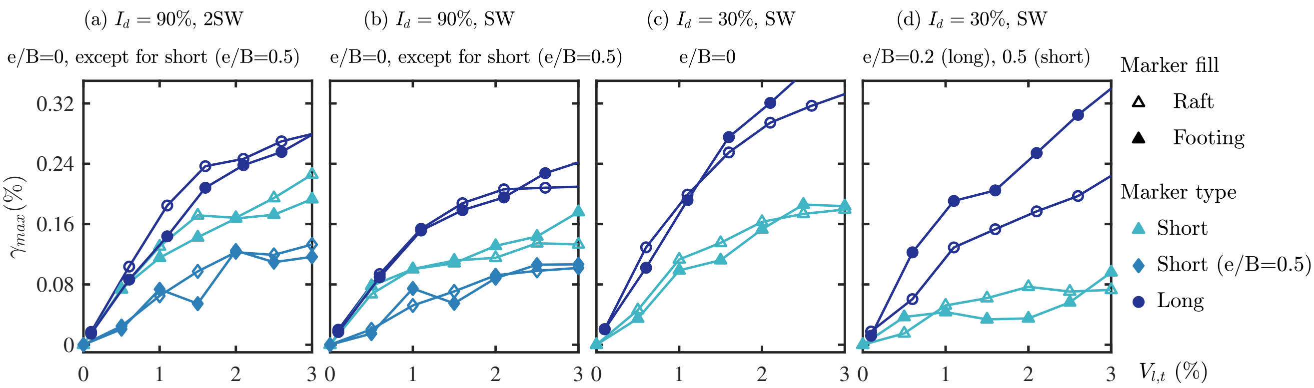

Fig. 12. Maximum shear distortion of the framed buildings with tunnel volume loss $V_{l,t}$

Level of building damage

Figures 13 and 14 show the deformed shapes of the framed buildings and the ground surface movements for 11 of the centrifuge tests at $V_{l,t}$=1 and 2%, respectively. While in the previous section, the focus was on maximum bay distortions, this section considers the distribution of distortion within panels. To assess the distortion level of panels, indicators are used for the range of shear strain γ and the category of damage. Shear strains were inferred from the corner displacements of panels using the approach from Cook (1994), while the tensile strains $\epsilon_t = \gamma/2$ were computed from γ using a Mohr's circle of strain under plane-strain conditions while neglecting the horizontal strain of the panels (Son & Cording, 2005). The category of damage was obtained from the thresholds of Boscardin & Cording (1989), shown in Table 5. A colour scheme was adopted to denote low (category 0-1); medium (category 2), and high (category 3+) levels of damage (see Table 5).

First, results at $V_{l,t}$=1% in Figure 13 are considered. Overall, most panels of the frames in most tests underwent low levels of damage (negligible or very slight). The frame with separate footings in Figure 13 embedded more into the soil than the frame with raft foundations, while columns underwent bending deflections (e.g. subplots (h) and (i)) due to the horizontal ground movements and the column head rotation at the first storey slab (caused by shear deflections of the frame). As expected, embedment was greater for the loose sand compared to the dense (compare subplot (b) to (e)), and for the

Table 5. Critical tensile strain and categories of damage (Boscardin & Cording, 1989).

Category of damage	Level of damage	Limiting tensile strain (%)
0	Negligible	0-0.05
1	Very slight	0.05-0.075
2	Slight	0.075-0.15
3 to 4	Moderate to severe	0.15-0.3
4 to 5	Severe to very severe	>0.3

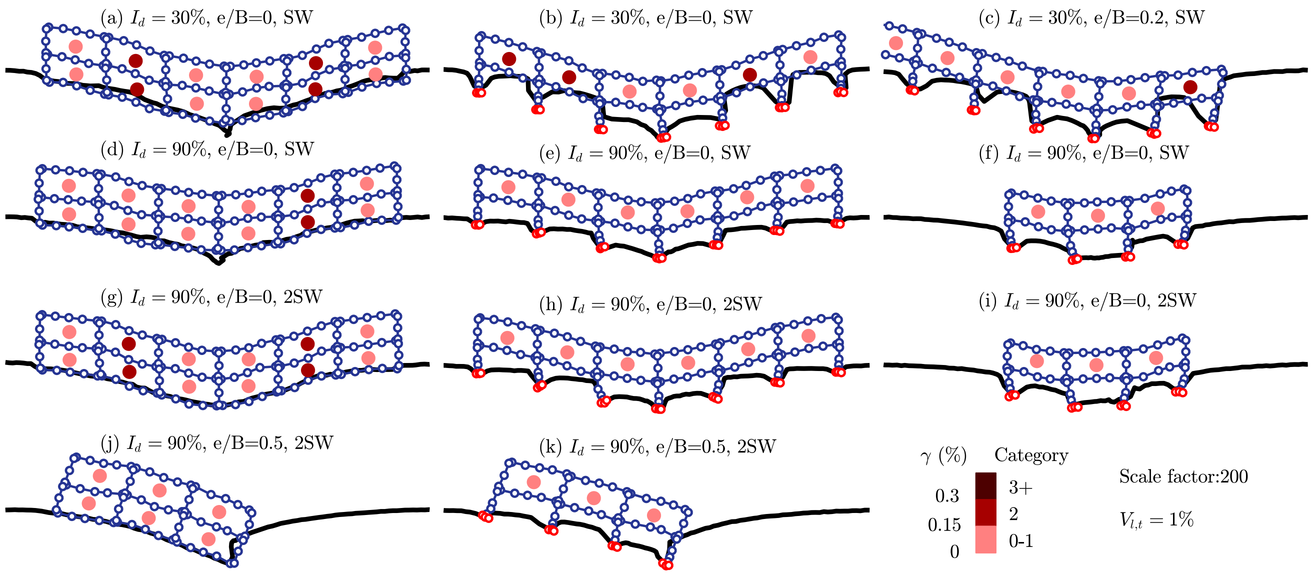

Fig. 13. Framed building deformed shapes and level of damage at $V_{l,t} = 1\%$ (scale factor: 200)

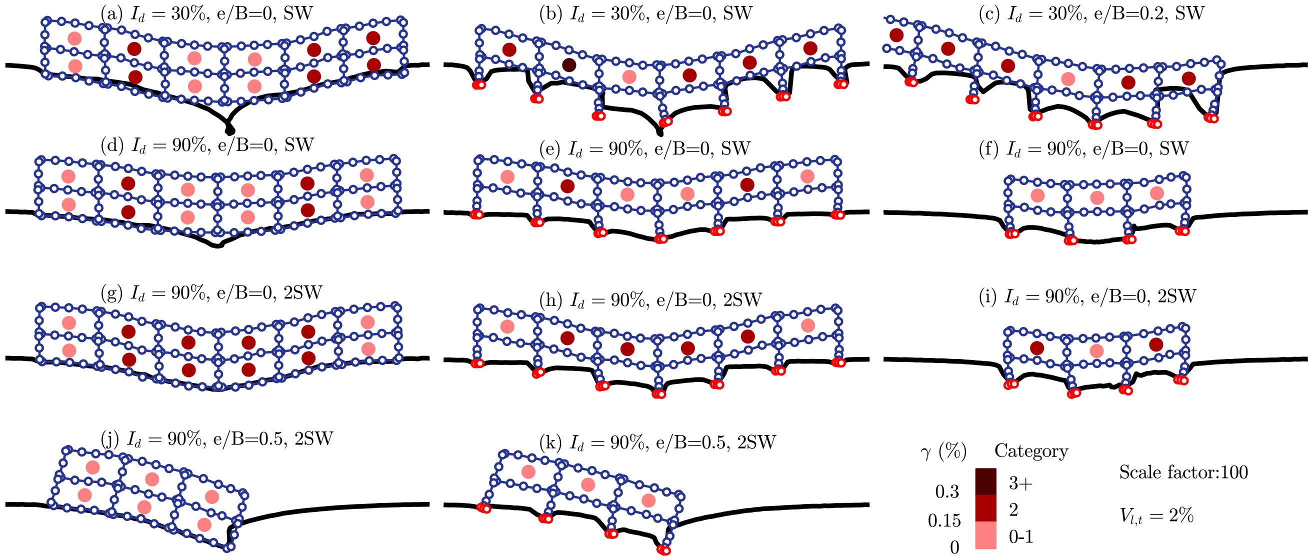

Fig. 14. Framed building deformed shapes and level of damage at $V_{l,t} = 2\%$ (scale factor: 100)

double self-weight 2SW compared to the standard self-weight SW (compare subplot (e) to (h)). Despite the decreased total stiffness of the frame with footings compared to the raft, only the distortion levels of the upper level panels in the loose soil (subplot (b)) are slightly higher than those in the raft (subplot (a)). For the dense soil cases (compare subplots (d)-(e) and (g)-(h)), the frames with rafts have larger deformations in specific panels compared to the footings. This indicates that the structure with separate footings is able to accommodate the differential ground settlement more readily than the raft, through the action of the footing embedment into the soil, thereby reducing the deformation of the structure.

Secondly, data presented in Figure 14 at $V_{l,t}$=2% is discussed. The upper level of panels of long frames with both rafts and footings in dense soil (compare subplots (d) to (e) and (g) to (h)) have the same deformation mode and equivalent distributions of maximum damage level. Interestingly, the decrease of soil density (from $I_d = 90$ to 30%) tended to increase the distortion of external panels (panel-1 and 6) of long frames (from low to medium, compare subplot (a) to (d), and (b) to (e), except for panel-1 in (a) to (d)), while the increase of building weight increased the distortion of the internal panels (panel-3 and 4, from low to medium, compare subplot (d) to (g), and (e) to (h)).

Finally, consistent with the findings on raft foundations (Xu *et al.*, 2020), results in Figure 14 confirm that the increase of building eccentricity (comparing (b) to (c), and (i) to (k)), as well as the decrease of the frame width (comparing (e) to (f), and (h) to (i)) decreased the deformation of the frame with separate footings. The short frame experienced lower levels of distortion than the long frame due to its freedom to tilt when subjected to tunnelling (see (g) to (j), and (h) to (k)).

Modification factor against relative soil-building stiffness

To link excavation-induced framed building angular distortion with relative soil-building stiffness, Xu *et al.* (2020) used the modification factor of angular distortion, M^{β}. This modification factor $M^{\beta} = \beta_{max}/\overline{GS}_{max}$ is obtained through normalising the maximum angular distortion β_{max}, obtained using the equation of Son & Cording (2005), by the maximum average slope of the portion of the greenfield surface settlement trough spanning a bay width, $\overline{GS}_{max} = \Delta U_{z,gf,max}/b_{bay}$. The trends of M^{β} were related to the relative soil-building shear stiffness $\kappa = (E_s B)/(GA_s^*) = (E_s BL)/(GA_s)$, where E_s is the representative Young's modulus of the soil, L is the length of the building in the longitudinal direction of the tunnel, $GA_s^* = GA_s/L$ is the building shear stiffness per meter run, and B is the building width.

In Figure 15, M^{β} is plotted against relative soil-building shear stiffness κ for $V_{l,t} = 1$ and 2% (numbers beneath markers indicate $V_{l,t}$). To highlight the effects of normalised building transverse width and building position relative to the settlement trough on the soil-structure interaction, a colour scheme was adopted to distinguish between values of e/B and the ratio B/i, where i is the distance to the inflection point of the greenfield settlement trough.

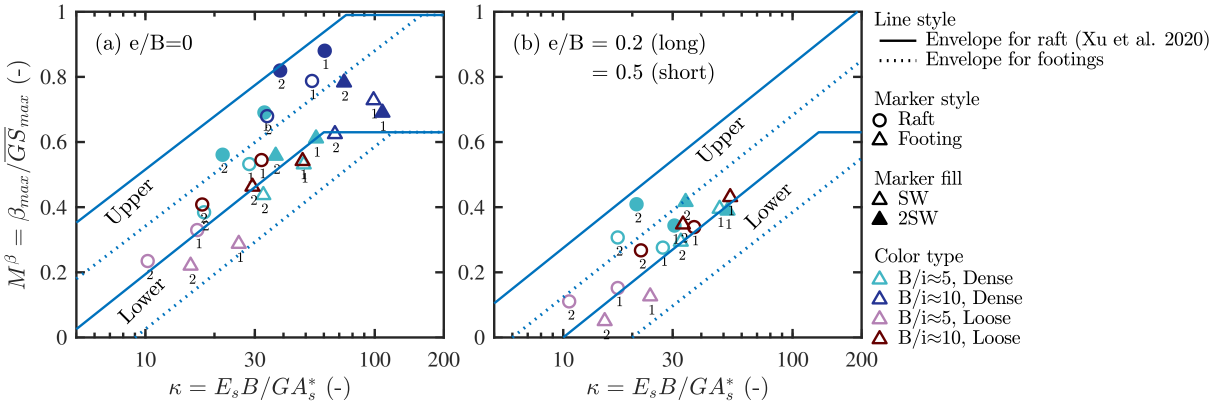

Fig. 15. Modification factors of β against relative soil-building shear stiffness at $V_{l,t}$ =1 and 2% ($V_{l,t}$ indicated by numbers below markers); (a) central structure cases; (b) eccentric structure cases

As can be seen in Figure 15, envelopes for separate footings are suggested and compared with those for raft foundations from Xu *et al.* (2020). An approximately linear increase of M^{β} for separate footings is observed in the semi-log scale with the relative soil-building stiffness. However, for a similar relative stiffness parameter κ, the frame on separate footings tends to have a smaller M^{β} value than the raft foundation. Additionally, this plot confirms that wider ($B/i \approx 10$) and heavier (2SW) frames, or structures with a smaller eccentricity e/B, tend to have a larger modification factor regardless of the foundation type (as also demonstrated in Figure 12).

CONCLUSIONS

This paper presented a centrifuge study on soil-framed building interaction, with specific focus on the influence of foundation scheme. Tunnelling-induced displacements of the building and underlying soil were illustrated, and structural and ground deformations were analysed. The following conclusions can be drawn.

- In addition to the building weight and position (e.g. Ritter *et al.* (2017)), the foundation configuration (i.e. raft or separate footings) significantly affects the ground response and impacts the soil-structure interaction. The foundation type had an impact on both the vertical and horizontal ground displacement fields as well as the shear and volumetric strain distributions. The action of the structure particularly affected the soil close to the foundation, with different trends depending on foundation type. Despite this and the differences in strain distributions, only marginal differences in the relationship between tunnel and soil volume loss was observed.

- Buildings with raft and separate footings acted to reduce flexural distortions caused by tunnelling in different ways; separate footings tended to embed into the soil in the areas where settlements were lowest, whereas raft foundations responded by uplifting the portion where settlements were greatest. Because of the embedment, the frame with separate footings settled significantly more than greenfield settlement at the corresponding location, as reported numerically by Elkayam & Klar (2019).
- In agreement with previous field (Goh & Mair, 2014) and modelling works (Fu *et al.*, 2018; Franza & DeJong, 2019), it was confirmed experimentally that tunnelling-induced differential horizontal movements are significant for separate footings, whereas they are negligible for raft foundations.
- For the considered two-storey framed buildings, when only the foundation scheme was changed, the level of shear deformation of the building panels was similar because of two distinct mechanisms: for the raft, shear deformations were reduced because of the higher overall structure stiffness resulting from the raft; for the separate footings, shear deformations were reduced because of higher levels of shear strains in the soil around the footings, reducing the soil-foundation stiffness and causing greater building embedment. The trends highlighted by Xu *et al.* (2020) for raft foundations were confirmed for separate footings: wider or heavier framed buildings display increased structural shear deformation, whereas building eccentricity reduces distortions for both foundation types.
- The modification factor of the frame angular distortion was linked to the relative soil-building shear stiffness. It was confirmed that the structural stiffness can play an important role in the soil-structure interaction of framed building configurations. With respect to raft foundations, frames on separate footings underwent slightly lower shear modification factors for a given relative stiffness; this is likely due to the fact that footings decreased the foundation footprint compared to rafts, which leads to greater flexibility of the soil-foundation system as well as higher levels of soil shearing (directly beneath the foundation, leading to greater stiffness degradation).

In this paper, the considered scenarios are limited to a tunnel with constant cover-to-diameter ratio constructed in dry sand beneath an elastic framed building. Future works considering the effects of tunnel relative depth, footing buried depth, and nonlinear building behaviour are ongoing.

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NOTATION

2SW	doubled self-weight of the building
SW	self-weight of the building
b_{bay}	width of the bay
b_{foot}	width of the footing
B	building width transverse to the tunnel
B_s	building width of the short frame
B_l	building width of the long frame
C	cover depth of the tunnel crown
D_t	diameter of the tunnel
e	building eccentricity with respect to the tunnel
EI	bending stiffness
$EI_{EB,eq}$	equivalent bending stiffness
EI_{exp}	experimental bending stiffness
E_s	representative Young's modulus of the soil
F	force
GA_s	building shear stiffness
$GA_{s,exp}$	experimental building shear stiffness
GA_s^*	building shear stiffness per meter run
$\overline{GS}_{max}$	maximum average slope of a portion of the greenfield surface settlement trough corresponding to b_{bay}
h_{storey}	height of the building storey
H	height of the building
i	distance to the inflection point of the settlement trough
I_d	relatively density of soil
K	total stiffness
L	length of the building in the longitudinal direction of the tunnel
M^{β}	modification factor of angular distortion
q_0	initial pressure beneath the footing
q_p	peak resistance of the footing
q_c	stress at which a significant change in the tangent stiffness occurred
s	slope
S	footing settlement in loading tests
S_c	footing settlement at q_p or q_c
t	thickness of the building element
$U_{i,j}$	corner point displacement; i is the displacement direction, and j is the location of the bay corner
U_x	horizontal displacement
U_z	vertical displacement
$V_{l,s}$	soil volume loss
$V_{l,t}$	tunnel volume loss
z	depth of interest
z_t	depth of the tunnel axis
γ	building shear strain
γ_s	soil engineering shear strain
β	building angular distortion
β_{max}	maximum building angular distortion
δ	total deflection
δ_b	bending deflection of the Timoshenko beam
δ_s	shear deflection of the Timoshenko beam
Δ_{tot}	total building differential settlement
Δ_{bend}	building differential settlement due to bending distortion
Δ_{shear}	building differential settlement due to shear distortion
Δ_{tilt}	building differential settlement due to tilt
$\Delta U_{z,gf,max}$	maximum differential settlement of a portion of greenfield surface settlement trough corresponding to b_{bay}
ϵ_t	tensile strain
ϵ_v	volumetric strain
κ	relative soil-building stiffness
ϕ_1	building/bay left edge tilt
ϕ_2	building/bay right edge tilt
θ	tilt

REFERENCES

Boldini, D., Losacco, N., Bertolin, S. & Amorosi, A. (2018). Finite Element modelling of tunnelling-induced displacements on framed structures. *Tunnelling and Underground Space Technology* **80**, No. April, 222–231, doi:10.1016/j.tust.2018.06.019.

Boone, S. J. (1996). Ground-Movement-Related Building Damage. *Journal of Geotechnical Engineering* **122**, 886–896, doi:10.1061/(ASCE)0733-9410(1996)122:11(886).

Boscardin, M. D. & Cording, E. J. (1989). Building response to excavation-induced settlement. *Journal of Geotechnical Engineering* **115**, No. 1, 1–21, doi:10.1061/(ASCE)0733-9410(1989)115:1(1).

Comodromos, E. M., Papadopoulou, M. C. & Konstantinidis, G. K. (2014). Numerical Assessment of Subsidence and Adjacent Building Movements Induced by TBM-EPB Tunneling. *Journal of Geotechnical and Geoenvironmental Engineering* **140**, No. 11, 04014061, doi:10.1061/(ASCE)GT.1943-5606.0001166.

Cook, D. (1994). Studies of settlement and crack damage in old and new facades. In *Proc., 3rd Int. Masonry Conference., London, England*, vol. 6, pp. 203–211.

Dimmock, P. S. & Mair, R. J. (2008). Effect of building stiffness on tunnelling-induced ground movement. *Tunnelling and Underground Space Technology* **23**, No. 4, 438–450, doi:10.1016/j.tust.2007.08.001.

Elkayam, I. & Klar, A. (2019). Nonlinear elasto-plastic formulation for tunneling effects on superstructures. *Canadian Geotechnical Journal* **56**, No. 7, 956–969, doi:10.1139/cgj-2018-0021.

Farrell, R. (2010). Tunnelling in sands and the response of buildings. *Ph.D. Thesis, Cambridge University* .

Farrell, R., Mair, R., Sciotti, A. & Pigorini, A. (2014). Building response to tunnelling. *Soils and Foundations* **54**, No. 3, 269–279, doi:10.1016/j.sandf.2014.04.003.

Finno, R. J., Voss, F. T., Rossow, E. & Blackburn, J. T. (2005). Evaluating Damage Potential in Buildings Affected by Excavations. *Journal of Geotechnical and Geoenvironmental Engineering* **131**, No. 10, 1199–1210, doi:10.1061/(ASCE)1090-0241(2005)131:10(1199).

Franza, A. & DeJong, M. J. (2019). Elastoplastic solutions to predict tunnelling-induced load transfer and deformation mechanisms of surface structures. *Journal of Geotechnical and Geoenvironmental Engineering* **145**, No. 4, 04019007, doi:10.1061/(ASCE)GT.1943-5606.0002021.

Franza, A. & Marshall, A. M. (2018). Centrifuge Modeling Study of the Response of Piled Structures to Tunneling. *Journal of Geotechnical and Geoenvironmental Engineering* **144**, No. 2, 04017109, doi:10.1061/(ASCE)GT.1943-5606.0001751.

Franza, A., Marshall, A. M. & Zhou, B. (2019). Greenfield tunnelling in sands: the effects of soil density and relative depth. *Géotechnique* **69**, 297–307, doi:10.1680/jgeot.17.P.091.

Franza, A., Marshall, A. M., Zhou, B., Shirlaw, N., Boone, S., Shirlaw, C. N. & Boone, S. (2020). Discussion: Greenfield tunnelling in sands : the effects of soil density and relative depth. *Géotechnique* doi:10.1680/jgeot.19.D.002.

Franzius, J. N., Potts, D. M. & Burland, J. B. (2006). The response of surface structures to tunnel construction. *Proceedings of the ICE - Geotechnical Engineering* **159**, No. 1, 3–17, doi:10.1680/geng.2006.159.1.3.

Fu, J., Yu, Z., Wang, S. & Yang, J. (2018). Numerical analysis of framed building response to tunnelling induced ground movements. *Engineering Structures* **158**, 43–66, doi:10.1016/j.engstruct.2017.11.039.

Goh, K. H. & Mair, R. J. (2014). Response of framed buildings to excavation-induced movements. *Soils and Foundations* **54**, No. 3, 250–268, doi:10.1016/j.sandf.2014.04.002.

Haji, T. K., Marshall, A. M. & Tizani, W. (2018). A cantilever approach to estimate bending stiffness of buildings affected by tunnelling. *Tunnelling and Underground Space Technology* **71**, 47–61, doi:10.1016/j.tust.2017.08.005.

Laefer, D. F., Ceribasi, S., Long, J. H. & Cording, E. J. (2009). Predicting RC frame response to excavation-induced settlement. *Journal of geotechnical and geoenvironmental engineering* **135**, No. 11, 1605–1619, doi:10.1061/(ASCE)GT.1943-5606.0000128.

Lanzano, G., Visone, C., Bilotta, E. & Santucci de Magistris, F. (2016). Experimental Assessment of the Stress Strain Behaviour of Leighton Buzzard Sand for the Calibration of a Constitutive Model. *Geotechnical and Geological Engineering* **34**, No. 4, 991–1012, doi:10.1007/s10706-016-0019-5.

Lau, C. K. & Bolton, M. D. (2011). The bearing capacity of footings on granular soils. II: Experimental evidence. *Geotechnique* **61**, No. 8, 639–650, doi:10.1680/geot.7.00207.

Mair, R. J., Taylor, R. N. & Burland, J. B. (1996). Prediction of ground movements and assessment of risk of building damage due to bored tunnelling. In *Proceedings of the International Symposium on Geotechnical Aspects of Underground Construction in Soft Ground* (Mair, R. J. & Taylor, R. N., eds.), London, United Kingdom: Balkema, Rotterdam, pp. 713–718.

Marshall, A. M., Farrell, R., Klar, A. & Mair, R. (2012). Tunnels in sands: the effect of size, depth and volume loss on greenfield displacements. *Géotechnique* **62**, No. 5, 385–399, doi:10.1680/geot.10.P.047.

Ritter, S. (2017). Experiments in tunnel-soil-structure interaction. *Ph.D. thesis, Cambridge University* .

Ritter, S., Giardina, G., DeJong, M. J. & Mair, R. J. (2017). Influence of building characteristics on tunnelling-induced ground movements. *Géotechnique* **67**, No. 10, 926–937, doi:10.1680/jgeot.SIP17.P.138.

Ritter, S., Giardina, G., Franza, A., Dejong, M. J. & Asce, A. M. (2020). Building Deformation Caused by Tunneling : Centrifuge Modeling. *Journal of Geotechnical and Geoenvironmental Engineering* **146**, No. 5, 1–17, doi:10.1061/(ASCE)GT.1943-5606.0002223.

Son, M. & Cording, E. J. (2005). Estimation of Building Damage Due to Excavation-Induced Ground Movements. *Journal of Geotechnical and Geoenvironmental Engineering* **131**, No. 2, 162–177, doi:10.1061/(ASCE)1090-0241(2005)131:2(162).

Son, M. & Cording, E. J. (2007). Evaluation of Building Stiffness for Building Response Analysis to Excavation-Induced Ground Movements. *Journal of Geotechnical and Geoenvironmental Engineering* **133**, No. 8, 995–1002, doi:10.1061/(ASCE)1090-0241(2007)133:8(995).

Vesic, A. S. (1963). Bearing Capacity of Deep Foundations in Sand. *Highway Research Record* **39**, 112–153.

Vorster, T. E. B., Klar, A., Soga, K. & Mair, R. J. (2005). Estimating the Effects of Tunneling on Existing Pipelines. *Journal of Geotechnical and Geoenviromental Engineering* **131**, No. 11, 1399–1410, doi:10.1061/(ASCE)1090-0241(2005)131:11(1399).

White, D., Take, W. & Bolton, M. (2003). Soil deformation measurement using particle image velocimetry (PIV) and photogrammetry. *Géotechnique* **53**, No. 7, 619–631, doi:10.1680/geot.2003.53.7.619.

Xu, J., Franza, A. & Marshall, M. A. (2020). The response of framed buildings on raft foundations to tunnelling. *Submitted to Journal of Geotechnical and Geoenvironmental Engineering* .

Xu, J., Marshall, M. A., Franza, A., Boldini, D., Amorosi, A. & DeJong, J. M. (2019). The response of framed buildings on raft foundations to tunnelling: a centrifuge and numerical modelling study. In *17th European Conference on Soil Mechanics and Geotechnical Engineering, Reykjavik, Iceland*, vol. 1, pp. 1–8.

Zhao, Y. (2008). In situ soil testing for foundation performance prediction. *Ph.D. Thesis, Cambridge University* .

Zhou, B., Marshall, A. M. & Yu, H.-S. (2014). Effect of relative density on settlements above tunnels in sands. In *2014 GeoShanghai International Congress: Tunneling and Underground Construction*, vol. 242 GSP, Shanghai, China: American Society of Civil Engineers, pp. 96–105, doi:10.1061/9780784413449.010.

SUPPLEMENTAL DATA

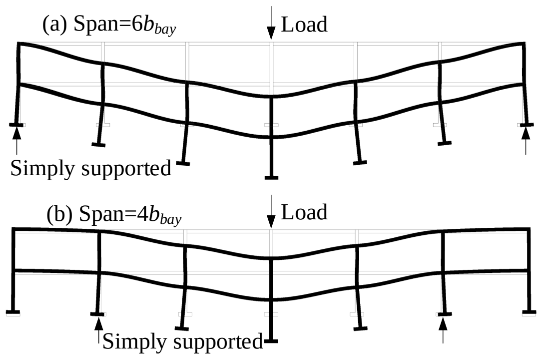


Fig. S1. Deformed shapes of the frames with rigid connections from finite element modelling

Response to reviewers and editors

Dear Editors and Reviewers,

Please accept our thanks for your valuable comments and suggestions on our submitted manuscript. We have carefully considered and addressed all of the comments in the revised manuscript. All the changes in the paper are shown in blue. Point-to-point responses are provided below.

Assessor's Comments to Authors:	**Authors' response**
The reviewers agree that the paper has the potential for publication, however the issues raised have to be addressed by the authors in the revised manuscript. This holds for technical content, e.g. interpretation of results as well as for presentation, e.g. overloaded graphs and text in places. It is also important to highlight clearly the differences with respect to the paper submitted to JGGE, any overlap has to be avoided.	We have attempted to address the issues raised by the reviewers, and a statement was also added in the paper to highlight the differences between this manuscript and the paper submitted to JGGE. See lines 23-27 in "Scope" section The scope section has been reworded to clearly address this point. The JGGE paper was limited to raft foundations. In this paper, novel centrifuge tests for separated footings were presented (and compared with the results from the JGGE paper). Although readers would benefit from reading both papers when (hopefully) accepted, we do not feel this is should be considered an incremental research; rather we had to partition the research outcomes into two self-contained manuscripts with clearly different objectives. In addition, dealing with the entire dataset of 34 tests consisting of both rafts and separated footings would not have been feasible within a single journal paper.
Reviewer #1 Comments to Authors:	**Authors' response**
The topic of the paper is quite interesting and the paper is well written with good presentation of the experimental results. However, the concluding remarks are poor consisting of rather self-evident statements (impact of the foundation type to surficial settlements, or 'tunnelling-induced differential horizontal movements are significant for separate footings, whereas they are negligible for raft foundation', 'It was confirmed that the structural stiffness can play an important role in the soil-structure interaction of framed building configurations'). Therefore the paper suffers in novelty. I believe that a further evaluation of the results is needed to draw more deterministic and useful conclusions.	Thank you for these positive comments and suggestions on the conclusion section. We have attempted to improve the concluding remarks. However, We do not fully agree with the statement that the "paper suffers in novelty". In fact, we presented a unique (and extensive) centrifuge dataset of framed buildings on separate footings and their response to tunnelling, while comparing it against that of raft foundation cases. To our knowledge, this is the first centrifuge data set of this kind for model framed buildings. Measured ground and building deformations were described and, more importantly, building distortion level with respect to the greenfield was related to relative stiffness within novel design charts (distinguishing between foundation and eccentricity effects). We feel that the outcomes presented are supported by both qualitative and quantitative assessments. However, we agree with the suggestions below to further analyse several aspects of

	the dataset which were omitted in the original version of the work.
The Authors can start by including the greenfield trough from a Gaussian distribution in the surficial settlement profile (greenfield and with frames) and compare the trough width (inflexion point) of these cases. Then they could examine the topic of ground loss more profoundly. Instead of comparing the soil loss (as arisen from the surficial settlement profile) to the tunnel volume (Fig. 7) they could reveal the variation of the ground loss with depth (obviously in the case of undrained analysis in clayey soils there should be no variation while in the current case there will be as a result of contraction or dilation). However the shear strain at the depth of 25%C or 50%C is rather low (with the exception of Id=30%, SW). Therefore the variation of the settlement profile at the depth of 25%, 50% and 75 of C may reveal the effect of foundation type to the settlement profile and the ground loss (I can hardly see remarkable differences, but any how this could be clarified and reveal that the effect may mainly limited at the foundation zone).	Following the reviewer's suggestions, we have now: 1) compared the greenfield settlement trough parameters obtained from a modified Gaussian curves, as suggested by Vorster et al., (2005) and Marshall et al. (2012), see Table 4. 2) added the variation of the ground loss with depth in selected tests, as shown in Figure 8. Regarding the settlement profiles with depth, the authors feel that Figure 6 sufficiently demonstrates the most important aspects of vertical and horizontal displacement fields in some important tests; due to the limitation of the space, additional settlement profiles have not been reported. As highlighted by the reviewer, the building primarily affects the soil in the foundation zone (Figure 6). We also highlighted this in the section "Ground deformations".
When raising the effect of frame stiffness I believe that the Authors should further discuss this topic (even if the results they have corresponds to the same frame sections). For instance one is anticipating that as frame stiffness increases the results of both configurations (footing and raft) tend to the same outcome.	Unfortunately, this comment is not fully clear to us. We discussed the effects of the structural stiffness in the interaction by plotting the modification factor (Mbeta) vs relative stiffness (k), which clearly quantifies the role of the building stiffness GAs to that of the soil . However, to attempt to address this comment, we have revised Fig 15 by adding distinguished envelopes for rafts and separated footings so that, for a given relative stiffness k, the role of the foundation scheme is clear. We have added this in the "Superstructure deformation parameters" section, lines 344-349
A similar paper, investigating the effect an adjacent building to a tunnel and vice-versa (Comodromos EM, Papadopoulou MC and Konstantinidis GK (2014) "Numerical assessment of subsidence and adjacent buildings movements induced by TBM-EPB tunneling", J Geotech Geoenv Engrg, ASCE Vol. 140, No. 11) could be helpful to the Authors in rendering the paper and the concluding remarks to be more sound and coherent.	Thanks for this. We have studied this paper and added it to the references.
Reviewer #3 Comments to Authors:	**Authors' response**
The paper examines the influence of the foundation type of framed buildings on the tunnel-soil-structure interaction effects caused by tunnelling excavation	Thanks for your positive comments. We have attempted to address the issues you raised.

underneath the buildings. An experimental campaign is carried out in the centrifuge, with framed building models, resting on dry sand through raft or separated footings, being tested under induced soil deformations caused by tunnel volume loss. In addition to the type of foundation, the effects of building width and self weight, as well as soil densification level are parametrically examined. The recorded response is interpreted and discussed in terms of soil displacements and strains, foundation displacements and superstructure deformations, while the induced damage level on the tested buildings is also examined. The subject of the article is certainly of interest since the performance of buildings during excavation of tunnels, passing underneath them, becomes a more frequent and important issue in densely constructed urban areas. Experimental works, like the one presented herein may be used for validation purposes of relevant analytical or numerical methodologies. In this regard, the presented experimental work might be of interest for the technical community. Moreover, the manuscript is well written. However, there are some issues that should be addressed by the Authors before publication is offered. This issues are summarized in the following:	
1. The Authors refer to the following manuscript: 'Xu, J., Franza, A. & Marshall, M. A. (2019a). The response of framed buildings on raft foundations to tunnelling. Submitted to Journal of Geotechnical and Geoenvironmental Engineering', which to the Reviewer's understanding is under evaluation at the moment. The Authors are requested to present clearly the main novelties of the present manuscript compared to the one submitted to Journal of Geotechnical and Geoenvironmental Engineering,	For the first time, framed building models founded on separated footings (oriented along the tunnel longitudinal direction) were tested in a geotechnical centrifuge, as opposed to a raft foundation (or strip footing transverse to the tunnel). This is to the main novelty aspect in comparison to the results presented in the submitted JGGE paper, which relates solely to the raft foundation case. Also note that the ground deformations in Fig 6 are, for the first time, presented in this manuscript; in fact, the submitted JGGE paper focused on the building distortions and surface ground movements only. As previously mentioned in the responses to Reviewer 1, the entire dataset of 34 tests, consisting of both rafts and separate footings, would have not been feasible illustrated within a single journal paper.

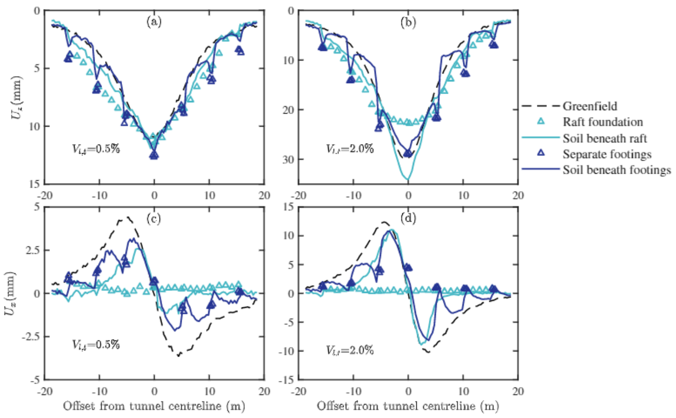
as well as compared to other existing studies (e.g. Farrell (2010); Ritter (2017)).	We have clarified the novelty of the manuscript with respect to the submitted JGGE paper in the “scope” section. • the work presented by Farrell (2010) simplify the building as an equivalent plate. In the submitted JGGE paper, framed buildings with similar stiffness, while matching the tunnelling prototype scenario of Farrell (2010), were investigated to highlight the limitations of equivalent plate models. It was found that these schematisations are not suitable for framed buildings (e.g. for similar total stiffness, different tunnelling induced settlement profiles, not accounting for the column/wall location, were observed). • Ritter et al. (2017) considered 3-D printed façades with openings resting on a strip foundation transverse to the tunnel longitudinal axis. In this paper we considered a framed building (behaving as a bare frame) resting on a raft (similar to the transverse footing of Ritter) or separated footings/strips longitudinally oriented with respect to the structure. Masonry buildings undergo both bending, axial and shear distortions while redistributing continuously the load/pressure beneath the foundation due to tunnelling. Bare frame buildings undergo primarily shear deformations and redistribute the load in a concentrated way, in correspondence of the ground level columns/wall. Although references to Ritter’s work is made when analysing the ground response, fundamental differences exist when describing the structural deformation modes. This paper presents the comparison of the response of the framed buildings on rafts and separate footings. Please refer to the third paragraph of the Introduction and the Scope section for details.
2. Although well written, the manuscript in several parts reads like a technical report. The Authors are advised to avoid listing observations and remarks (e.g. (i)…, (ii)…) and instead present their findings in a more 'continuous' format that is normally used in scientific articles.	We attempted to review the entire paper accordingly, also modifying in a more 'continuous' and critical format the abstract and scope sections.
3. The figures are all well depicted; however, they contain a lot of information, which makes the reading and understanding difficult. For instance, the reading of Fig. 5 is quite difficult with all these lines and relative information presented together. Additionally, in accordance with the guidelines of the Journal, the figures should be readable in black and white version. This is expected to make the reading of some figures even more difficult.	Thanks for these constructive suggestions. • We have simplified figure 5 in the revised manuscript. • In addition, we added a description of subplots in the captions for Figs 3, 4, 7, 8, and 15. • We checked the readability of the figures in black and white. For instance, in preparing the original manuscript, care was paid to creating contours in Fig 6 that could be interpreted in grayscale.

Finally, the description of subplots (i.e. (a), (b)…) should be introduced in the legends of the figures. Please consider revising the presentation of figures (e.g. adding subplots etc) to improve readability.	
4. In page 3, lines: 75-77 the Authors state: 'Tunnel volume loss Vl,t was then simulated by extracting water from the model tunnel in increments up to a maximum Vl,t of 10%.' It is presumed that the water extraction happens throughout the length of the model, to preserve plain strain conditions. Please elaborate.	Yes. The water extraction occurred throughout the length of the model tunnel to achieve the plain strain condition. This modelling technique has been widely used in the experimental studies on tunnelling and tunnel-structure interaction problems. Among others in the UK, Jacobsz, 2002; Marshall, 2009; Farrell, 2010; Zhou 2014; Franza 2016; Ritter 2017. We have now explained this in more detail in the updated "EXPERIMENTAL DETAILS" section of the paper.
5. The Authors are strongly advised to present clearly the limitations of their work in the manuscript. This is of great importance, given that the geometric properties of the tunnel (cover C, diameter D) remain constant throughout the campaign.	The fact that a unique tunnelling scenario in dry sand was addressed while changing the structure case was detailed in the paper. However, to stress this point, the conclusions were revised by adding the following. "In this paper, the considered scenarios are limited to a tunnel with constant cover-to-diameter ratio constructed in dry sand beneath an elastic framed building. Future works considering the effects of tunnel relative depth, footing buried depth, and nonlinear building behaviour are ongoing."
Reviewer #4 Comments to Authors:	**Authors' response**
I have to start by stating that there are multiple references to another manuscript by the same authors (Xu et al. 2019a), currently under review. I do not have access to that manuscript, but I believe that there the authors present results of tests with a structure on raft foundation. Given that, I am not sure whether results of the same tests are repeated here, and if so why. I would expect to see a clear statement in the introduction discussing overlapping with previous publications, if that is the case.	Yes, the submitted JGGE paper presents the greenfield and the raft foundation tests (see also the * in Table 1). Raft foundation test results were repeated here only to highlight the influence of the foundation scheme (by a direct comparison of raft vs footings). We have clarified the novelty of the manuscript with respect to the submitted JGGE paper in the "scope" section. All tests for separated footings are novel (presented for the first time, except for a conference paper in which only preliminary test results from one test were given). Also note that the ground deformations in Fig 6 are are, for the first time, presented in this manuscript; in fact, the submitted JGGE paper only focused on the building distortions and surface ground movements. As previously mentioned, dealing with the entire dataset of 34 tests consisting of both rafts and separated footing would not have been feasible within a single journal paper.
The authors present results of centrifuge tests physically modelling a very complex problem: Soil-foundation-structure	We acknowledge that multiple parameters were varied, however we attempted to consistently isolate the effect of weight, eccentricity, and soil density on results.

interaction due to excavation of a near-surface tunnel in the vicinity of a building. This study goes one step further than the earlier works of e.g. Farrell et al. by modelling different foundation configurations, as well as buildings with two storeys. While unquestionably this is more realistic, compared to modelling the building as a slab, it adds to the complexity of the problem and makes the evaluation of the results of the tests particularly cumbersome, considering also that multiple other parameters are varied in the tests, such as sand density, building load, building width and tunnel eccentricity. Therefore claiming that this work results to a method to "efficiently predict building distortions considering soil-structure interaction effects" is probably an overstatement, as Fig. 13 provides a range of expected values, rather than a means to predict βmax. This does not imply that the presented experimental results are of low value, but I would probably see this effort as an intermediate step, useful for calibrating/validating an analysis methodology that can systematically take into account the effect of the multiple parameters that govern this problem.	Regarding Figure 13 (now Figure 15 in the revised manuscript), • we have introduced distinguished envelopes for the raft foundations (Xu et al., 2019a) and separated footings. This makes the design charts more efficient, and clearly illustrates the impact of the foundation type. • we could not identify where we stated that "this work results to a method to efficiently predict building distortions considering soil-structure interaction effects". In contrast, in the introduction we stated that "To minimise the potential risk of tunnelling-induced ground movements on existing structures, it is important to be able to efficiently predict building distortions considering soil-structure interaction." That is a general and, we feel, reasonable statement. • considering the uncertainties in tunnelling and existing building characterisation, we feel that the estimation of tunnelling-induced building distortion level (e.g. if Mbeta= 0 , 0.25, 0.5 , 0.75 , 1) through the provided design charts is a robust practical approach for engineers, more suitable in the case of framed buildings than the use of deflection ratios. We expect (hope) that these envelopes will have an impact on practical-oriented preliminary risk assessments. We do not think they can replace in any way rigorous numerical modelling which are needed for more detailed (and expensive) analyses where the risks warrant the additional costs. • we do not think the text contains any overstatements. The limitations of the work have been highlighted in the conclusions along with the fact that several conclusions were drawn by previous researchers. Indeed, we are currently working on numerical models of varying complexity (equivalent Timoshenko beams founded on the continuum; advanced numerical models considering the complex ground behaviour) to confirm centrifuge observations and enhance design methods, to achieve a balance between fidelity and simplicity.
I also have to comment that figures are quite small and loaded with information (see for example Fig. 5) and that the text is rather difficult to follow, as the authors attempt to describe with words every single detail of the measurements, instead of simply referring the reader to the figures, and focusing on the main observations.	1. Following the reviewer's suggestions, Fig.5 has been simplified. Moreover, we have also tried to improve the clarity of writing of the text.
Technical comments, for the authors' consideration	Goh and Mair (2014) used the terms "continuous footings" and "individual footings" to refer respectively to strip footings

1. You should clarify that you are modelling a structure on strip footings, the term "separate footings" that you use is a bit misleading. In addition, you should probably revise line 14. You are modelling continuous strip foundations, as Ritter et al. did.	oriented transversely and longitudinally to the tunnel. We preferred the term “separated footings” rather than “individual footings” to highly the fact that their behaviour is “nearly” independent when subjected to transverse tunnelling, (i.e. the footings would be independent if it wasn’t for the action of the connected superstructure). We think that the statement “You are modelling continuous strip foundations, as Ritter et al. did.” may be misleading. Ritter et al. considered a different direction for their strip footing. Our centrifuge model may be interpreted as a longitudinally oriented strip or pad foundations, considering 2D models are often adopted in tunnelling as an approximation. For both cases, it is very important to stress that the footing orientation with respect to the tunnel axis makes them behave “separately” (if not for the structure action). Clearly there are various terminology that can be applied. We believe our applied terminology is appropriate and, importantly, the geometric condition to which it applies is clearly defined within the paper. The text was additionally clarified to reduce the possibility of misinterpretation of the terminology - See lines 20-23 in Section “SCOPE”
2. The main conclusion I drew from your results is that distortions of the structure are not particularly sensitive to the type of foundation (e.g. Fig 10-12). This is a bit counterintuitive, given also that relative axial movements were observed in the case of the structure founded on strip footings. Of course, the distortions you are measuring are very small and the structure remains in the elastic range, therefore I am wondering whether the technique you are using to measure structural displacements and strains (PIV) is sensitive enough to capture such small variations in displacements, given the scale of the problem.	As detailed in the text (see lines 125-135), because of the issues related to welding of the model frames, only the distortions of the panels comprised between two columns and beams are analysed in the paper. The impact of relative axial movements (differential horizontal displacements of footings) is neglected. With respect to the panels, revised Fig 16 displays that separated footings, despite leading to greater levels of structure settlements (this latter point is also indicated by several previous numerical studies), may be subjected to smaller distortion levels for equal relative stiffness. Therefore, the foundation scheme has an impact on the tunnel-structure interaction and its quantification, we believe, is important to reduce uncertainties and provide more rational design schemes. The authors are confident on the displacements (thus distortions) measured during tests. By improving the image analysis system, we have reached increased levels of accuracy (compared to Franza et al., 2019) for evaluating ground volumetric strain distributions from displacement data. As an example, the following figure (not included in the paper for the sake of brevity) shows the horizontal displacements (at prototype scale) of the foundations and surface soil movement for the long structure (SW). We believe that the PIV results are reliable when measuring a movement of 0.5~1 mm at prototype, and less than 0.01 mm at model scale.

<table>
<tr>
<td>Having said that, you mention that tunnel volume loss up to 10% was modelled (line 76), but the results go up to 2% in Fig. 13 and 3% in Fig 10.

It is worth commenting on that, as one of the limitations of this study is that strains/displacements are quite low and that the structure behaves elastically.</td>
<td>

In practice, tunnel volume losses of 0.5-1% are frequently achieved during TBM excavation, while values up to 2-3% may be the local result of TBM operational issues. This is the reason we focussed on this practical range of volume loss in the paper. We do not feel that data associated with Vlt>5% is generally applicable or of general interest. To support this, most previous works on tunnel-structure interaction limited their data analyses to Vlt,max=5%.
Consequently, we prefer to only report results up to Vlt=3%.

In Figs 13-14, despite the structure stiffness action, buildings at Vlt =2% reached a level of distortion associated with “Moderate to severe”; as such, the deformation of any infills (assumed fully flexible) would be remarkable in this tunnelling context.

However, we agree with the Reviewer that framed model buildings are expected to exhibit a fully elastic behaviour, as now highlighted by the text added in the conclusions. Future work will need to model the presence of damageable infills.</td>
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<td>Also, consider revising lines 277 to lines 285: I found that explanation confusing and could not really understand what you mean.</td>
<td>Thanks for this. We have simplified this paragraph. Please see lines 297-301.</td>
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<td>3. line 100 & Table 2: Was the ratio between shear and bending deflections measured experimentally? How? Is that the ratio of experimentally measured deflection over deflection calculated while modelling the structure with Euler-Bernoulli beams? It is worth providing some more details on this part.</td>
<td>The text was revised stating that the deflection ratio is obtained from the Timoshenko beam theory with GAs and EI properties.

The approach of Son and Cording (2005) was followed to characterise the global stiffness from loading tests.
In particular, frames were subjected in the lab to two load-deflection tests with varying BCs, to obtain a system of two equations (of the measured total deflection from the two experiments) in the two unknows (GAs, EI).
Full details and equations are provided in the figure below from the submitted ASCE JGGE paper (Xu et al. 2019a, 2020 in the revised manuscript).
The adopted formulas are deflection equations from the well-known Timoshenko beam theory; for simplicity this figure was</td>
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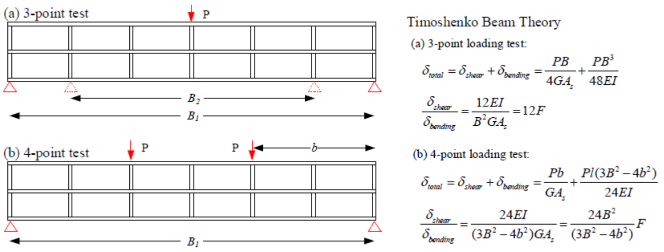
<table>
<tr><td></td><td>omitted from the manuscript (whose length is already above the Geotechnique word limit).


Figure from Xu et al. 2019a</td></tr>
<tr><td>4. Fig. 3: Why did you estimate the stiffness with 3-point deflection tests, and not by applying a load on the structure founded on sand? The latter would provide you a more realistic estimate of the stiffness of the soil-structure system.</td><td>We disagree with this suggestion.

The stiffness of a building is considered an inherent property of the structure, not depending on the boundary conditions provided by the soil, but rather on the BCs applied to the building. In the loading tests, we know exactly the BCs (both load values and constraints).

If the building stiffness was estimated from loading the frame resting on the soil, the building-foundation deflection would certainly depend on the ground behaviour. In this case, it would not be clear what analytical/numerical model should be used for the ground. Also, should the structure resting on the soil (as suggested) be loaded at 1g or Ng. We think the approach suggested by the Reviewer would lead to increased uncertainties because of the complex boundary conditions provided by the ground response.</td></tr>
<tr><td>5. Fig. 8e: Why axial displacement developed in the raft during the test in loose sand? Did slippage take place?</td><td>For loose soil, the sample preparation is not as reliable and uniform as for the dense sample. Heterogeneities in the ground may lead to an asymmetric horizontal displacement field that resulted in some displacements of the central building. We did not feel that this point was significant and it was not commented in the paper.</td></tr>
<tr><td>6. I really do not see the merit in presenting the bearing capacity tests.</td><td>We believe that the bearing capacity tests provide a useful reference for the appreciation of the footing safety factor and illustrates the minor influence that placing the building on the ground surface at 1g had. They can also provide guidance (through simple configurations) to researchers interested in the numerical modelling of the problem. Ultimately, the behaviour of the footing foundation to tunnelling depends on the pressure variation – settlement relationship (along with shear force and bending moments neglected for simplicity). As a result, and considering that this issue was not raised by the other two Reviewers, we have kept the footing load tests in the manuscript.</td></tr>
<tr><td>7. It is worth providing a reference to a laboratory characterisation study of the sand used in your experiments, that the interested reader could refer to.</td><td>References to the works of Lanzano et al- (2016) and Zhao (2008) were added.</td></tr>
</table>

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Prof. David Potts
Editor in Chief
Géotechnique

Re: Submission of General Paper:
'Tunnel-framed building interaction: comparison between raft and separate footing foundations'

Dear Prof. Potts,

Kindly consider the revised manuscript entitled *'Tunnel-framed building interaction: comparison between raft and separate footing foundations'* by Jingmin Xu, A. Franza, A. M. Marshall, N. Losacco and D. Boldini for publication within the Journal of *Géotechnique*.

Please feel free to contact me at the above given details if there is any further information required.

Regards,

Jingmin Xu

24/03/2020

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Manuscript reference number: 19-P-393R1

Authors: Jingmin Xu; Andrea Franza; Alec Marshall; Nunzio Losacco; Daniela Boldini

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