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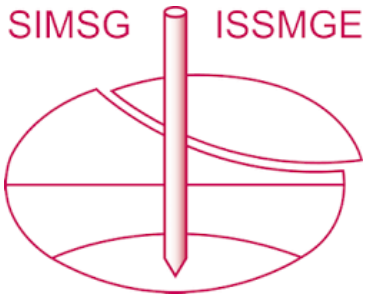

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Calibration of a simplified soil-structure interaction model for rapid assessment of tunnelling-induced damage in masonry buildings founded on shallow footings

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ABSTRACT: Tunnel construction in urban areas typically requires the assessment of a large number of buildings for potential damage. A commonly encountered building typology is low-rise masonry structures built on shallow strip foundations. A numerical modelling approach called S2M (Simplified 2D Assessment Model) was recently developed to conduct rapid damage assessments for this building type. S2M takes assumed greenfield displacements as an input; the behaviour of the building is then determined accounting for the building's stiffness as well as potential pull-out, gapping and sliding behaviour of an embedded strip foundation. The paper discusses the calibration of the S2M and evaluates its ability to capture building displacements and strains with respect to a fully-coupled 3D finite element model. A new, simplified, calibration procedure for the S2M is described.

Keywords: Building damage; Tunnelling; Foundations; Nonlinear Winkler model; FEM modelling.

1 INTRODUCTION

Routine assessment of the impact of urban tunnelling activities involves rapid screening to identify surface structures that are likely to be affected by ground movements. Within this context, masonry structures are often idealized with equivalent beam models which are subjected to tunnelling-induced greenfield settlements (e.g. Boscardin and Cording, 1989; Burland and Wroth, 1975 Mair and Taylor, 1997). For structures 'at risk' (i.e. characterised by moderate and above damage states according to limiting tensile strain criteria), a detailed assessment using numerical models may be conducted.

To minimize the computational resources required for detailed assessments, semi-coupled modelling techniques have been proposed. These techniques simplify the representation of the building and/or the soil while still incorporating soil-structure interaction mechanisms. In previous studies (e.g. Losacco et al., 2014; Pickhaver et al., 2010), the soil and the excavation process were modelled using 3D finite elements (FE), while adopting equivalent beam or solid representations for the structure. The resulting models can capture building displacements, but equivalent solid properties need to be calibrated to capture building damage and the building's influence on soil-structure interaction (Pascariello et al., 2023). An alternative semi-coupled modelling strategy adopts high-fidelity representations of the structure (e.g. using 2D or 3D finite elements) while idealizing the soil-foundation interaction using interface elements. This treatment facilitates the evaluation of structural damage, but it is strongly influenced by the constitutive models employed for the interface. In previous studies (e.g. Dalgic et al., 2021; Giardina et al., 2013) interface elements employing elastic behaviour with no-tension in the vertical direction and frictional behaviour in the horizontal direction were employed. These approaches capture some soil-structure interaction aspects but they neglect the important influence of foundation embedment.

To achieve improved soil-foundation interaction models for strip footings in semi-coupled models, Burd et al. (2022) developed the S2M (Simplified 2D Assessment Model). The S2M combines 2D elastic continuum finite elements (to represent a building façade), elastic bar elements (simulating a strip footing) and specially-formulated interface elements (to simulate the soil-foundation interaction). The soil-foundation interaction model considers the uplift capacity of embedded strip footings and the mobilization of friction on the strip footing surfaces. Greenfield tunnel-induced displacements are treated as inputs to the soil-foundation model; the resulting building displacements are computed by coupling the various S2M components. Computed strains in the façade are employed to predict the likely level of tunnel-induced structural damage. The S2M – which is implemented via bespoke MATLAB code – is described in Burd et al. (2022); readers are referred to this previous publication for full details of the formulation and implementation of the model.

Burd et al. 2022 describe a procedure in which 3D FE analysis is used to determine the calibration parameters for the soil-foundation interaction modelling component

of the S2M. The current paper develops this approach to explore simplified S2M calibration procedures; instead of 3D models, the use of simpler 2D models is investigated. The response of an elastic masonry façade, with two different footing depths, to tunnelling-induced ground movements is examined. The accuracy of the proposed S2M calibration procedure is evaluated by comparing results obtained using the S2M with a fully-coupled 3D FE model (in the current context, the term 'fully-coupled' refers to models where the tunnel excavation, soil-structure interaction and building response are all explicitly and simultaneously modelled).

2 PROBLEM STATEMENT AND THE 3D FULLY-COUPLED MODEL

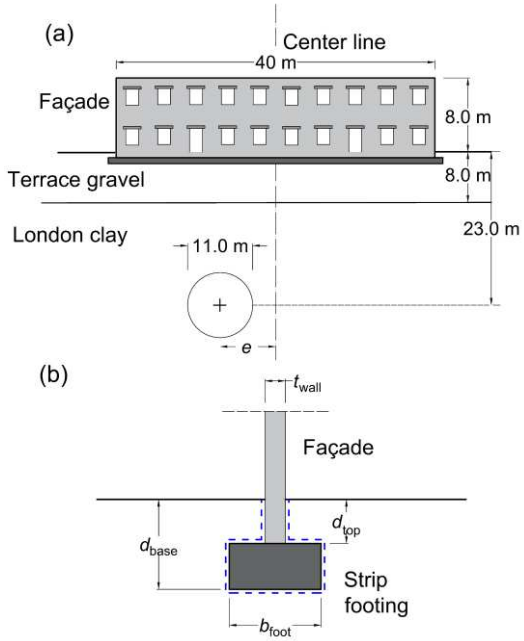

Figure 1. Geometry of (a) the tunnel-soil-structure interaction scenario and (b) the strip footing examined in this paper. Blue dashed lines around the foundation and the embedded facade indicate interface locations in the 3D finite element model.

The investigated structure – based on previous work – is a masonry façade with above-ground height H = 8.0 m, length L = 40.0 m and thickness t = 0.215 m (Figure 1(a)). It is supported by a 0.5 m thick strip footing which is founded at a depth d_{base} = 1.0 m (Figure 1(b)). Detailed information on building dimensions are reported elsewhere (Amorosi and Sangirardi, 2021; Burd et al., 2022; Yiu et al., 2017). A single tunnel of eccentricity e = 0, with depth and diameter shown in Figure 1(a), is built under the façade. The soil stratigraphy comprises a Terrace gravel layer, overlying London clay. The groundwater level lies at the base of the gravel layer.

A fully-coupled 3D finite element model is built in Plaxis 3D to simulate the scenario described above. The gravel and the clay layers are modelled via the Hardening Soil Model with Small Strain (HSsmall) (Schanz et al. 1999). A linear elastic constitutive model (Young's modulus E = 800 MPa and Poisson's ratio ν = 0.2) is assigned to the façade. The unit weight of the footing and the Terrace gravel is 19.5 kN/m^3; the façade is assigned a unit weight of 23.75 kN/m^3. Further details on material properties are given in Amorosi and Sangirardi (2021) and Burd et al. (2022).

Interfaces are introduced to model the contact between the structure (embedded facade and footing) and the soil (Figure 1(b)). The interfaces inherit their constitutive properties from the surrounding Terrace gravel. To capture the likely reduced stiffness and strength of the interface, a 'strength reduction factor' R_{inter} = 0.5 (corresponding to behaviour that is intermediate between rough and smooth) is assigned to the interface (Brinkgreve et al., 2022); this provides an interface friction coefficient μ = 0.35 on the basis of a Terrace gravel friction angle of $\phi' = 35^{\circ}$.

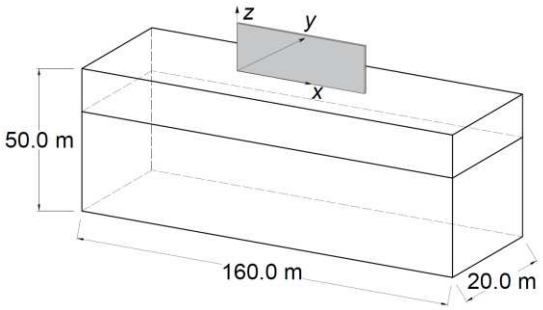

Figure 2. Geometry of the fully-coupled 3D FE model developed in PLAXIS 3D.

The resulting 3D model (Figure 2) comprises 66268 tetrahedral elements and 106444 nodes. Normal displacement constraints are assigned at the vertical soil boundaries while the bottom of the model is fixed. The façade is placed at a central location where boundary effects are expected to be minimal. A staged analysis model is adopted. The stresses in the soil are initialized with the 'K0 procedure' (where K0 is equal to 0.562 and 0.425 for London clay and Terrace gravel respectively). The footing, façade, interface elements and gravity loads are then activated. Strains are set to zero after this stage and the tunnel excavation is simulated in a single analysis step. The excavation is modelled by uniformly contracting the tunnel section. This procedure successfully reproduces the analytical greenfield settlements reported in Yiu et al. (2017); further details are given in Amorosi and Sangirardi (2021).

3 CALIBRATION PROCEDURES FOR THE S2M

The tunnel-soil-structure interaction scenario described in Section 2 is also analysed with the S2M. A plane-stress mesh of six-noded triangles (representing the façade) is attached to a 1D footing and soil-foundation in-

teraction model (Figure 3) comprising: (i) elastic bar elements simulating a strip footing having a defined axial stiffness and zero bending stiffness, and (ii) an interface, simulating the soil and soil-foundation interaction. The tunnel-induced greenfield movements are treated as inputs to the model as described in Burd et al. (2022). For the S2M analyses described in the current paper, the greenfield displacements are obtained from a version of the 3D fully-coupled model in which the building and foundation is absent. Greenfield displacement data are extracted at depth d_{base} along the spatial location of the footing centreline; this facilitates direct comparisons between the 3D FE and S2M modelling approaches.

The S2M soil-foundation model requires five parameters (p_t, μ, k_h, k_v, a_v); procedures to select these parameters are described below.

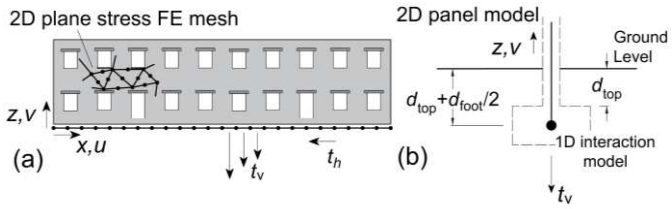

Figure 3. (a) Elevation view of the S2M. Net horizontal and vertical line traction reactions t_h and t_v (units force per unit length) are applied by the soil onto the foundation; positive directions are indicated in the figure. (b) Cross section view of the S2M. Adapted from Burd et al. 2022.

Parameter p_t defines the limiting uplift resistance of the foundation. It is estimated using the equation (Murray and Geddes, 1987):

$$p_t = \gamma_s\left(b_{foot}d_{top}\right)\left[1+\frac{d_{top}}{b_{foot}}\tan\phi'\right] \qquad (1)$$

where $\gamma_s$is the unit weight of the soil, b_{foot} and d_{top} are the width of the strip footing and the depth of the top of the footing beneath the ground surface and $\phi' = 35^{\circ}$ is the Terrace gravel friction angle.

Separate calibration analyses are needed to determine the other model parameters. When the interface is compressed (i.e. traction-induced vertical displacements v_{def} are negative), the vertical traction t_v is determined by the equation:

$$t_v = \frac{k_v v_{def}}{1+a_v|v_{def}|} \qquad (2)$$

where k_v is the small-displacement stiffness and a_v is a parameter that governs the nonlinearity of the response. These parameters are determined by fitting Equation (2) to the applied traction - average displacement curves obtained from a calibration analysis in which the embedded footing is 'pushed' into the soil. Following Burd et al. (2022), the curves are generated using 3D finite element models, where an external traction t_v is applied to the footing, which displaces (on average) by v_{def} (Figure 4(a)). Alternatively – as explored in the current paper – the traction-displacement response of a plane strain cross-section of the footing can be considered (Figure 4(b)).

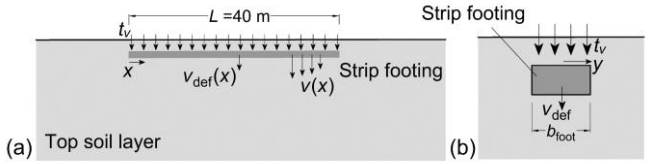

Figure 4. (a) 3D and (b) 2D vertical stiffness calibration configurations.

Computed values of (v_{def}, t_v) for the cases in Figure 4(a) and (b) are plotted in Figure 5 for the foundation and soil conditions described in Section 2. The data shown with circular and triangular markers are associated with 3D and 2D calibration configurations, respectively. The applied traction-average displacement curves obtained from the 2D and 3D configurations are similar and are approximated well by the analytical expression in Equation (2) (shown with dashed solid line) with selected values of k_v and a_v.

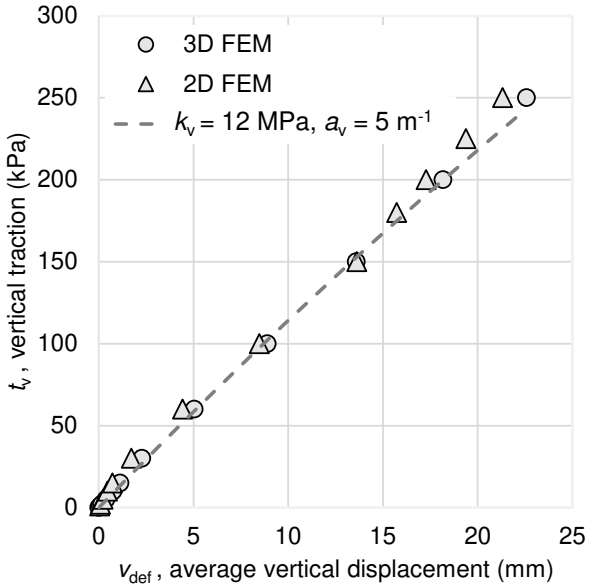

Figure 5. Calibration of k_v and a_v in the S2M model using a 3D and 2D calibration configuration. This case adopts $d_{top} = 0.5m$ and $d_{base} = 1m$. The dashed line shows a fit of Equation (2) to the data

In Burd et al. (2022), the horizontal stiffness k_h is calibrated via a separate 3D analysis in which the footing is subjected to a horizontal external traction $p_{e,h}$ as shown in Figure 6. The magnitude of the external traction $p_{e,h}$ is chosen such that frictional sliding does not occur at the soil-footing interface. The corresponding horizontal displacements $u_f(x)$ of the footing centre nodes are extracted along the length of the footing; these computed displacement data are used to determine k_h. To do this,

an analytical expression that describes the horizontal displacements of a rod being pushed with an applied external traction in an elastic Winkler medium with a horizontal stiffness k_h is used:

$$u_f(x) = \left[u_f(L)\,\mathrm{sech}\,\alpha L + \frac{p_{e,h}}{\alpha E_f}\tanh \alpha L\right]\cosh \alpha x - \frac{p_{e,h}}{\alpha E_f}\sinh \alpha x \quad (3)$$

$$\alpha^2 = \frac{k_h}{E_f A_f} \quad (4)$$

where E_f is the Young's modulus of the footing, A_f its cross-section area and $u_f(L)$ is the far-end footing horizontal displacement. The calibration value of k_h is determined by fitting Equation (3) to the displacement data from 3D calibration analyses.

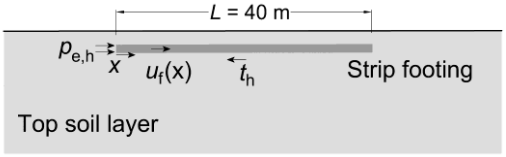

Figure 6. 3D horizontal stiffness calibration configuration.

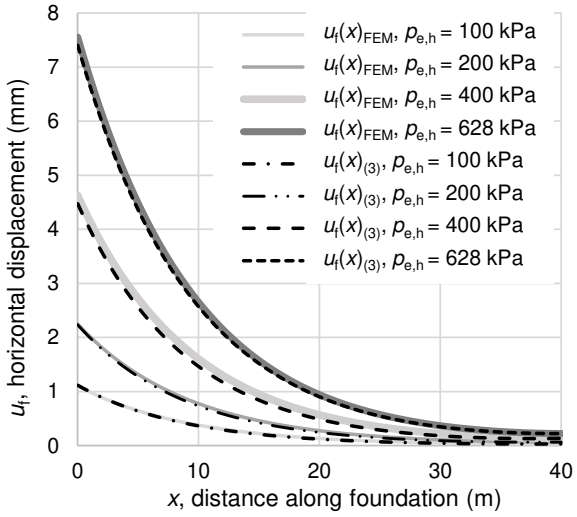

Figure 7. Calibration of k_h in the S2M using a 3D configuration. Solid lines represent 3D FEM extracted displacements $u_f(x)_{FEM}$, dashed and dot-dashed lines represent analytical expression of $u_f(x)_3$ determined using Equation (3).

In Figure 7, the calibrated value of k_h for the foundation presented in Section 2 is used to show the variation of horizontal displacements along the footing for four values of the applied traction, $p_{e,h}$. The dashed and dot-dashed lines demonstrate an excellent agreement with the solid lines which describe nodal displacements extracted from the 3D finite element results. This agreement indicates that the 3D calibration configuration proposed in Burd et al. (2022) captures the behaviour well.

The S2M parameters, determined as described above, are listed in Table 3. These parameters are used for the analyses in Section 4.

Table 3. Calibrated constitutive parameters of the S2M for the foundation and soil configuration in Figure 1(b).

Parameter	
Horizontal stiffness, $\boldsymbol{k_h}$	5 MPa
Vertical stiffness, $\boldsymbol{k_v}$	12 MPa
Softening parameter, $\boldsymbol{a_v}$	5 m^{-1}
Soil-footing interface friction coefficient, $\boldsymbol{\mu}$	0.35
Limiting uplift resistance, $\boldsymbol{p_t}$	13.2 kNm^{-1}

4 COMPARISONS BETWEEN 3D AND S2M SIMULATIONS

Numerically calculated horizontal and vertical footing displacements are compared in Figure 8, together with the corresponding greenfield displacements. A good agreement exists between S2M and the fully coupled 3D finite element (denoted by '3D FEM') horizontal displacement results; as expected the footing displacements are significantly smaller in magnitude than the greenfield displacements. Minor differences in the vertical displacements at the footing edges can be observed for '3D FEM' and 'S2M' simulations in Figure 8(b).

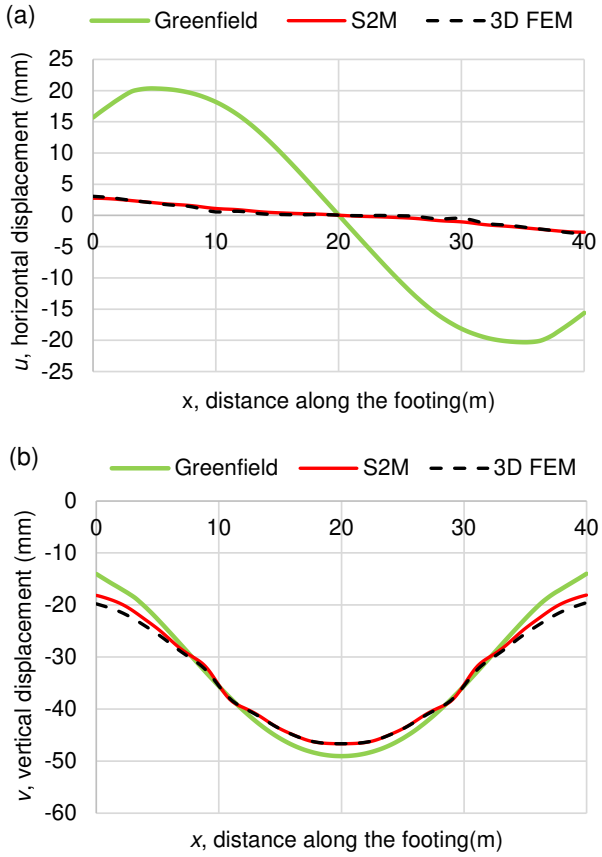

Figure 8. (a) horizontal and (b) vertical computed greenfield and foundation settlements (d_{top}= 0.5 m, d_{base}= 1 m).

5 INFLUENCE OF INCREASED FOUNDATION DEPTH

A further comparison is conducted for a deeper footing depth (d_{top}= 1.5 m and d_{base}= 2 m). The geometry of

the façade is modified accordingly, by employing an increased embedment for the façade to maintain the above-ground height of the façade at $H = 8$ m. Other aspects of the modelling approach are unchanged.

A new set of calibration analyses was performed, resorting to a 2D calculation for the vertical coefficients and the bespoke 3D horizontal calibration procedure. The S2M parameters determined in this way are: k_v = 36 MPa, a_v = 60 m^{-1}, k_h = 7 MPa, p_t = 60 kNm^{-1}. Footing displacement plots for this case, indicated in Figure 9, demonstrate that the 3D FEM behaviour is captured well by the S2M.

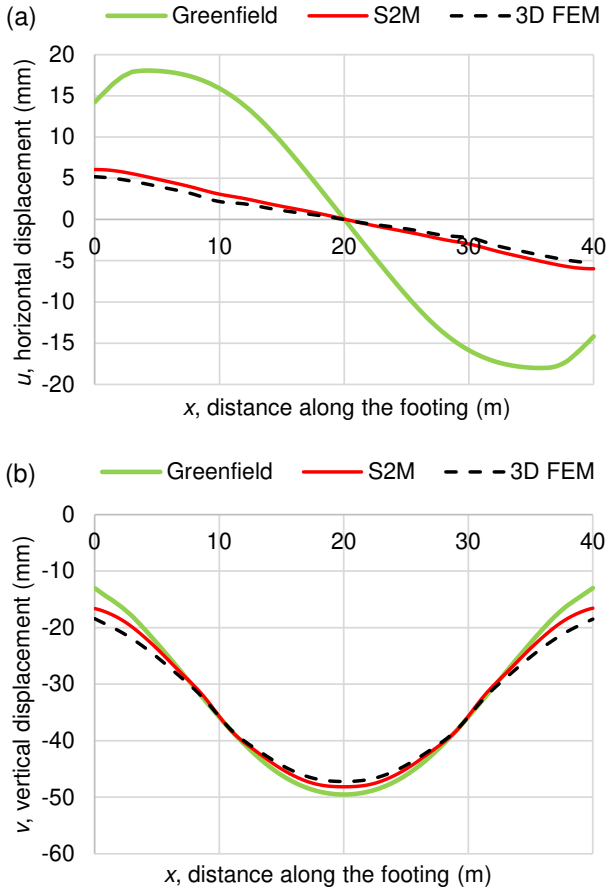

Figure 9. (a) Horizontal and (b) vertical computed greenfield and footing displacements (d_{top}= 1.5 m, d_{base}= 2 m).

6 DAMAGE ASSESSMENT

Tunnelling induced structural damage is often interpreted on the basis of the principal tensile strains, (e.g. Boscardin and Cording, 1989). The maximum principal tensile strains computed in the 3D FEM and S2M models (we only refer to incremental strains due to the construction of the tunnel) are plotted in Figure 10. Good agreement between the two modelling approaches is evident. Strains are mostly in the range 0-800 $\mu\varepsilon$.

Stress singularities occur at the corners of the openings. The maximum computed tensile strain therefore depends on mesh refinement; finer meshes result in higher strain predictions. This mesh dependency would introduce a modelling bias to the damage assessment if only maximum strain magnitudes are considered. Therefore, the element-size insensitive 'characteristic strain' approach (Yiu et al., 2017) is followed. In this approach, 'characteristic strain' ε_η^t refers to the maximum tensile strain that is not exceeded in an area $\eta A_{\text{façade}}$ (for the 2D case) or in a volume $\eta V_{\text{façade}}$ (for the 3D case) where $A_{\text{façade}}$ and $V_{\text{façade}}$ are the total area and volume of façade being assessed and η is a characteristic proportion arbitrarily chosen as $\eta = 0.99$.

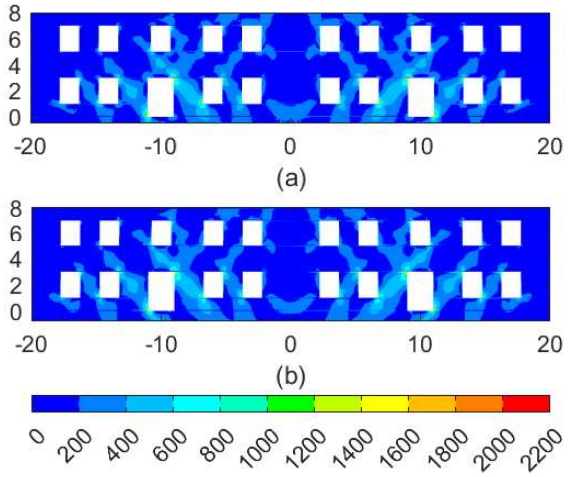

Figure 10. Principal maximum tensile strains in the (a) 3D FEM and (b) S2M models (d_{top}= 0.5 m, d_{base}= 1 m).

Characteristic strain data are reported in Figure 11 for d_{foot}= 1 m and d_{foot} = 2 m. The S2M models predict strains with good accuracy and they capture the increase in strain for the deeper footing case. It is noteworthy that this agreement was achieved with the simple 2D calibration of k_v proposed in the current study. A single S2M analysis took approximately one minute to run while 3D FEM analyses required more than 1 hour.

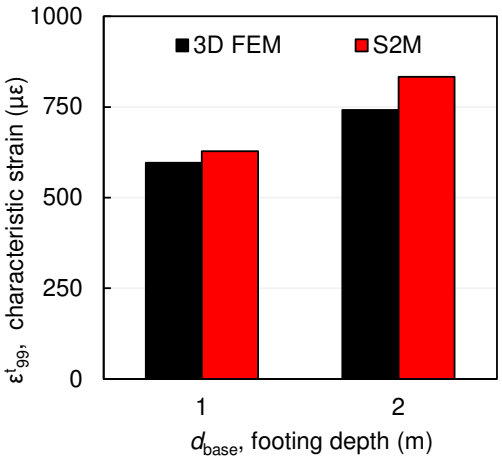

Figure 11. Characteristic strain values for the analysed configurations.

7 ANALYTICAL CALIBRATION OF THE HORIZONTAL STIFFNESS

As an alternative to the determination of the horizontal foundation stiffness, k_h, using the finite element calibration procedure described in Section 3, the possible use of a simpler procedure – not requiring a bespoke finite element analysis – was explored. In this alternative procedure the horizontal and vertical stiffness of a footing embedded in a homogeneous elastic soil was determined using the solutions in Vaziri et al. (1982). The ratio, R_{stiff} of the horizontal to vertical foundation stiffness determined from these solutions is then used to estimate k_h by the approximation $k_h = R_{stiff} k_v$ where k_v is determined from the 2D finite element calibration analyses described in Section 3. This procedure provided values of k_h that were larger – by a factor of about 2 – than those obtained from the bespoke finite element calibration analyses described in Section 3. It is considered that this discrepancy is likely due to assumptions inherent in the Vaziri et al. (1982) modelling approach (e.g. the soil stiffness is assumed to be uniform whereas in the case study being considered the soil stiffness varies with depth). Consistent with the findings in Burd et al. 2022, the S2M is relatively insensitive to changes in k_h; when the alternative values of k_h, determined using the Vaziri et al. (1982) formulation, where employed in the S2M, the calculated values of ε_{99}^t differed by only 0.3% for the $d_{base} = 1m$ case and 1.1% for the $d_{base} = 2m$ case.

8 CONCLUSIONS

This paper discusses a case study application of S2M (Simplified 2D Assessment Model), which is a modelling approach designed for rapid evaluation of tunnelling-induced damage in masonry buildings founded on shallow footings. The S2M features a 1D soil-foundation interface component, which requires accurate calibration. The paper first demonstrates that existing calibration procedures, involving 3D finite element calculations, may be simplified by employing a 2D calibration analysis for the vertical footing response. Then, a tunnel-soil-structure interaction scenario involving two different foundation schemes was examined using S2M calibrated via the simplified procedure. The S2M results demonstrated a good agreement with the higher fidelity 3D finite element model and indicated the possibility for significant time savings. The possibility of employing analytical solutions for the horizontal stiffness of the footing is also demonstrated.

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