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Structure-soil-structure interaction in changing urban areas

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ABSTRACT: Widespread damage within urban centres has highlighted the need to better understand seismic structure-soil-structure interaction (SSSI), particularly given population growth and increasing urbanisation. This paper will explore the performance of low-rise structures when the presence of adjacent structures is explicitly accounted for, based on centrifuge model tests and validated Finite Element analysis. The sensitivity of SSSI to pre-earthquake initial conditions (particularly tilt of foundations) and subsequent evolution of these due to successive earthquakes will be demonstrated, along with sensitivity to the relative dynamic characteristics of the adjacent structures (e.g. changing the urban environment to address urbanisation). Sensitivity to position within a larger group of adjacent structures will also be investigated along with the subsequent impact of building underground infrastructure for urban mass-transit systems. The results presented will demonstrate the importance of accurately describing and modelling the surrounding urban environment in soil-structure interaction analyses, in order to understand the future influence of increasing urbanisation on seismic hazard within populous areas.

1 INTRODUCTION

Soil-structure interaction for single isolated buildings on shallow foundations is generally well understood. In contrast, relatively little is known about seismic structure-soil-structure interaction (SSSI) between multiple adjacent, closely-spaced structures, such as is common in urban areas. Considering such interaction raises additional questions, including:

How are the structural and foundation responses altered by SSSI?

Is the hazard posed to a given structure increased, requiring additional remedial measures, or are there protective mechanisms active that may be harnessed in seismically-resistant design?

How do the relative dynamic characteristics of the adjacent structures (i.e. building form and design) affect response?

How do changes to the urban environment affect the existing buildings that remain?

Understanding SSSI is becoming increasingly important as the World's population grows and becomes increasingly urbanised. Figure 1 shows predicted population growth in urban

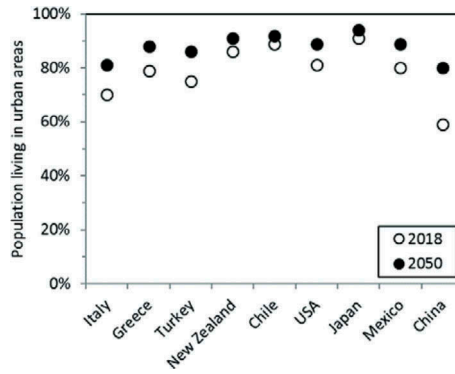


Figure 1. Predicted urban population growth to 2050 (United Nations, 2018)

areas from 2018 to 2050 (United Nations, 2018) for selected seismically-active countries of varying size (from New Zealand, with an urbanized population of ~4M to China with an urban population of ~835M). In all cases the proportion of the population living in urban areas is expected to increase significantly. Even in locations where overall population is expected to decrease (e.g. Japan), the remaining population will be increasingly concentrated in urban areas. This will necessitate substantial changes to the built environment and it is important to understand the implications of this on engineering demand for resilient design.

This paper will initially review some recently published physical modelling work exploring fundamental interactions between pairs of adjacent structures. Following this, new results obtained from a series of subsequent smaller studies using non-linear Finite Element (FE) modelling, validated against the physical modelling data, are presented to begin to answer some of the questions posed above. A particular focus will be on the effects of modifying elements of the urban environment to increase urban capacity on existing structures, by ‘building out’ – here considered as extending a linear row of structures; and subsequently, by ‘building up’ – replacing older structures with taller ones. The paper will finish by investigating the influence of tunneling beneath a group of adjacent structures in an existing urban area (e.g. to add a new underground mass-transit system to service new suburban construction).

2 SUMMARY OF PHYSICAL AND NUMERICAL MODELLING APPROACHES

2.1 Structural models

Five different low-rise structures will be referenced within this paper. These are based on centrifuge model structures at scales of 1:50 and 1:40 which have been tested on the University of Dundee geotechnical centrifuge across a range of projects. A photograph of the five physical models is shown in Figure 2. Structures A and B are equivalent single-degree of freedom (SDOF) models, while structures C, D and E are multi-degree of freedom (MDOF) models of two, three and four storeys, respectively. Table 1 summarises the key structural and geotechnical properties of the structures at prototype scale. Further information on the design of models A and B can be found in Knappett et al. (2015), and further information on model C in Qi and Knappett (2017). Structures D and E have similar design to structure C, but with one or two additional identical storeys added, respectively, lengthening the fundamental period and increasing the bearing pressure on the foundations.

The key parameter that has previously been identified as controlling SSSI is the fundamental period of the structures. Figure 3 shows that the structural models are representative of measured periods for buildings in Los Angeles, USA (after Stewart et al., 1999). Models A

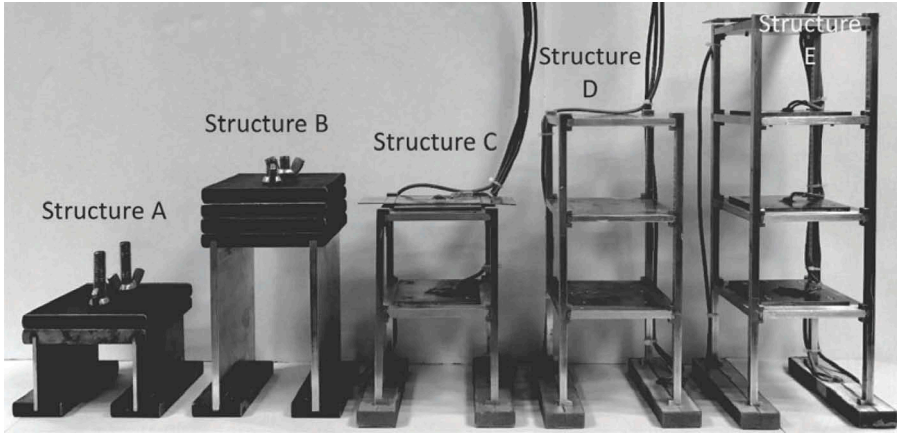


Figure 2. Centrifuge model structures (strip foundation cases shown)

Table 1. Key properties of idealised structures

Structure	Height* (m)	Natural period** (s)	Foundation type	Bearing pressure	Static factor of safety***
A	6	0.33 s	Strips	161	9.5
B	15	0.65 s	Strips	276	5.5
C	6	0.21 s	Strips / Raft	50 / 31	5.0 / 15
D	9	0.30 s	Strips / Raft	75 / 46	4.5 / 14
E	12	0.40 s	Strips / Raft	100 / 62	4.0 / 13

* Height of SDOF models (A and B) represents equivalent structure modelled (actual height of these models is the height of the centre-of-mass).

** Natural period of MDOF models (C, D and E) is that of the fundamental mode.

*** Static vertical factors of safety are calculated for medium dense sand which is dry for models A and B and fully saturated for models C, D and E, following the procedure outlined in Knappett et al. (2015).

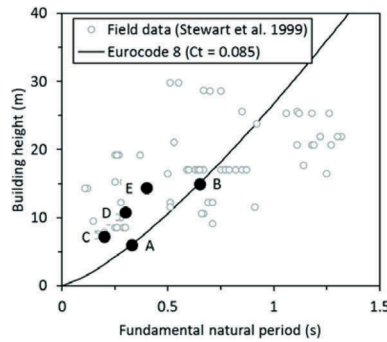


Figure 3. Dynamic characteristics of model structures

and B are consistent with the recommendations of Eurocode 8 (BSI, 2005), where for framed buildings less than 40 m high,

$$T_n \approx C_t H^{0.75} \quad (1)$$

with $C_t = 0.085$ and T_n and H expressed in seconds and metres, respectively. Models C, D and E represent $T_n \approx 0.1N$, where N is the number of storeys.

2.2 Earthquake ground motions

A number of different earthquake ground motion scenarios have been considered in the various sections of this paper. Response spectra for nominal 5% structural damping are shown in Figure 4 and represent rock outcrop motions input at the base of the soil layer in both centrifuge tests and numerical simulations. The motions shown in Figures 4a and 4b were tested in sequences to understand the effect of pre-shaking/aftershocks. Figure 4a shows a motion from the Nishi-Akashi station in the 1995 $M_w=6.9$ Kobe earthquake, rescaled to a peak ground acceleration of 0.1g or 0.5g. These motions were used in sequence as a crude model of multiple earthquakes/strong aftershocks occurring at the same location. The motions in Figure 4b are a re-arranged sequence of motions recorded during the 2010-2011 Canterbury Earthquake Sequence, recorded at the Christchurch Botanical Gardens recording station, and include the 2010 Darfield Earthquake and February 2011 Christchurch Earthquake. This sequence is not in chronological order, being reordered in descending order of earthquake strength (Peak Ground Acceleration PGA=0.36g, 0.18g, 0.15g and 0.13g); however, they also represent multiple earthquakes all occurring at the same location, but include more representative motion-to-motion variability than Figure 4a. These motions were all band-pass filtered compared to the original recordings to enable their simulation on the Actidyn QS67-2 centrifuge-mounted servo-hydraulic earthquake simulator (EQS) at the University of Dundee (having a controllable frequency range at model scale of 40-300 Hz).

The motions shown in Figures 4c and 4d were used in numerical studies only and were not filtered. Figure 4c shows twenty normalised spectra for motions of varying duration between 10-80 s, all recorded in ground with shear wave velocity $V_s > 600$ m/s (i.e. bedrock motions), downloaded from the PEER (Pacific Earthquake Engineering Research) NGA database. Figure 4d shows a motion from the Llolleo recording station during the 1985 $M_w=7.8$ Valparaiso Earthquake rescaled to two different levels which is used in the final part of this paper to

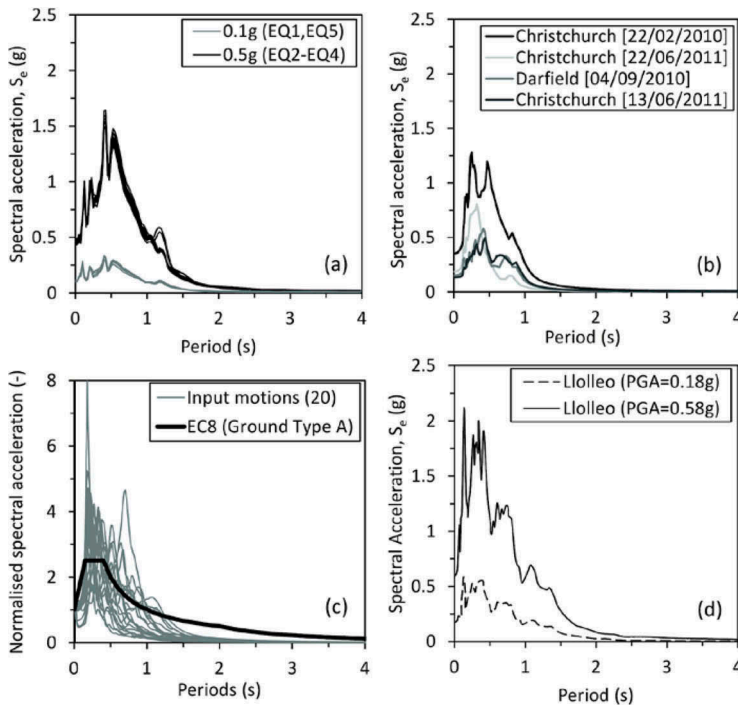


Figure 4. 5% damped response spectra of input motions from various earthquakes: (a) Kobe 1995; (b) Canterbury Earthquake Sequence 2010-2011; (c) various events; (d) Valparaiso 1985.

study the influence of tunneling on urban areas, as this is based on a new tunnel recently constructed in Santiago, Chile.

2.3 *Ground properties*

All of the structural arrangements considered in this paper are founded on/in the same ground, representing a non-liquefiable medium dense coarse-grained soil. In the centrifuge tests, dry uniform beds of Congleton HST95 sand at a target relative density of 55% were prepared, to ensure that there would be no excess pore water pressure (EPWP) generation. The use of dry sand required relatively high bearing pressures to achieve the vertical factors of safety against bearing capacity failure for structural models A and B shown in Table 1.

The FEM simulations reported in Section 4 of this paper utilised a numerical idealisation of the soil conditions described above, modelling fully drained response but with the water table at the surface to allow more representative bearing pressures to be applied to achieve appropriate static factors of safety of the foundations. These simulations were also used as non-liquefiable benchmark cases for a recently completed study investigating SSSI in variously liquefiable soil, which was fully saturated. A non-linear constitutive model was used within various versions of the software PLAXIS 2D (from 2012, onwards). This was the ‘Hardening soil model with small strain stiffness’ (Benz, 2006) which incorporates non-linear elastic behavior which is both confining stress and induced shear strain dependent and captures small strain shear modulus (G_0) conditions at very small strains, with non-associative Mohr-Coulomb plasticity with both deviatoric and volumetric hardening of the yield surface. The model parameters were calibrated against laboratory element tests (shearbox and oedometer) of the centrifuge test sand across a range of relative densities from 10-90% by Al-Defae et al. (2013), who also validated the dynamic response of the resulting model parameters against stress-strain behaviour measured in centrifuge tests (in the absence of cyclic element test data). Further information, including the specific properties used in the FEM can be found in Knappett et al. (2015) and Qi and Knappett (2017).

3 INTERACTION BETWEEN PAIRS OF ADJACENT STRUCTURES

An analytical model of seismic SSSI has recently been developed by Alexander et al. (2013) for two adjacent equivalent SDOF elastic structures on a linear elastic subgrade. This study indicated that the presence of an adjacent structure of longer natural period could result in an increase in the elastic structural demand (expressed in terms of spectral power change). The presence of a shorter period structure could produce a modest reduction in structural demand. In each case the magnitude of the change was between 5-10% of the isolated structure demand. These findings were subsequently validated through 1-g shaking table testing by Aldaikh et al. (2016) using a foam block to simulate the elastic subgrade, though the potential detrimental increases in demand were observed to be larger than suggested by the analytical model.

A fully linear model cannot account for the effects of elasto-plasticity within the foundation soil on response, and therefore cannot properly consider the effect of earthquake strength. Centrifuge testing has been used to investigate this in greater detail, and an example dissimilar test layout is shown in Figure 5, where dimensions are in metres at prototype scale. Structures of type A and B at a scale of 1:50 were used in either similar or dissimilar pairs on medium dense non-liquefiable soil as described in Section 2. Isolated structures were also tested for comparison. All models were subjected to a sequence of five successive ground motions from Figure 4a. An initial 0.1g motion was used to induce a predominantly elastic response, followed by three 0.5g motions and a final 0.1g motion.

3.1 *Structural demand*

Figure 6 shows the effect of SSSI on peak structural demand, expressed in terms of the peak acceleration measured at the vibrating mass within the equivalent SDOF structures.

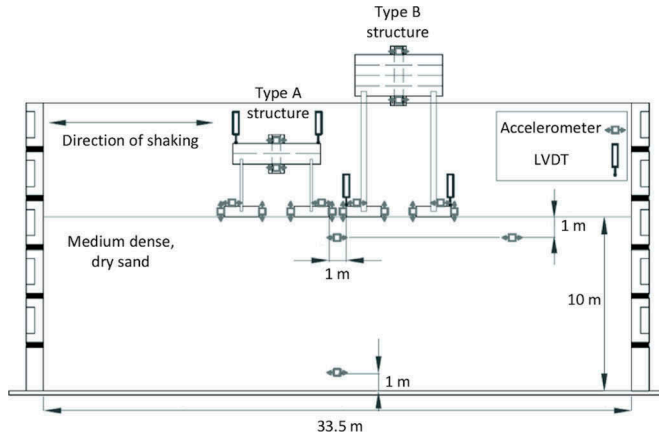


Figure 5. Example centrifuge test layout (all dimensions in m at prototype scale)

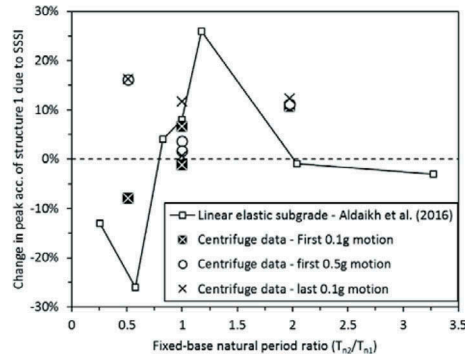


Figure 6. Effect of SSSI on peak spectral structural acceleration from physical model tests.

The fixed-base natural period ratio represents the natural period of the adjacent structure (structure 2; T_{n2}), divided by that of the structure of interest (structure 1; T_{n1}). This allows comparison with similar data measured from the 1-g tests of Aldaikh et al. (2016), where the points plotted are average responses across a range of input ground motions. It can be seen that in the first ‘small’ (0.1g) motion, there is some consistency with the shaking table data. The centrifuge data suggests a reduction in response for $T_{n2}/T_{n1} < 1$ for this motion, and a similar increase of up to 10% when $T_{n2}/T_{n1} = 1$. A larger amplification is expected for $T_{n2}/T_{n1} > 1$, possibly as the taller adjacent structure in this case has increased bearing pressure and generates a more strongly inelastic response. In the subsequent motions, amplification is observed for all values of T_{n2}/T_{n1} , with this being larger when the structures are dissimilar. This suggests that non-linear soil response is important to account for and that SSSI is most likely to result in increased structural demand, irrespective of the value of T_{n2}/T_{n1} , i.e. the results of SSSI appear to be universally detrimental to structural seismic demand.

To validate the generality of this result, numerical FE simulations were conducted using structures of types C, D and E in either similar or dissimilar pairs, using the alternative sequence of input motions shown in Figure 4b. For the taller structures, some of the structures were extended to two bays wide, while maintaining the same natural period and foundation bearing pressures. Figure 7 shows peak accelerations at storey 1 (ground floor) which represent a point close to the centre of mass of the structure (as for the accelerations shown in

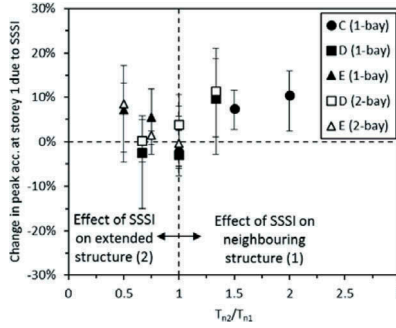


Figure 7. Effect of SSSI on peak spectral structural acceleration from numerical parametric study.

Figure 6). In each case, the datapoint in Figure 7 represents the gradient of the linear best-fit line between adjacent and isolated responses across the four ground motions of the sequence; the error bars indicate the maximum and minimum individual ratios observed in any given motion.

Figure 7 is similar to Figure 6 in appearance and suggests that it would be prudent to always allow for increased structural demand due to SSSI, irrespective of the period ratio. Considering these results in terms of modifying the urban environment, dissimilar pairs can arise if one building is extended or replaced with a new taller design compared to a neighbouring unaltered building. Figure 7 therefore indicates that as well as accounting for SSSI in the design of the extended structure ($T_{n2}/T_{n1} < 1$), decisions made during this design will affect the existing neighbouring structure ($T_{n2}/T_{n1} > 1$, and potentially under different ownership) and suggests that a ‘seismic impact assessment’ may be necessary in urban areas, analogous to an environmental impact assessment.

3.2 Foundation response

In the centrifuge tests, earthquake-induced settlement and tilt (global rotation due to differential settlement) are also possible. In all adjacent structure events, post-earthquake (gross) settlement was reduced as a result of SSSI compared to isolated cases. In fact, this was also true of all subsequent numerical simulations that will be discussed in Sections 4 and 5. Post-earthquake tilt was observed to be very sensitive to the initial pre-earthquake tilts, which are difficult to control accurately in small-scale physical models, e.g. due to small variations in soil density or surface level. An example can be seen in Figure 8 where reversing the direction of the small initial tilts of the two adjacent structures results in very different post-earthquake tilts, particularly across the multi-event seismic sequence. As a result, FEM simulations (using a dry soil profile) were firstly validated against the centrifuge data after simulating the measured initial rotation conditions. An example of this validation for foundation rotation is also shown in Figure 7; further details of the validation across free-field ground response, structural response and settlement can be found in Knappett et al. (2015). This sensitivity to initial conditions suggests that it is important to measure these if existing structures are to be modelled numerically, and to update these after large earthquake events for future predictions if possible. Figure 9 summarises the results of FEM simulations of the centrifuge tests with comparable initial conditions and suggests that SSSI results in increased rotations for both similar and dissimilar layouts, at least for pairs of structures.

In summary, for the simplest possible case of pairs of adjacent structures, SSSI appears to worsen distortional responses within the structures and their foundations (peak inter-storey drift and post-earthquake tilt), while it appears to have a universally beneficial effect on foundation settlement.

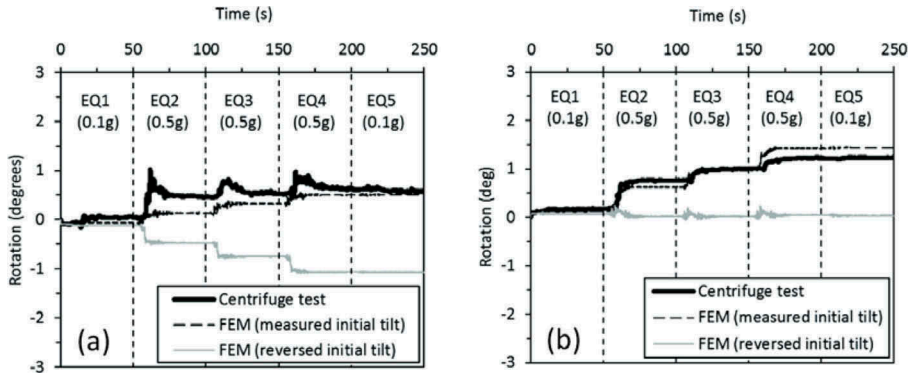


Figure 8. Rotation of two adjacent structures from centrifuge testing and FEM: (a) structure type B; (b) adjacent structure type B.

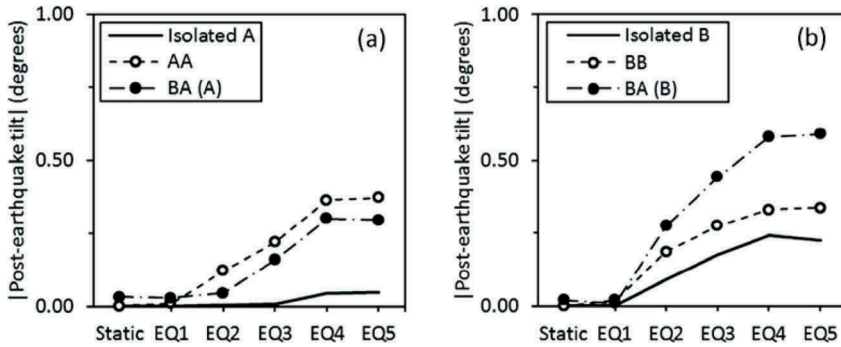


Figure 9. Effect of SSSI on post-earthquake tilt from FE simulations for comparable initial conditions.

4 MODIFYING THE ABOVE-GROUND URBAN ENVIRONMENT

4.1 ‘Building out’ – linear rows (blocks) of adjacent structures

One possible way of increasing urban capacity is to build outwards (if land is available). In this sub-section, building out will be represented by considering linear rows of n closely spaced structures, where $n \geq 2$, to build on the results from Section 3. The structures will be of identical design, and may therefore represent the construction of a set of similar low-rise buildings by a developer (e.g. a housing estate in a suburban area).

Figure 10 shows an example FE model for $n=3$ structures (of type C). This was subsequently increased up to $n=9$ structures by progressively adding a structure to each end of the row. The distortional measures of building performance (inter-storey drift at storey 1 and post-earthquake tilt of the foundations) are shown in Figure 11. Peak inter-storey drift may be preferable to peak acceleration as an engineering demand measure for the structures as this is a more direct quantification of the distortion of the columns (and therefore of the induced bending moments), removing any effect of cyclic rocking which may be incorporated within the acceleration measure shown previously in Figures 6 and 7. The ground motion sequence shown in Figure 4b was used, though only data for the first motion (Christchurch, 2011; PGA = 0.36g) is shown in the figure for clarity. The simulations were conducted both for structures on separated strip foundations (see Figure 10) and for identical structures with one-piece rafts having much higher static vertical factors of safety.

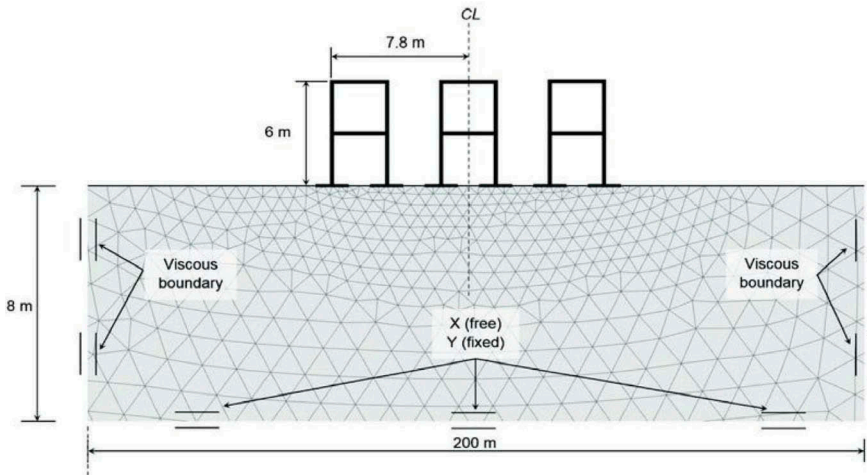


Figure 10. FE model of multiple adjacent structures (type C)

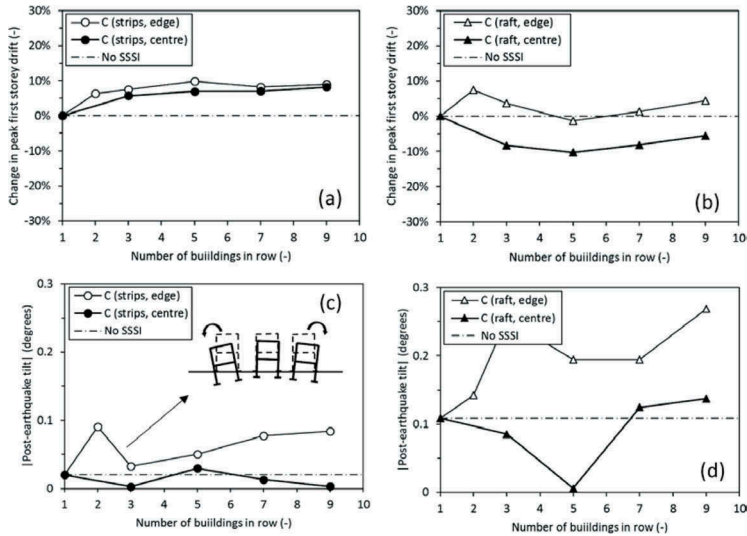


Figure 11. Effects of SSSI on distortional deformations of linear rows of adjacent similar structures ('building out').

For both types of foundation, the central structure within the group appears to be protected compared to the structures on the edge of the groups. This is particularly true for the post-earthquake tilt, where the central structure is in many cases improved compared to that of a single isolated structure (indicated by the dashed line in Figures 11c and 11d) for both foundation types. In contrast, the end structures are rotated more than the isolated structures. These rotational observations can be explained in terms of the yield acceleration associated with bearing capacity failure (which under horizontal force and moment acting on the foundations from the earthquake loading will correspond to a rotational or rocking mode). The central structure has an increased yield acceleration for rotation in both left and right directions due to the equal additional confinement from the adjacent structures. The edge structures are only confined on one side, resulting in increased yield deformations in the outward direction (away from the other structures) due to the much lower yield acceleration in this direction. This was

confirmed from the direction of the tilts from the FEM simulations, which are shown schematically in Figure 11c for $n=3$.

It is also apparent from Figure 11 that the three or five adjacent building cases provide a reasonable approximation of the end-of-row and confined central structure performances. This suggests that it may be possible to reduce a large problem with many adjacent similar structures to a smaller group for analysis, reducing computational effort or enabling modelling within the limited space of a centrifuge model container, while capturing the key behaviour of the constrained internal structures and also the very different behavior of the end-of-row structures.

Finally, as in Section 3, all post-earthquake gross-settlements were reduced due to SSSI compared to the isolated structure case. The magnitude of this reduction became constant between $n=3-5$, as for the drift and post-earthquake tilt. This reduction in settlement is also consistent with increased yield acceleration against transient bearing capacity failure provided by the additional confinement from the adjacent buildings.

4.2 ‘Building up’ – impact of replacing old structures with taller ones

As an alternative to building out, additional urban capacity may be added by building up – replacing existing short structures with taller ones. This sub-section will consider the case where some of the buildings in group are increased in height (and therefore in fundamental natural period and bearing pressure) before a major earthquake occurs, focusing on the effect that such changes have on existing unaltered buildings. This is important as the structures which are modified may have different ownership to those that are not. While, in principle, the effects of SSSI can be accounted for in the design of the new taller structure(s), it may be that the change of building type/properties results in undesirable modification to the performance of the existing urban environment. This would not be in the interests of the owners of the existing structure(s), and would not necessarily result in reduced total cost of seismic damage across a large urban area.

Following from the results Section 4.1, a group of five adjacent structures were modelled numerically. The unmodified (reference) case, hereafter termed ‘pre-modification’, consists of five adjacent identical buildings of type A. ‘Post-modification’ cases change maintain the key central and end-of-row structures as type A, with the intermediate structures modified to type B (arrangement ABABA). These arrangements were repeatedly simulated using the twenty different ground motions shown in Figure 4c. For the cases shown in this paper, these motions were all scaled to have a $PGA=0.5g$.

Figure 12 shows the results of these analyses, focusing on the distortional movements (peak inter-storey drift and post-earthquake tilt). As with all of the previous numerical analyses and centrifuge tests, gross settlements were observed to be reduced in all cases due to SSSI, compared to the isolated cases, due to the additional confinement provided by the adjacent structures and therefore increased yield acceleration against transient bearing capacity failure and therefore settlement accrual. Considering first the pre-modification cases in Figure 12, it is clear that the central structure has reduced peak drift and post-earthquake tilt compared to the end structures. These observations are consistent with Figure 11 (which considered a structures of type C).

Post-modification, the drifts of both the central and edge unmodified structures are increased. These observations are consistent with Figure 7 (for a pair of structures), given that $T_{n2}/T_{n1}>1$ as structure B is taller than structure A. These results suggest that in larger groups of mixed structural types, confined structures within the group will not be significantly protected (as was suggested for identical structures in Figure 11) and it would be prudent to consider that all structures in the group may see amplification of structural demand due to SSSI. In Figure 12, all of the post-modification central structures have an amplification $\leq +10\%$, compared to the isolated building case.

Modification appears to increase the post-earthquake tilts of both central and edge unmodified structures. However, in the case of the central structures (Figure 12b), the majority of the data points after modification are still reduced compared to the isolated case (beneficial SSSI effect). In the case of the edge structures (Figure 12d), the post-earthquake tilts are

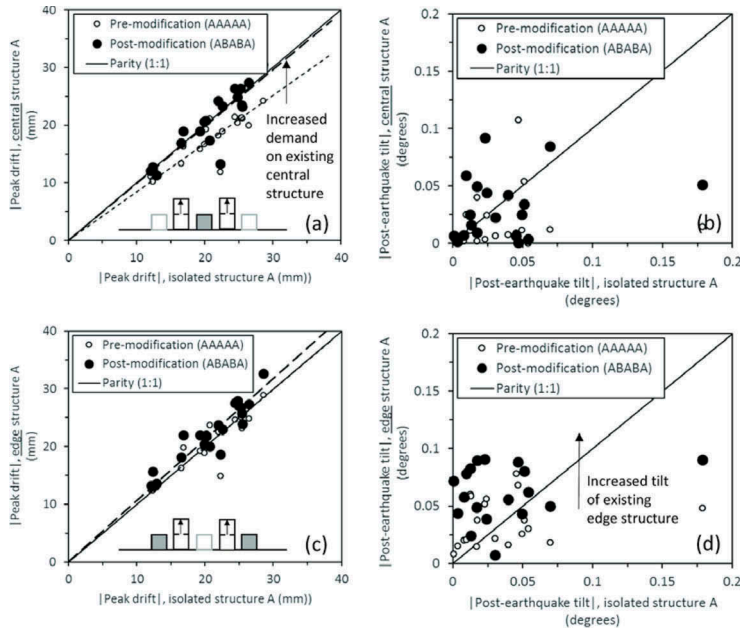


Figure 12. Effects of modifying some structures within a linear row (‘building up’).

consistently increased following modification, meaning that the detrimental effect of the SSSI already present from the pre-modification identical structure grouping is increased as a result of modification. This is consistent with the yield acceleration for inward rotation being increased by modification (higher confinement from increased bearing pressure of the taller structure), amplifying the difference between outward and inward yield accelerations and hence amplifying the tendency of the buildings to rotate outwards (as there will be less accumulated rotation towards the other structures).

5 TUNNELING BENEATH SEISMICALLY-ACTIVE URBAN AREAS

The expansion of existing urban areas as a result of urbanization may require new supporting transport infrastructure. The example considered here is that of constructing a tunnel beneath an existing urban area to connect new suburban development to the central business district. This arose out of a recently completed collaborative research project with the University of Leeds, UK and the Pontifical Catholic University of Valparaiso (PUCV), Chile, considering the installation of smart sensor networks on newly built metro tunnels in Santiago, Chile. The University of Dundee’s principal role was to understand the seismic performance of the tunnel to inform interpretative methods that would be applied to the sensor measurements.

5.1 Numerical modelling approach

The tunnel cross-section considered represented part of the Line 6 extension to the Santiago Metro, which was under construction in 2016 (see Figure 13a). The tunnel was constructed open-face using sprayed concrete within a dense clayey gravelly soil containing significant cobbles and plastic fines. Based on site investigation and laboratory element test data (Metro de Santiago S.A., 2012), the soil properties could be well approximated using the constitutive model described in Section 2.3, i.e. based on medium-dense to dense sand, depending on the location along the tunnel, with additional cohesion (of between 0-50 kPa), thought to be

provided by the fine material. The water table was well below the tunnel soffit. The data presented here considers soil properties consistent with a relative density of 60% in the property correlations of Al-Defae et al. (2013), with $c'=20$ kPa. The geometry, as modelled in FE is shown in Figure 13b.

Kampas et al. (2019) explored various approaches to modelling the structural behaviour of the reinforced concrete tunnel in FE, including elastic idealisations and non-linear moment-curvature relationships accounting for hoop stress confinement. The modelling approach was found to significantly affect the internal forces generated within the tunnel lining and induced damage; however, the effect of the tunnel on modifying the ground motion was found to be largely insensitive to the modelling approach. As a result, a simple elastic tunnel model based on uncracked bending stiffness (EI) was considered herein as this also closely replicated the post-construction settlement trough of a fully non-linear tunnel (Kampas et al., 2019) which allows the tunnel to influence the initial conditions (particularly initial tilt) of the building foundations.

The FE simulations consisted of multiple stages. After initialisation of the geostatic stress field (pre-tunnel), the surface structures were initialised and loaded. A group of six adjacent identical two-storey structures similar to Type C, having identical fundamental natural period and bearing pressure but with two bays per structure were simulated (similar to the approach in Figure 7). These have an edge-to-edge spacing between structures of 2.4 m, such that the spacing normalised by the building width was the same as that considered in Section 4.1. Subsequently, the tunnel was created at a with a cover depth of 18 m above the tunnel crown to the ground surface using a load reduction method (β -method – e.g. Mödlhammer, 2010). In this approach, the soil within the tunnel boundary is removed and the surrounding soil allowed to contract until a target settlement, consistent with the expected greenfield Gaussian settlement trough for a given amount of volume-loss, is reached. Here, a settlement of 10 mm at the ground surface above the tunnel crown was obtained in greenfield simulations (no surface structures), simulating 0% volume loss, and the load reduction required to achieve this was subsequently applied to the cases with structures. Once both the structures and tunnel had been numerically constructed, a single ‘small’ or ‘large’ ground motion from the 1985 Valparaiso Earthquake was applied, as shown in Figure 4d.

5.2 Impact of tunnel presence on above-ground SSSI

Figure 14 shows the effect of the tunnel on the behaviour of the six structures, compared to a ‘pre-tunnel’ case (where the earthquake occurs after the structures have been built but before the tunnel). Structures in similar positions are grouped together and the peak of the two responses is plotted for each. In terms of structural demand (Figure 14b), the peak inter-storey drift at storey 1 is increased as a result of the tunnel construction at all positions and

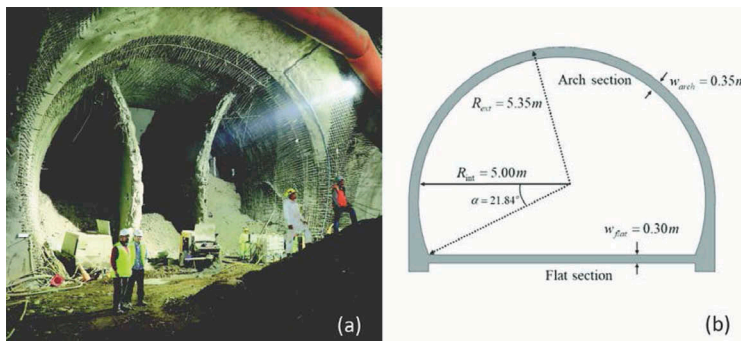


Figure 13. Sprayed concrete tunnel beneath Santiago, Chile: (a) image taken during construction; (b) geometry used in FE modelling.

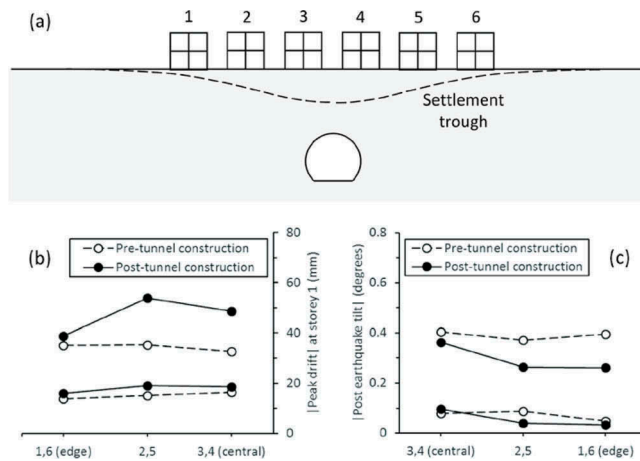


Figure 14. Effect of tunnel construction on distortional deformations of a group of surface structures.

for both strengths of ground motion. The amplification is also only marginal for the edge structures and much larger for the confined structures nearer the centerline of the tunnel. This is consistent with the ground accelerations (input motions to the structures) being amplified above the crown of the tunnel compared to the free-field (see Kampas et al., 2019).

In Figure 14c, the magnitude of the post-earthquake tilts of the foundations are largely unchanged in the smaller earthquake, as the lower induced shear stresses will result in only a small amount of permanent deformation being induced. In the larger motion, the tilts of all of the structures are reduced as a result of the tunnel's position, and this is more pronounced towards the edge of the group. This appears to be as a result of the tunnel-induced deformations inducing initial inwards rotation of the structures which are an order of magnitude larger than those induced by construction of the buildings without the tunnel (see settlement trough in Figure 14a). This effect is most pronounced in structures 1, 2, 5 and 6 as these fall close to the points of maximum angular distortion in the ground associated with the settlement trough. Further investigation with a wider group of structures is necessary to confirm whether this is the controlling mechanism by observing whether the rotation effect reduces at greater distance from the tunnel centerline where the settlement trough is less pronounced.

6 CONCLUSIONS

Much of the World's population live in densely populated urban areas in seismically-active regions. Population growth, alongside increasing urbanisation, makes understanding of seismic structure-soil-structure interaction (SSSI) increasingly important. This paper has summarised the results of recent physical modelling studies to understand SSSI in non-liquefiable ground conditions and used numerical simulation, validated against this data, to extend the study to increasingly complex arrangements of interacting structures. SSSI typically increases structural demand (expressed in terms of peak inter-storey drift) and post-earthquake tilt. These distortional responses are typically the most damaging to a structure. Typically drift is amplified by up to 10% if the structures in a group are identical and up to 20% if the structures are in a dissimilar group. In larger groups of structures, end-of-row structures suffer increased outwards post-earthquake tilts compared to isolated structures, while confined structures within the row are largely protected by their neighbours. This suggests that remedial efforts to improve foundation performance should be focused on end-of-row structures. SSSI-induced rotational changes are highly sensitive to the initial rotation conditions, so these should be carefully measured when existing structural groups are to be analysed. Structural settlements

were observed to be universally improved as a result of SSSI. Construction of underground transport infrastructure beneath an urban area can result in SSSI with overlying surface structures. Increased ground motion amplification due to the presence of a tunnel increases structural demand, while the ground deformations induced by tunnel construction alter the initial rotations of the structures, modifying the post-earthquake tilts beneficially. The results shown in this paper indicate that it is important to account for SSSI in seismic design of buildings within urban areas, both for new developments and for assessing the impact of changes to an urban environment on the existing structures.

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REFERENCES

- Aldaikh, H., Alexander, N.A., Ibraim, E. & Knappett, J.A. 2016. Shake table testing of the dynamic interaction between two and three adjacent buildings (SSSI). *Soil Dynamics & Earthquake Engineering* 89: 219-232.
- Al-Defae, A.H., Caucis, K. & Knappett, J.A. 2013. Aftershocks and the whole-life seismic performance of granular slopes. *Géotechnique* 63(14): 1230–1244.
- Alexander, N.A., Ibraim, E. & Aldaikh, H. 2013. A simple discrete model for interaction of adjacent buildings during earthquakes. *Computers & Structures* 124: 1–10.
- Benz, T. 2006. *Small-strain stiffness of soils and its numerical consequences*. PhD thesis, University of Stuttgart, Germany
- BSI 2005. BS EN 1998-1:2005: *Eurocode 8: Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings*. British Standards Institution, London, UK.
- Kampas, G., Knappett, J.A., Brown, M.J., Anastasopoulos, I., Nikitas, N. & Fuentes, R. 2019. The effect of tunnel lining modelling approaches on the seismic response of sprayed concrete tunnels in coarse-grained soils. *Soil Dynamics & Earthquake Engineering* 117: 122-137.
- Knappett, J.A., Madden, P. & Caucis, K. 2015. Seismic structure-soil-structure interaction between pairs of adjacent building structures. *Géotechnique* 65(5): 429–441.
- Metro de Santiago S.A. 2012. *Ingeniería de detalle de Piques y Galerías Línea 6*. Memoria de Calculo. L6-ID-03-MCA-931-TU-110. Santiago. Chile (In Spanish).
- Mödlhammer, H. 2010. *Numerical methods for tunnelling using ABAQUS and investigation of long-time-effects of the shotcrete shell and its impact on the combined support system*. M.Sc. Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA.
- Qi, S. & Knappett, J.A. 2017. Implications of changes of building use on seismic performance of adjacent structures. *Proc. 3rd International Conference on Performance based design in earthquake geotechnical engineering, Vancouver, 16-19 July 2017*. Article no. 236.
- Stewart, J.P., Seed, R.B. & Fenves, G.L. 1999. Seismic soil-structure interaction in buildings, Part II: Empirical findings. *Journal of Geotechnical and Geoenvironmental Engineering, ASCE* 125(1): 38–48.
- United Nations 2018. *World Urbanization Prospects: The 2018 Revision, Online Edition*. Department of Economic and Social Affairs, Population Division. Available from <https://esa.un.org/unpd/wup/Publications>.