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Consideration of Soil-Foundation Induced Deformations in Building Design

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ABSTRACT

The consideration of seismically induced deformations at the foundation level is an important, but often overlooked part of building design. Foundation deformations, both uniform and differential, can make buildings unusable, irreparable and can induce additional stresses and damage to the superstructure. It is therefore essential for any performance-based design to consider foundation deformations in the design and assessment process. In recent years there have been a large number of experimental tests investigating dynamic soil-foundation-structure interaction, allowing foundation deformations to be measured and better understood. This has allowed the development and validation of numerical modeling techniques that attempt to capture the transient and residual deformations at the soil-foundation interface. This paper uses an experimentally validated macro-element modeling technique to demonstrate the key mechanisms of residual and transient foundation deformations and their implications on structural performance and design. The unique influences of frame action on the soil-foundation interface are discussed and quantified as well as the influence of the static axial load ratio, i.e. factor of safety against bearing capacity failure, on the level of energy dissipation and residual deformations.

Introduction

The effects of soil-foundation-structure interaction (SFSI) have been a topic of discussion amongst the structural and geotechnical community for many decades. The complexity of the mechanisms in SFSI as well as the need for inter-disciplinary knowledge of geotechnical and structural dynamics has plagued the advancement and the consequent inclusion of SFSI effects in design. It is well established that SFSI modifies the seismic response of a building, however, the modification is often considered 'beneficial' and thus buildings are often designed assuming rigid soil and foundations. The assumption of a rigid base for the structure, is reinforced by following a capacity based design process to avoid foundation and soil yielding, often resulting in an over-strengthened foundation. However recent events (eg. Christchurch earthquake sequence 2011-2012) and research (eg. Mylonakis and Gazetas, 2000) have provided evidence to the contrary of this beneficial effect.

The transient deformations in the foundation can lead to additional displacements and stresses in

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the structure and residual deformations at the foundation level can leave the building potentially irreparable.

There is a need to consider both the transient and residual foundation deformations in building design. This paper systematically reviews the major effects of SFSI to highlight how they could be controlled through design.

Conventional Design

In a conventional design of a building and foundation, the building and foundation are designed separately (Figure 1). The superstructure loads are determined by considering the dynamic behaviour of the superstructure as if the foundation and soil are rigid (Step 1). The superstructure is designed based on the internal actions from the superstructure loads (Step 2). The foundation loads are determined by considering how the internal forces of the superstructure will act on the foundation when considering the superstructure to behave with some additional over-strength (Step 3). The foundation loads are considered as pseudo static forces acting on the foundation and the foundation is then sized and designed to avoid static bearing capacity failure, foundation uplift and excessive static settlement (Step 4).

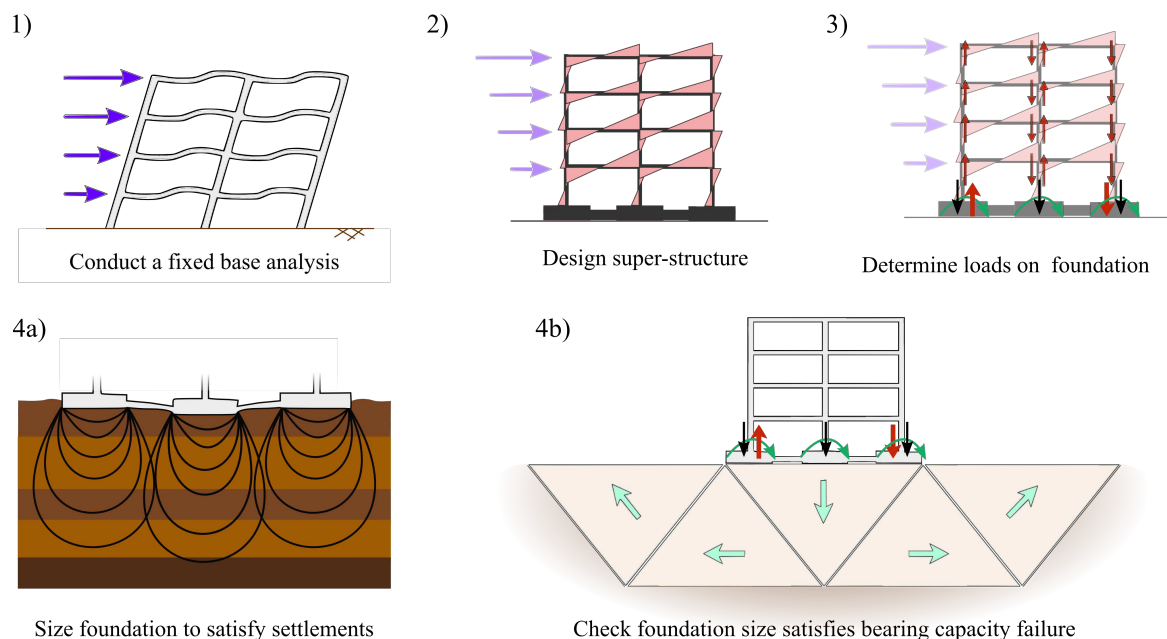


Figure 1. Conventional structure and foundation design procedure

The conventional design approach essentially designs the superstructure assuming zero foundation deformation, while the foundation design only attempts to prevent foundation uplift and does not consider further deformations in the soil at all. The repercussions of such a design procedure are uncontrolled transient and permanent foundation deformations and potentially large and expensive foundations.

Considering Rigid Foundations on Deformable Soil

By releasing the constraint of a rigid-base, rigid-body SFSI mechanisms can be considered (Figure 2).

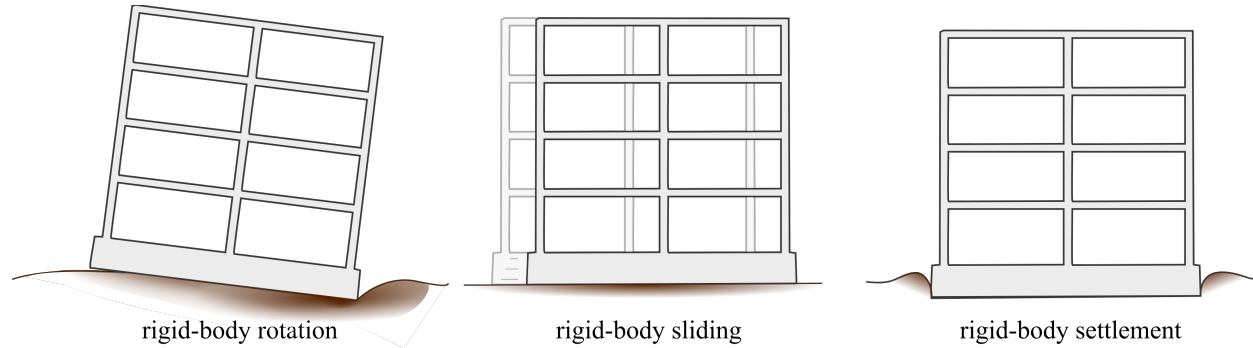


Figure 2. Rigid-body mechanisms

The rotation of the foundation can provide considerable modification to the seismic response, especially for structures with large aspect ratios (height-to-foundation length). The change in response is due to the additional flexibility of the system, attributable to the deformations of the soil and uplifting of the foundation.

Foundation rotation can be considered as three separate mechanisms: elastic rotation, foundation uplift and soil yielding (Figure 3). The elastic rotation is a linear elastic mechanism, where the rotation is fully recoverable. The uplift mechanism is a non-linear elastic mechanism, whereby the deformation is fully recoverable but the rotational stiffness reduces as uplift occurs, due to a geometric non-linearity. The soil yielding mechanism is a non-linear inelastic mechanism, whereby the rotation is not recoverable and the stiffness changes as the soil yields.

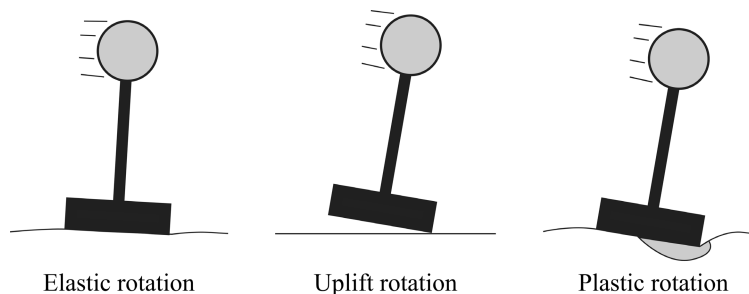


Figure 3. Mechanisms of foundation rotation

Each of these mechanisms contributes different amounts of rotation depending on the level of axial load and amount of rotation. The elastic rotation tends to dominate for small levels of rotation, while for large rotations the heavily loaded footings have mainly soil yielding and the lightly loaded footings have mainly uplift. Although each mechanism affects the other, this approach provides a convenient explanation for why foundations with different axial load ratios (ie. static factor of safety against bearing capacity failure) have different levels of hysteretic

energy dissipation, non-linear behaviour and effective stiffness.

The foundation sliding can also provide additional flexibility to the translational mode of vibration, thus modifying the seismic response of the building. Furthermore the additional shear force from the footing on the soil can cause additional plastic response in the rocking mode.

The additional rotation and sliding mechanisms increase the flexibility of the system and can limit the seismic loads entering the structure; however, they tend to result in increased displacements.

A mechanism approach can also be applied to the settlement. Two mechanisms contribute to settlement, gravity-induced settlement and SFSI-induced settlement. The gravity-induced component can be considered as the settlement from the compressibility of the soil under the applied gravity loads and will not be discussed further here. The SFSI-induced settlement occurs due to a shakedown of the foundation into the soil through subsequent cycles of irrecoverable soil yielding through rotation (Figure 4).

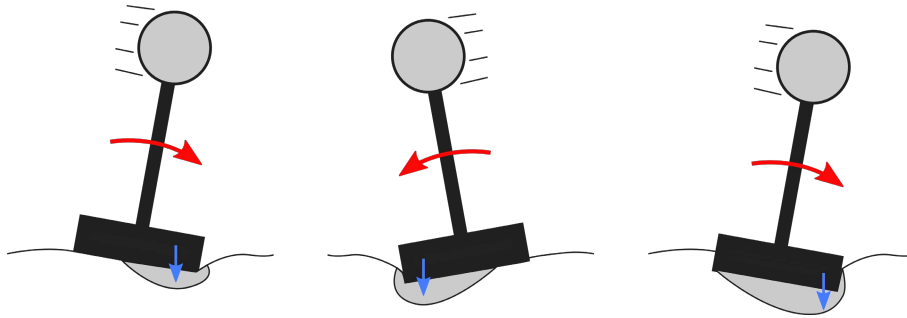


Figure 4. SFSI-induced settlement through shakedown

The level of settlement induced in a single cycle has been experimentally investigated by Gajan et al. (2005) through an extensive set of cyclic loading tests of footings under centrifugal conditions. Gajan et al. (2005) findings demonstrated a strong influence on settlement from the axial load ratio, the level of rotation and the relative density of the soil. Further experimental research by Deng and Kutter (2011) investigated the link between settlement and ‘cumulative plastic rotation’, where the axial load ratio was also recognised as an important parameter.

Case Study Pier Structure

To investigate these effects, two single-degree-of-freedom (SDOF) structures were numerically modeled in Ruaumoko3D (Carr, 2015) (Figure 5) using default parameters for the adopted macro-element. Both SDOFs were designed to have a period of 1.5s, and other properties are given in Table 1, however, the second structure had five times larger vertical load resulting in axial load ratios (\tilde{N}) of two and ten for the two structures. Each structure was subjected to 35 ground motions from the NGA-West database (Chiou et al. 2008) used in a previous study by Millen et al. (2015), where the five strongest ground motions (NGA0143_1, NGA1495_1, NGA0183_1, NGA0292_1, NGA0292_1) were omitted, since the ground motions were unscaled and the moment demand on the lightly loaded footing was too large for the numerical model to

yield useful results.

Figure 6 shows the behaviour of the structures subjected to the Imperial Valley, 1979 – El Centro Array #12 ground motion, where the difference in behaviour between the two structures is evident. The foundation moment capacity of the first structure is considerably larger due to the additional axial load, but exhibits a more plastic response. The greater plastic response led to larger SFSI-induced settlement and residual rotation. The lightly loaded footing exhibited uplift behaviour at large rotations and therefore had a severe reduction in rotational stiffness but achieved better recentring.

The plot at the bottom of Figure 6 shows the non-linear response of the SDOF compared to the linear elastic response. In this case both structures have less displacement than the elastic response, however, this is not always the case and displacements can even be amplified depending on the ground motion and level of non-linearity. This variation must be accounted for in a performance-based design where the estimation of displacements is of great importance.

The results from the 35 ground motions show clear trends in the relationship between the residual deformations and the peak foundation rotation (Figure 7). Both piers show SFSI-induced settlements increasing with peak foundation rotation, with the heavily loaded foundation showing larger levels of settlement than the lighter footing. There was also a clear trend with the residual rotation, however there was no significant difference between the two piers. As expected the residual rotation was negligible at very low levels of rotation where the elastic response dominates, as the peak rotation increased the residual rotation approached the peak rotation.

Table 1. Properties of pier structure

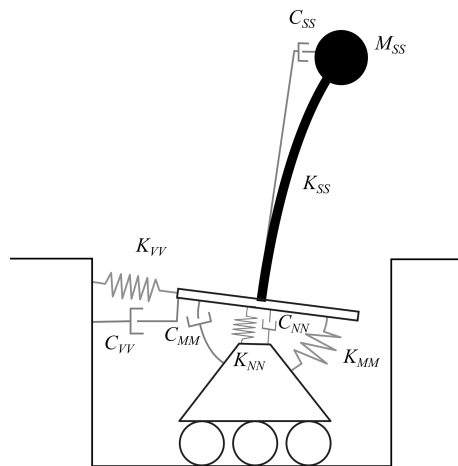


Figure 5. Pier numerical model

Properties	Value
Soil friction angle	35
Soil shear modulus	90 MPa
Soil density	1.7 T/m ³
Foundation vertical stiffness (KNN)	2.92 GN/m
Foundation shear stiffness (KVV)	2.38 GN/m
Foundation rotational stiffness (KMM)	60.0 GNm
Foundation bearing capacity (Ncap)	170 MN
Structure height	18 m
Vertical weight	17, 85 MN
SDOF mass	8650 T
Structure stiffness	152 MNm ⁻¹
Super structure damping	5 %

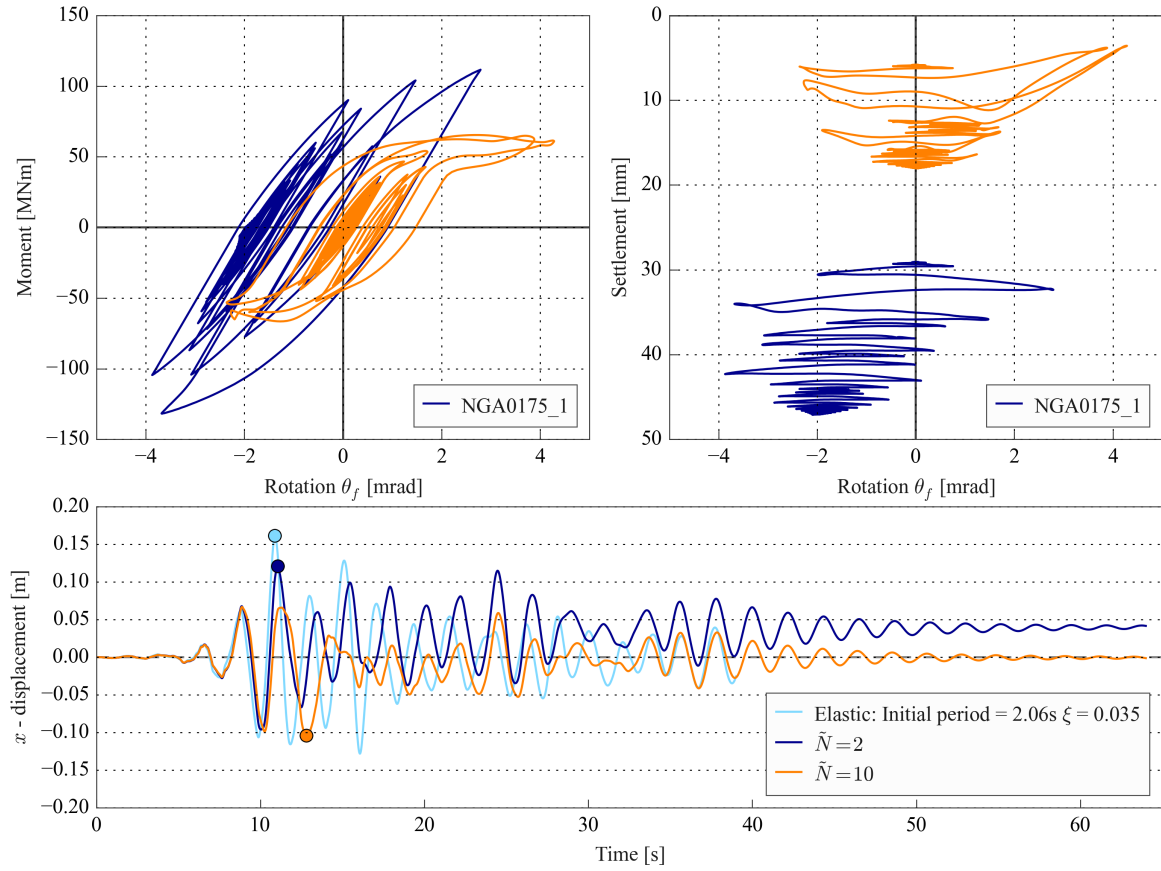


Figure 6 Behaviour of pier structures during the Imperial Valley 1979 ground motion

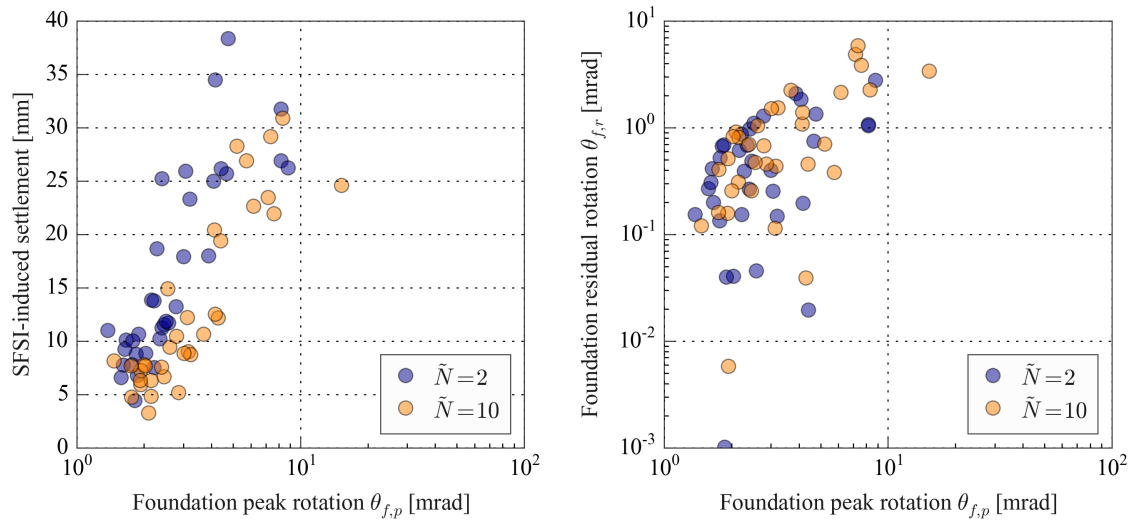


Figure 7. Residual foundation and peak rotation trends

Considering Flexible Foundations on Soil

The flexibility of the foundation is important to both the overall stiffness and the potential to induce additional stresses in the structure. Figure 8 considers the deformations in the foundation as three separate mechanisms and shows the stresses and deformations they cause in the structure.

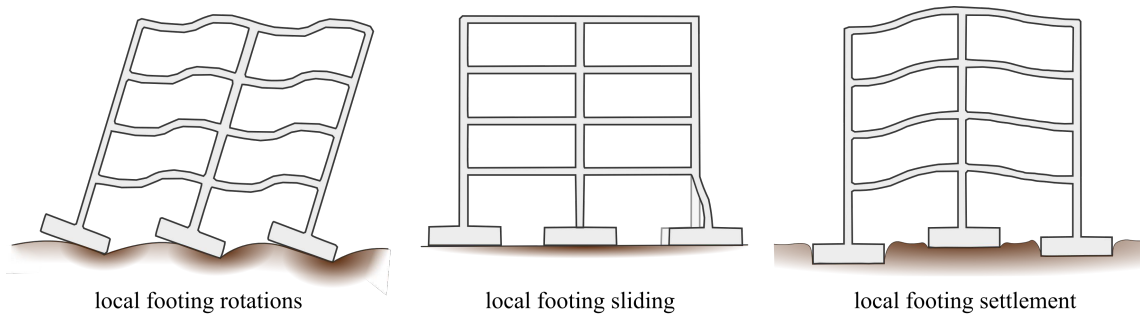


Figure 8: Flexible foundation deformations

In reality all deformations, both rigid-body and due to foundation flexibility, can be present, and the induced stresses can compound in some cases. The level of each deformation from each mechanism is governed by the geometry of the structure and its footings. Figure 9 considers two hypothetical frames to demonstrate this. The left frame has long thin footings, which have large rotational stiffness and small vertical stiffness; the right frame has short wide footings, which have small rotational stiffness but a comparatively high vertical stiffness. The two buildings have the same superstructure but under loading the internal moments that develop are noticeably different. The low vertical stiffness in the left frame limits the shear and moment demand that can be generated in the beams; while the low rotational stiffness in the right frame means that the moment is largely distributed to the top.

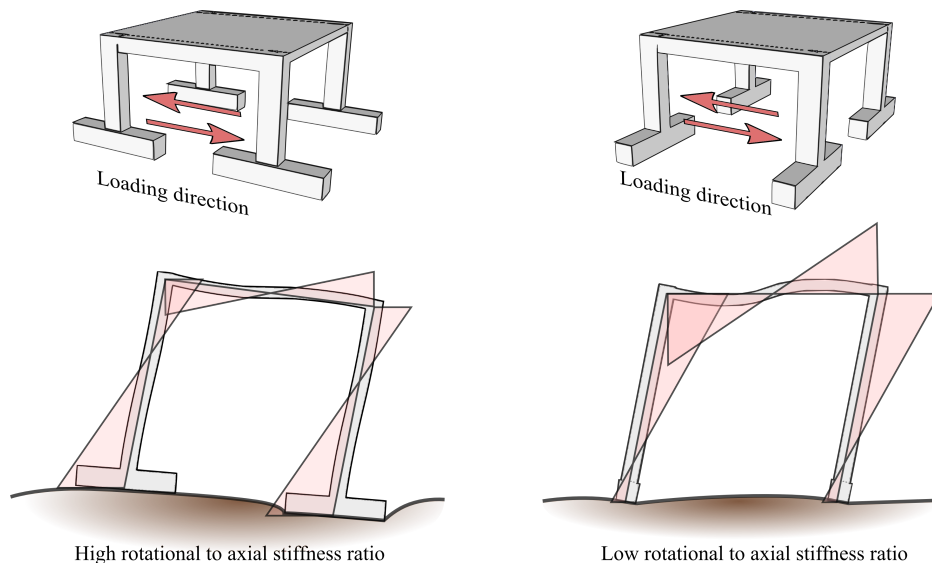


Figure 9: Variations in foundation rotational and vertical stiffness and corresponding displaced shape and moment demand

Case Study Frame Structures

The theoretical frames were numerically modeled (Figure 10 - left) and subjected to the Chi-Chi 1999 (CHY037) ground motion. The influence of the different footings is apparent in the moment demands (Figure 10 - right) in the frame. The moments in frame two (low rotational stiffness) are limited at the base due to the increased rotation of the footings. The ratio of moments between the column base and the beams is noticeably different, with more moment demand distributed to the beams for the footing with low rotational stiffness, as expected.

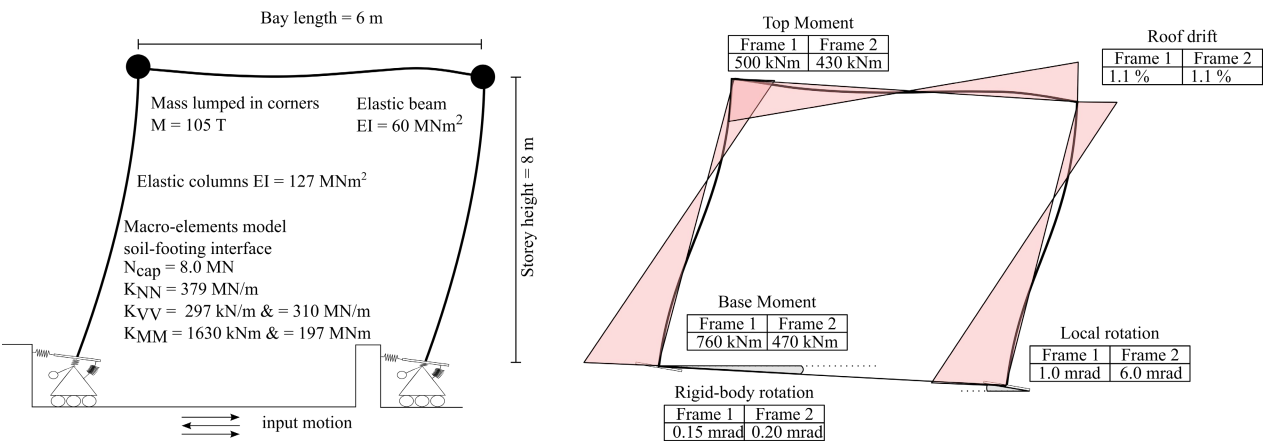


Figure 10. Left – Frame numerical model, Right – Frame moment demand and deformations

Figure 11 shows the deformation behaviour of the footings. The left footing moment-rotation behaviour shows the asymmetric behaviour that occurs due to the changes in the axial load through frame action. The cyclic increase in the footing axial load causes increased stiffness and moment capacity. The asymmetric behaviour can also be seen in the rotation-settlement response where the changes in axial load result in greater plastic/settlement response for increased axial load and greater tendency to uplift under reduced axial load. The cyclic axial loading also results in an up-down motion of footings, where the behaviour is more apparent in the high rotational stiffness frame as the shakedown effect is less prominent.

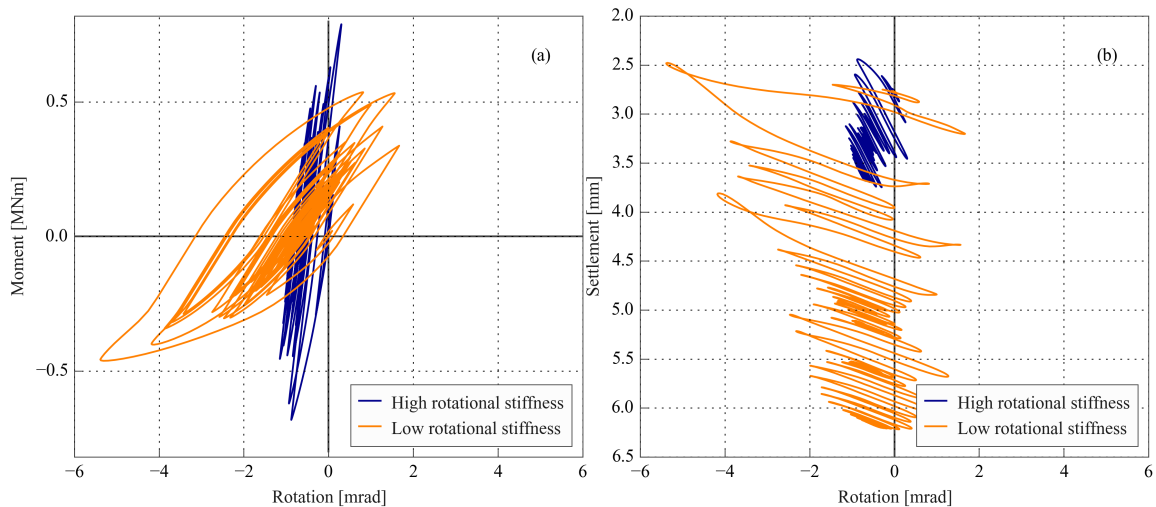


Figure 11 a) Left footing moment-rotation, b) Left footing settlement-rotation

Conclusions

This paper discussed the lack of SFSI considerations in current building and foundation design. The mechanisms of SFSI-induced settlement and residual rotation were investigated through simple pier structures. The effects of SFSI on frame structures were explored and the governing parameters were explained using two theoretical frame buildings, which were analysed using time history analysis. The development of performance-based design methods needs to recognise the modification of SFSI on the performance of buildings.

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