

3D modeling of masonry tower soil-structure interaction in OpenSees using mixed implicit-explicit material integration

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Abstract

This study aims to elucidate the possible relationship between foundation deformations and structural cracking, as well as to identify sources of hysteretic energy dissipation within the SSI of shallow-founded masonry structures. A virtual SSI laboratory has been developed by modeling the St. Maria Maggiore Cathedral's bell tower in the town of Guardiagrele, Italy. Analyses reveal that the foundation ratcheting can influence the accelerations experienced by the structure, presenting a trade-off between foundation deformations and structural damage. Increased plastic response in the foundation soil may mitigate structural response, and conversely, reduced foundation deformations may result in increased structural damage.

1. Introduction

Unreinforced masonry (URM) towers are part of the historical heritage and were often constructed as security structures or bell towers during the Renaissance period. They can be found as standalone edifices or as components of larger architectural complexes. The inherent brittleness of masonry renders tower structures particularly hazardous, as collapses can occur without warning and lead to catastrophic results.

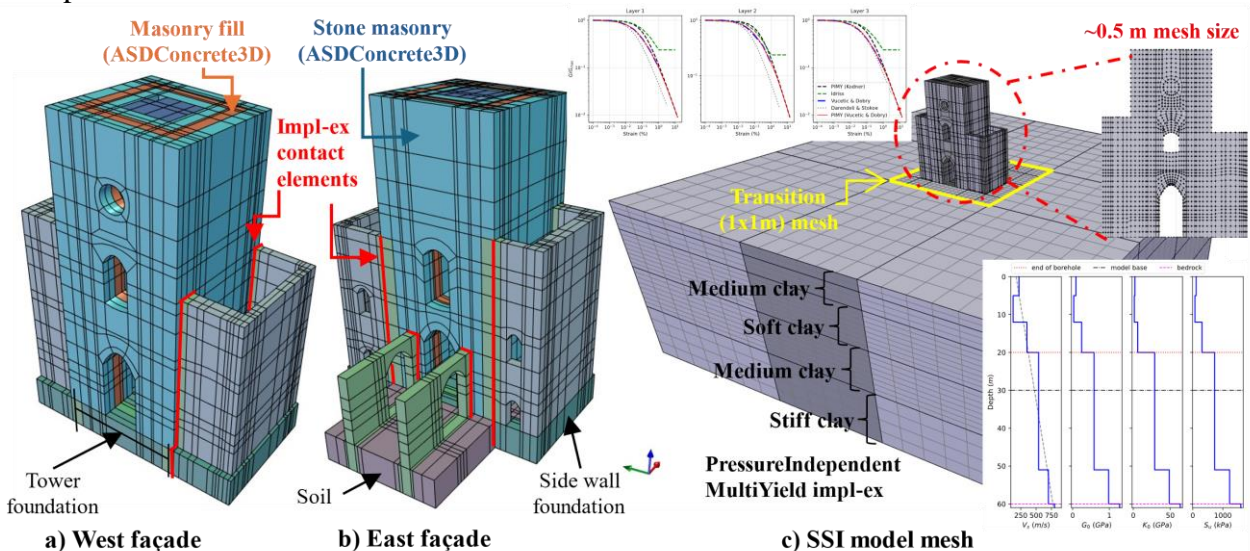


Figure 1. The virtual laboratory in STKO. The material distribution: a) West facade, b) East facade, and c) The meshed view of the SSI model: The soil profile and the G/G_{max} curves for each layer

The mechanisms that lead to the damage and collapse of masonry towers are still an open research question and require studying complex material, geometric, and interaction nonlinearities. Over the

years, the numerical investigation of various URM tower systems has received increasing attention from researchers [1]. The modeling of direct soil-structure interaction (SSI) for large structures and foundation size effects [2], indicates that SSI effects may significantly alter the response of stiff structures due to soil amplification, kinematic, or the inertial effects of an oscillating heavy body.

This study investigates the combined effect of cyclic damage-plasticity behavior in the masonry structures (i.e., the period shift) and stiffness reduction in the foundation soil on the system response. To achieve this, a virtual laboratory is prepared in OpenSees with the help of the STKO pre-processor. The bell tower and the cathedral of Guardiagrele are modeled considering the underlying soil profile up to the bedrock, the nonlinear material characteristics, and the pounding interaction between the bell tower and the church walls. A novel impl-ex contact element and the impl-ex version of the pressure-independent soil material are implemented in OpenSees to make the computation feasible and control the computational cost of running multiple analyses.

2. The modeling of the virtual laboratory

The structure is modeled with 8-node brick solid elements and consists of four separate bodies: the bell tower, the north and south church walls, and the rear church walls. Individual bodies are put in contact with each other using node-to-node ZeroLengthContactASDimplex elements. Contact elements model contact-separation and stick-slip behavior between these bodies during dynamic analysis using a highly stable impl-ex Mohr-Coulomb law [3]. The stone masonry and the fill materials are modeled using the ASDConcrete3D damage-plasticity material [4] (Figure 1). The capabilities of this model include tension-compression damage, fracture energy regularization and impl-ex integration. The soil behavior is modeled with the kinematic hardening PIMY material [5]. The undrained strength of layers is computed as a linear function of the undrained Young's modulus. Finally, the stress-strain backbone is calibrated to match the shear modulus reduction characteristics proposed by Vucetic and Dobry. The mesh size at the structure level is around 0.5m, whereas the soil mesh is tuned to capture a vertically propagating wave with a maximum frequency of 18 Hz. The foundation soil consists of 1x1x1m elements to prevent any size effects. The mismatching meshes are tied to each other using ASDEmbeddedNode elements. The model has around 240,000 elements and is solved in parallel using 24 partitions in OpenSeesMP.

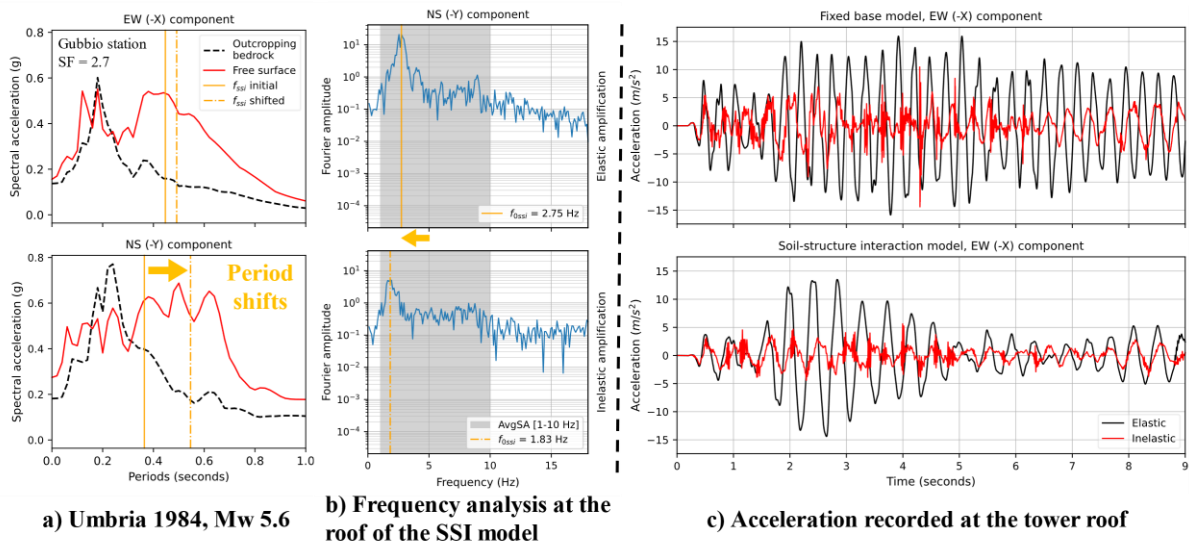


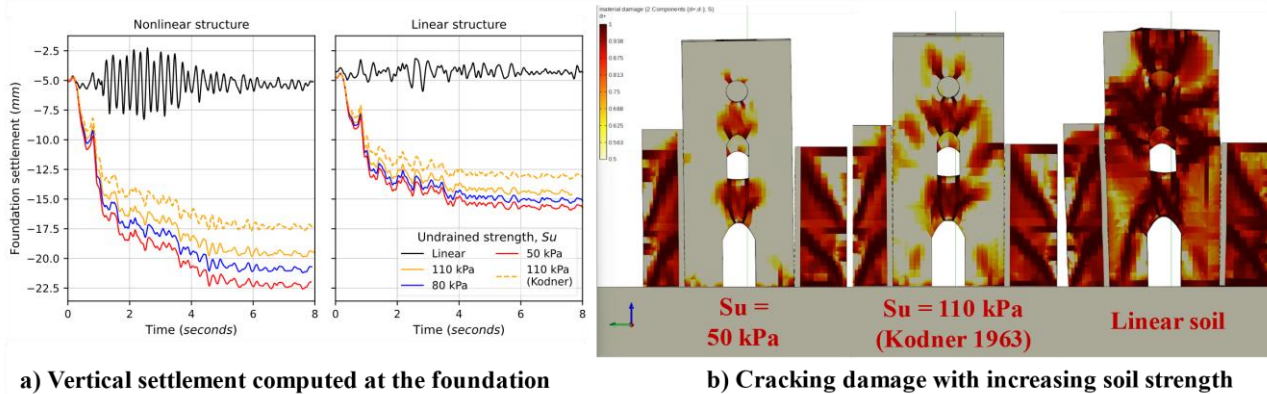
Figure 2. Dynamic response of the bell tower SSI system. a) The input and the amplified motion response spectra. b) Computed system frequency shift (N-S). c) Fixed base versus SSI roof accelerations.

3. Effect of foundation soil nonlinearity on the masonry damage pattern

The input motion is applied at the model base as force history in the SSI model, whereas the surface acceleration history is applied at the fixed base model (Figure 2a). As a result of impl-ex materials,

the solution always converges in two iterations. The results do not change significantly after decreasing the time step beyond the 1/4th of the seismic record sampling step.

In Figure 2c, the difference between the roof accelerations recorded in the fixed and SSI models is attributed to the two models' different fundamental periods, which are 0.29s and 0.44s for the EW direction, respectively. The SSI period is a result of elastic foundation rocking. In the fully linear model, the recorded roof displacements strongly match the foundation rotation angle times the tower height. Hence, the SSI behavior is chiefly governed by the foundation rotations with limited contributions from structural modes.



a) Vertical settlement computed at the foundation

b) Cracking damage with increasing soil strength

Figure 3. The effect of soil strength and stiffness reduction on a) foundation settlements and b) cracking damage. Moreover, structural nonlinearities lead to increased foundation deformations.

The detrimental effect of increasing soil strength is shown in Figure 3. However, the rate of stiffness reduction is the primary contributing factor. This is proved by comparing the “110kPa” curves in which the stiffness reduction is provided with a reduced rate in the default (Kodner) PIMY soil (Figure 1c). Finally, the nonlinear structure leads to increased settlements due to the shift in the fundamental period. This is due to softening in the foundation material and increased structural response. In Figure 2a, the structure NS initial period shifts towards amplified ranges once the cracking damage accumulates. The increased structural response amplifies settlements.

4. Conclusions

The foundation rotation in shallow-founded towers is identified as a significant factor determining the fundamental period of an SSI system. Furthermore, the rate of stiffness reduction in the foundation soil is shown to affect the damage patterns of a masonry tower. Finally, the inelastic period shift may trigger increased foundation response based on the spectral shape of the input motion.

5. References

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