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# Simplified method for modelling of compliant soil with comparison to experimental results

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## Abstract

Since numerical modelling of soil properties in seismic design of buildings is usually a complex and demanding task, practicing engineers and researchers aim to keep numerical models as simple as possible. Therefore, the goal of this research is to verify soil-structure interaction (SSI) modelling parameters for buildings founded on compliant soils. For this purpose, the results of a large-scale SSI experiment were considered. The TRISEE experiment was chosen as a reference since it is well known in the scientific community and commonly used by researchers. In the scope of this experiment, the SSI effects were determined on a simplified model of the superstructure, consisting of a rigid column and foundation slab placed on the sand bed subjected to dynamic loading. Based on these results a refined non-linear numerical model for SSI was developed, in which the soil behaviour was modelled through its stiffness, hysteresis model and p-y curve. The model was implemented in the SAP2000 numerical modelling software which is based on the finite-element method. It has been shown that numerical models represent experimental behaviour with a sufficient degree of accuracy. Since structural models exhibit different dynamic properties when placed on compliant soils, the authors recommend the implementation of SSI effects into the design of buildings in seismically active regions.

***Key words:*** soil-structure interaction, experiment, numerical models, finite element method, SAP2000

## 1 Introduction

Experimental research campaigns of soil properties and buildings structures usually involve meticulous planning, expensive equipment, and skilled staff. Due to their complexity and high costs they are not always feasible. However, experimental data provides crucial support in the verification of simpler, numerical models. This is especially important when analysing the effects of soil-structure interaction (SSI) on buildings in the case of seismic actions [1-3]. Experiments that include soil-structure interaction can be conducted statically or dynamically, but also in large or small scale. Considering significant costs of this type of experiments, small-scale experiments are most common. Most of the small-scale experiments are conducted in geotechnical centrifuges [4-7]. On the other hand, large scale experiments are commonly conducted using shaking tables [1, 2] or using large rigid tanks and static or cyclic loading [3, 8, 9]. Large scale experiments are encouraged [10] since this type of models describe behaviour of buildings more accurately. Further, research on buildings with shallow foundations on compliant soils is of great importance since a large number of buildings are built in this manner [11, 12].

One of the available large scale SSI experiments with a structure founded on compliant soils is TRISEE [9, 13-15]. A set of large-size experiments within the TRISEE project was designed to investigate the nonlinear behaviour of a structure with shallow foundation founded on compliant soil subjected to cyclic loading. More information regarding this experiment is provided in further chapters of this paper.

In order to study numerical modelling of SSI effects this study is composed. The main guideline for authors is to keep numerical models as simple as possible, therefore the soil component of the models is observed by existing general link elements commonly found in numerical software.

## 2 TRISEE experiment

Research of non-linear soil-structure interaction under simulated seismic loading was conducted within the TRISEE research project. The project was carried out in the late 1990s and comprised several different large-scale experiments. The structure model comprised of a rigid steel column and a slab representing typical shallow footing. The column was used to introduce simulated seismic loading into the model. Through the column horizontal force and overturning moment simulating the inertial loads were transmitted to foundations. The research programme included experiments conducted on dense and on loose sand with the relative density $D_r$ of 85 % and 45 %, respectively. Square footing of 1,0 x 1,0 m in plane was embedded to the depth of 1,0 m so that the overburden pressure was simulated. A large sand box, measuring 4,6 x 4,6 m in plan and 4 m in height (Figure 1. Experimental setup (m) [9], was constructed. Saturated Ticino sand was used to simulate the soil. Ticino sand is silica sand with uniform sized grains.

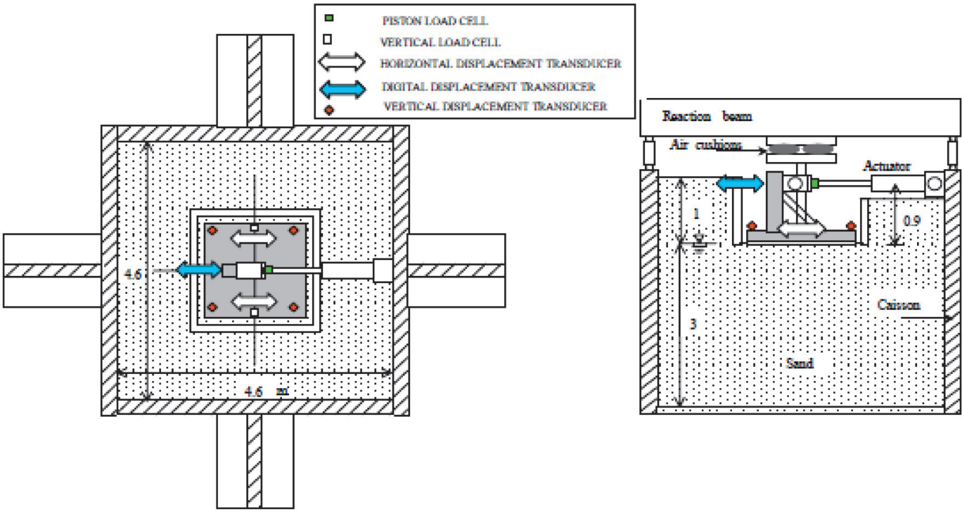

**Figure 1. Experimental setup (m) [9]**

The model founded on loosely built-in sand was loaded with 100 kN of vertical load, while the model founded on dense sand was loaded with a vertical force equal to 300 kN. In both cases, the vertical load applied was considerably lower than the soil bearing capacity. The vertical load was introduced to the model using air cushions and a reaction beam while the horizontal cyclic load was applied at the top of the column using a hydraulic actuator. The vertical load was firstly applied to the model as it represents the weight of the superstructure. After the full vertical load was applied, cyclic load was introduced to the model. The cyclic load was applied to the model in three series, starting with small amplitude force-controlled cycles in Phase I, followed by application of earthquake-like time history loading in Phase II and finished with sinusoidal displacement cycles of increasing amplitude.

Experimental model was observed by many different instruments. First group of instruments embedded into the sand was used for the assessment of the initial soil conditions. Following sensors were placed in the soil: 9 mini geophones which were used to measure saturation of the soil, 6 thermal and 6 electrical probes for the local check. Further, soil was tested by three cone penetration tests (CPT) performed by standard cone with 35,7mm diameter. Also, body-wave velocities were measured during the different phases of sample preparation. Second group of instruments was used for observation of the foundation. Applied forces, horizontal and vertical displacements of the foundation, total and effective soil pressures underneath the foundation were monitored. The following sensors were installed: 11 load cells for horizontal and vertical stresses in the soil, 2 mini-piezometers for measuring the water pressure, 5 pressure cells underneath the foundation, 4 vertical displacement transducers at the corners of the foundation to measure settlements and rotations, 2 horizontal transducers in the foundation, a digital transducer to measure the horizontal displacement of the actuator, 2 load cells for the vertical force and 1 load cell (in the piston) for the horizontal.

For this research the authors used the Phase II record and the setup comprising the structure founded on the loose sand.

## 3 Numerical modelling

In the scope of the research at hand, the model tested within the TRISEE project was modelled using finite element analysis software SAP2000 v21.0.2 [16]. The physical model of the structure was modelled using shell finite elements representing the foundation slab and frame elements representing the column. The loading curve recorded during the experiment was applied at the top of the column as the horizontal cyclic loading.

Multilinear plastic links were used to simulate the soil compliance in the vertical direction. The foundation model was supported by 25 identical link elements. Vertical stiffness of the soil was calculated according to Gazetas [17] and Mylonakis et al [18] which are presented in expressions 1-3. According to this proposal, the axial stiffness of the spring is a function of the soil's shear modulus (G), Poisson ratio ($\nu$) and geometry of the foundation strip (L,B) where L is half of the foundation strip length and B is half of the foundation strip width.

$$k_x = k_y - \frac{0{,}2 \cdot G \cdot L}{0{,}75 - \nu} \cdot \left(1 - \frac{B}{L}\right) \tag{1}$$

$$k_y = \frac{2 \cdot G \cdot L}{2 - \nu} \cdot \left[2 + 2{,}5 \cdot \left(\frac{B}{L}\right)^{0{,}85}\right] \tag{2}$$

$$k_z = \frac{2 \cdot G \cdot L}{1 - \nu} \cdot \left[0{,}73 + 1{,}54 \cdot \left(\frac{B}{L}\right)^{0{,}75}\right] \tag{3}$$

Multilinear links require information regarding the force-deformation backbone curve as well as the hysteresis type for the soil. The backbone curve was determined according to Rees and Van Impe [19]. A step-by-step procedure for backbone curve calculation in sand can be found in [20]. To simulate the hysteretic behaviour of the soil-foundation system the Takeda model [21] was chosen from the available hysteretic models in the software. The Takeda model was primarily developed for the purpose of modelling the response analysis of reinforced concrete structures, yet due to similar shape of the curve to sand response, it can be used for soil modelling. In recent years it has also been successfully implemented to model the nonlinear response of soils [22].

Compression part of the hysteresis loop is modelled by force-deformation (p-y) curve (Figure 2. Force deformation curve for link elements) while the tension part is neglected. It is important to stress out that usage of simplified modelling approaches leads to certain limitations, therefore, initial imperfections of the soil-structure system are not included in the numerical model as well as saturation of the foundation soil.

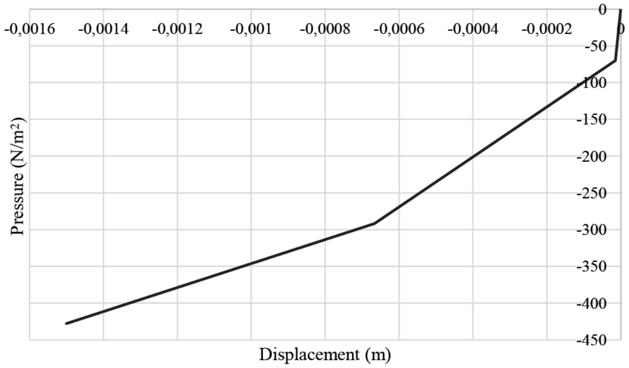

**Figure 2. Force deformation curve for link elements**

Gap elements and horizontal linear springs are assigned along the edges of the model. As the foundation model is symmetrical, both, the stiffness in x and y direction have the same properties (Figure 3. Scheme of the numerical model). Model was loaded with three different functions. Two functions simulated gravitational loading in the vertical direction and one function simulated seismic loading in the horizontal direction. The vertical load was applied directly on the foundation slab, while the horizontal load was applied at the top of the column. The recorded loading curve taken from the TRISEE experiment was imported to the numerical model as a Time history load.

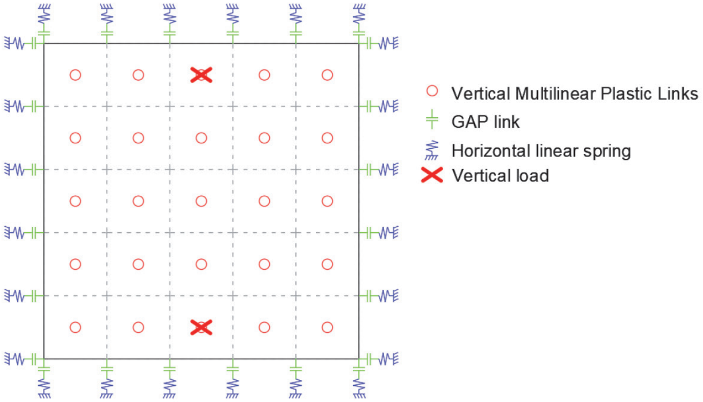

**Figure 3. Scheme of the numerical model of the foundation slab**

## 4 Results and discussions

Comparison of experimental and numerical results (Figure 4. Comparison of numerically and experimentally obtained data: (a) rocking angle-overturning moment; (b) time-rocking angle; (c) rocking angle-settlement; (d) time-settlement.) are presented through: (a) rocking angle-overturning moment curve; (b) time-rocking angle curve; (c) rocking angle-settlement curve and (d) time-settlement curve. Observing Figure 4. Comparison of numerically and experimentally obtained data: (a) rocking angle-overturning moment; (b) time-rocking angle; (c) rocking angle-settlement; (d) time-settlement. it can be concluded that rocking of the foundation in the numerical model matches well with the experimental results, although the settlement of the foundation shows difference in the numerical model (8,5 mm) and experiment (10,0 mm). Moreover, rocking of the foundation shows significant difference at the beginning until the plastfication of foundation soil is reached when the amplitude of rocking is matched well with the experiment.

A preliminary parametric study showed that numerical results are highly sensitive to both the shape of the force-displacement backbone curve and hysteretic model selected to simulate the soil behaviour. It is important to emphasise here that the structural model of the experimental setup was not fully horizontal when placed on the sand bed. It is assumed that tilting of the model resulted with plastification of the sand on one end of the foundation. Model was tilted by around 2 ° in the loading direction which resulted in horizontal shift of the top of the column by 3,33 mm. Implementation of the initial tilting in the numerical model would consider the adoption of additional assumptions, therefore, tilting was not implemented into the numerical model. Furthermore, numerical model describes model on dry sand in contrary to experiment with saturated soil under the foundation.

Figure 5. Horizontal displacement time history of the top of the column shows comparison between the numerical and experimental horizontal displacement of the top of the column. To exclude the tilting of the physical model, numerical results were shifted by 3,33 mm in the direction of the horizontal load.

After the occurrence of pronounced plastification, under the action of the maximum horizontal force, the numerical model well describes the behaviour of the experimentally tested model. In spite of all of the above, the hysteretic cycles in the moment-rocking angle, as well as rocking time-history and the vertical settlement (Figure 4. Comparison of numerically and experimentally obtained data:

- rocking angle-overturning moment
- time-rocking angle
- rocking angle-settlement
- time-settlement, describe the behaviour of the experimentally tested model with satisfactory accuracy.

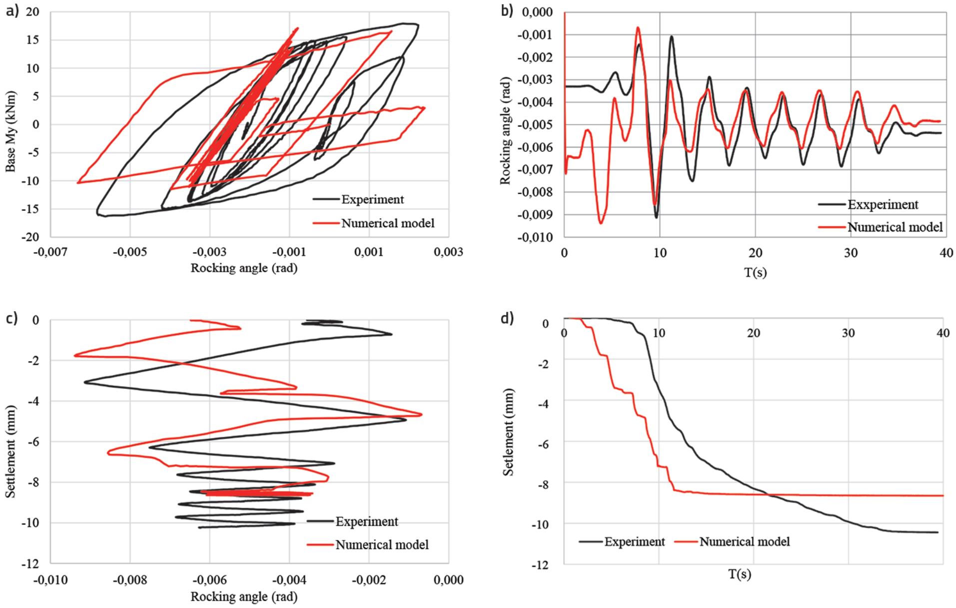

**Figure 4. Comparison of numerically and experimentally obtained data: a) rocking angle-overturning moment; b) time-rocking angle; c) rocking angle-settlement; d) time-settlement**

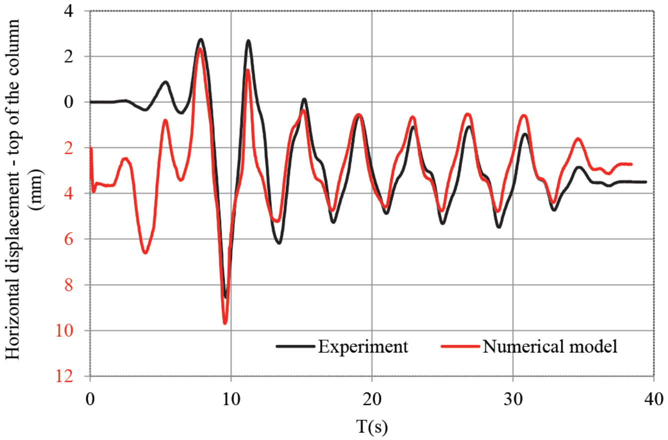

**Figure 5. Horizontal displacement time history of the top of the column**

## 5 Conclusion

This paper provides an attempt to simulate the seismic behaviour of soil-structure systems using a simple numerical model. A well-documented experimentally tested model was used to validate the numerical model. The physical model was experimentally tested within the TRISEE project. The physical model comprised of a relatively simple superstructure and a foundation slab. It was founded on a loose sand embedded in a large rigid tank and subjected to horizontal cyclic loading.

The soil-structure system was modelled adopting simplified approaches. The soil was modelled using multilinear link elements and the Takeda hysteretic model while the structure and foundation were modelled using elastic frame and shell elements, respectively. Simplified models present the advantage of inducing low computational costs.

This research shows that for the case of SSI simple numerical models can describe the overall behaviour of experimentally obtained data with a satisfactory level of accuracy in the light of rocking of foundation and energy dissipation in the soil. In contrary, settlement of the foundation soil and behaviour of the model in early stages – before plastification of the soil is achieved - contains larger discrepancies due to imperfections of the experimental setup that were not taken into account in the numerical model.

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