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# VALIDATION OF SIMPLIFIED METHODS FOR MODELLING OF SOIL WITH COMPARISON TO EXPERIMENTALLY TESTED SCALED MODEL

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**Abstract**

*A frequent dilemma in seismic design of buildings founded on soft soils is how to include soil compliance in numerical models. Although various international building codes propose methods for soil-structure interaction (SSI) modeling, common engineering practice is to model and design buildings as being fixed into the ground.*

*Different codes propose different methods for including SSI effects into the seismic design of buildings and they are mostly based upon impedance functions. Impedance functions serve as an efficient replacement for demanding soil models under buildings. Since codes from around the world use different expressions and different models for soil modeling, numerical research and parametric study on a scaled model of a two-dimensional frame is conducted in order to determine the efficiency of each tested method. To verify the efficiency of the tested methods, a numerical model was developed in which a frame model was subjected to nonlinear static pushover analysis. Results obtained from the numerical analysis are compared to the results obtained on the experimentally tested frame at the Laboratory for experimental mechanics at the Faculty of Civil Engineering and Architecture Osijek.*

**Keywords:** Soil-Structure Interaction, Numerical Research, Experiment, Soil Compliance, Norms

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## 1 INTRODUCTION

If the seismic map of the Europe is observed, it is clear that many European countries are endangered by earthquakes. Not so distant historic events provided us with knowledge on destructivity of earthquakes, especially if we observe structures that were designed without considering seismic loads. Nowadays European norms [1] propose several approaches in seismic resistant building design: (i) the "lateral force method of analysis" for structures with dominant first mode of vibration, (ii) the "modal response spectrum analysis" which is valid even for structures with higher mode effects (iii) nonlinear static (pushover) analysis and (iv) nonlinear time history (dynamic) analysis.

Also, considering that (i) almost 95 % of the world's total building fund comprises low and medium rise buildings [2], and (ii) that people in earthquake-active areas of Europe live in reinforced concrete buildings that are up to 20 floors height ($T_1 < 2$ s), it is clear that there is a great need to check the safety of such structures with regard to possible effects of soil and structure interactions. In addition, papers that report on the effects of actual earthquakes on structures [3,4] show that particularly 4-storey buildings are highly sensitive to the earthquake loads. It is common that this type of buildings incline or turn-over while the structural elements remain completely undamaged [10], i.e. in its elastic range of behavior.

In engineering practice and academia, it is common to assume that structures are fixed into a non-deformable medium. On the other hand, it is well known that the behavior of structures is affected by the deformability of the media below them [9],[14]. Theoretically, only buildings founded on rock can be considered fixed into the ground, while the shallow-founded structures on compliant soils can lean in translational, rotate in torsional direction or sway. American guidelines for design of buildings [5] propose that fixed numerical models are unsuitable for assessment of seismic behavior of shallow founded buildings with very stiff elements. Recent research [6] has shown that soil-structure interaction effects are more pronounced in buildings with first period of oscillation lower than 0,6 s. Although, this field is yet not fully investigated, there are many researchers who studied the importance of including the soil compliance into the seismic response of the buildings [7-9].

Hitherto, it is still not sufficiently clear how the soil's compliance affects the non-linear earthquake behavior of shallow-founded buildings, enabling plasticizing of vertical bearing elements. While norms indicate that structures are not allowed to have shallow foundations when built on soft soil, recent studies show that soil compliance can have a favorable effect on structural behavior in terms of their protection [6,7,10-13]. Rocking of shallow-based structures on the ground can create a mechanism for the dissipation of seismic energy and consequently reduce earthquake effects on the structure [12]. Also, damping of the foundation soil can affect the reduction of the required ductility in the structure [12]. Among other things, it has been demonstrated [15] that incorporating the soil-structure interaction effects in seismic analyses provides more economical structures.

As there are different suggestions on incorporating soil compliance into numerical models, numerical research and parametric study for a two-dimensional plane frame is conducted. An experimental analysis on a scaled 2D frame model subjected to nonlinear static (pushover) analysis was performed. Two-dimensional model and pushover analysis were chosen for the experimental research considering limitations of the laboratory, also, pushover analysis is good replacement for the time-consuming and expensive time history analysis. The results were verified by numerical models, incorporating different types, distribution and number of supports (linear springs). Results of the numerical analyses are presented by the use of capacity curves and compared to experimental results for the equivalent physical model tested on a sand bed.

## 2 REVIEW OF APPROACHES FOR THE MODELLING OF SOIL

This chapter is composed of reviewed norms and guidelines for soil modelling in numerical models. Chapter includes recommendations for European and American practice for modelling of shallow founded buildings on compliant soil.

### 2.1 Eurocode 8

European codes for seismic design [1] still do not have detailed procedures for modeling of soil for numerical models. Eurocode 8 provides that soil-structurer interaction effects will result in: (i) different foundation motion of the flexibly-supported structure when compared to a fixed base counterpart, (ii) longer fundamental periods of flexibly supported structure, (iii) different natural periods, mode shapes and modal participation factors and (iv) different overall damping.
Also, Eurocode code proposes that the effects of dynamic soil-structure interaction shall be taken into account for structures: (i) with significant effect of P-Δ effects, (ii) with massive or deep-seated foundations, (iii) which are slander and tall and (iii) supported on very soft soils with average shear wave velocity less than 100 m/s. Although there are instructions for the need on inclusion of SSI effects, there are no suggestions on exact procedures and numerical models.

### 2.2 NIST (National Institute of Standards and Technology)

NIST [18] addresses fundamental questions regarding SSI effects in seismic analysis. In this guideline, approaches for including SSI effects are divided regarding the type of foundations and the soil under the structure. Equations (1-6) are related to foundations placed freely on the ground. When the soil is included into the design of the building, few properties need to be determined in order to calculate the springs. First of all, dimensions of the shallow foundation have to be defined in order to calculate contact area between the foundation and soil. Second, soil stiffness is represented via shear modulus and Poisson ratio.

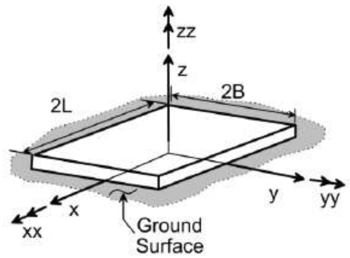

Figure 1: Geometry of the foundation [18]

Following equations proposed in NIST [18] are developed by Gazetas [23] and Mylonakis et al. [14] for Equations (1-3) and Pais and Kausel [24] for Equations (4-6).

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

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

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

$$k_x = \frac{G \cdot B}{2 - \nu} \cdot \left[6{,}8 \cdot \left(\frac{L}{B}\right)^{0{,}65} + 2{,}4\right] \tag{4}$$

$$k_y = \frac{G \cdot B}{2 - \nu} \cdot \left[6{,}8 \cdot \left(\frac{L}{B}\right)^{0{,}65} + 0{,}8 \cdot \left(\frac{L}{B}\right) + 1{,}6\right] \tag{5}$$

$$k_z = \frac{G \cdot B}{1 - \nu} \cdot \left[3{,}1 \cdot \left(\frac{L}{B}\right)^{0{,}75} + 1{,}6\right] \tag{6}$$

In Equations (1)-(6) $G$ is representing the shear modulus of the soil, $\nu$ is Poisson ration, $L$ is half of the length of the foundation, while $B$ is half of the width of the foundation as showed in Figure 1.

### 2.3 ASCE (American Society of Civil Engineers)

Selected method for SSI design must reflect key characteristics of the foundation-soil system which are: (i) the shape of foundation-soil interface, (ii) the amount of embedment, (iii) the nature of the soil profile and (iv) the mode of vibration and the frequency of the excitation.

ASCE [19] provide two different methods for SSI modelling. First method is based on spring stiffness formulas developed by Pais and Kusel [24] presented in Equations (4)-(6) for foundations on surface.

On the other end, second method uses different springs for different areas under the foundation as shown in Figure 2, this method should be used for rigid foundations. Spring stiffness is presented with equations 7 and 8 where $G$ is representing the shear modulus of the soil and $\nu$ is Poisson ratio. Since the second method does not include horizontal stiffness of the soil, horizontal spring from the first method was used.

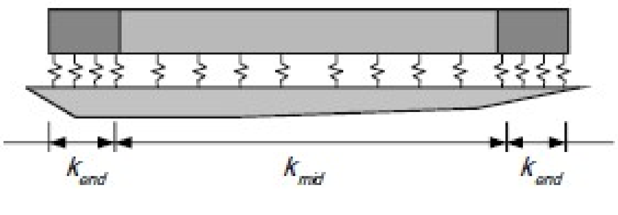


Figure 2. Springs distribution [19]

$$k_{end} = \frac{6{,}83 \cdot G}{1 - \nu} \tag{7}$$

$$k_{mid} = \frac{0{,}73 \cdot G}{1 - \nu} \tag{8}$$

### 2.4 FEMA (Federal Emergency Management Agency)

FEMA [5] proposes spring stiffness calculations according to Wolf [20]. Here are only horizontal and rotational springs and dashpots provided. For the purpose of providing numerical results, sliding supports were attached to model foundation and the horizontal stiffness is calculated using Equation 9.

$$k_x = \frac{8 \cdot G}{2 - \nu} \sqrt{\frac{A_f}{\pi}} \tag{9}$$

## 3 EXPERIMENTAL RESEARCH

Within the ongoing scientific research project PENDULARUM 15-04 which is being carried out at the Faculty of Civil Engineering and Architecture Osijek, Croatia, soil-structure interaction effects on the performance of the model are being investigated. Testing of models is done by using a reactive RC wall (8,60 m long, 3,90 m high, 0,80 m thick) and reactive RC slab (17,12 m long, 8,60 m wide, 1,00 m thick). Structural model (Figure 3) comprises three columns (b/h=20/30 mm) 400 mm high that are weakened on their top and bottom in order to force hinging. Moment of plasticization ratio for the weak and regular cross section is around 1:3. Columns are connected to the rigid beam and rigid foundation using bolts. Experimental model is 1:7,5 scaled version of a frame geometry (height and spam) similar to frame extracted from building analyzed by Kilar and Koren [21].

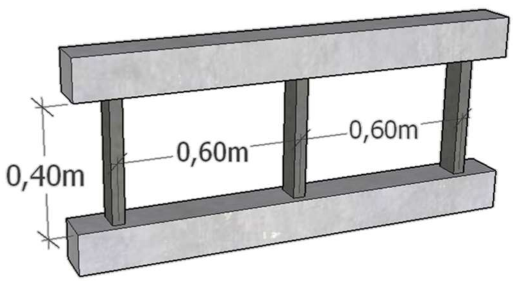


Figure 1: Physical model of the structure

The top mass of the model is 380 kg, total mass of the columns was around 10 kg while the foundation mass is 100 kg. The model is positioned in the container freely on the sand. Foundation beam was 1,34 m long with cross section of 120 x 120 mm while the area withstanding the soil in longitudinal direction was enlarged to be 590 x 120 mm. After placing the model on the sand, sand was embedded to align with the top of the foundation. Container is 6,00 m long, 0,60 m wide and 1,30 m tall (Figure 4).

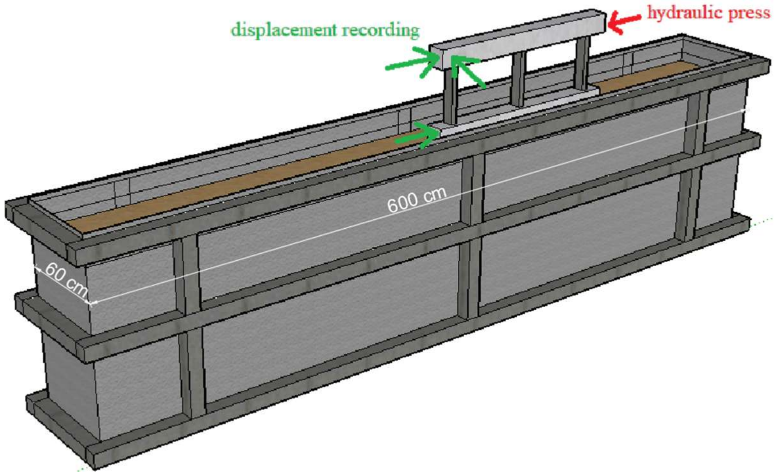


Figure 4: Container model showing proposed place for the structure

The sand used for this experimental research was local sand and it was homogenously embedded into the container. Detailed data regarding the properties of this local sand will be shown in some of the future publications. Accelerometers were placed inside of the sand volume as well as on the model. Also, instruments for measuring the displacement were placed on the model in order to measure translation and rotation of the model. The model (Figure 5) was pushed using a 10 kN capacity press attached to the reactive wall.

Figure 5: Experimental setup with the model on sand

## 4 NUMERICAL MODEL

For the purpose of this research, methods for soil modelling provided in various codes and guidelines were used. The soil was modelled with density of 1550 kg/m$^3$ with shear wave velocity 135 m/s. Poisson ratio that was chosen for this type of sand is 0,3. All the information regarding the geometry of the foundation are provided in Chapter 3. Models of soils as described in Table 1 are used in numerical models representing the experimental soil-structure setup.

| Soil model ID | Description |
|---|---|
| NIST-G&M | NIST guidelines based on Gazetas and Mylonakis expressions |
| NIST-P&K | NIST guidelines based on Pais and Kausel expressions |
| ASCE-equal | ASCE guidelines based on Pais and Kausel expressions |
| ASCE-zonal | ASCE guidelines for rigid foundations |
| FEMA | FEMA guidelines according to Wolf |

Table 1: Soil model ID and description

Numerical models were made using SAP2000 software [22]. Columns were modeled as frame elements divided in 5 parts consisting of full cross section and the hinge cross section in order to suit the real model. Plastic hinges were modelled using hinges for steel columns while the plasticization moment and Euler buckling force were added manually for every hinge separately. Rigid beam is modeled as frame element with adjusted density in order to simulate the mass on the model. Foundation beam was modeled as rigid with high elasticity modulus. Under the foundation beam, elastic springs were placed according to guidelines. The model was taken and analyzed as two-dimensional model since in the experiment model was forced to act as a two-dimensional model. Pushover analysis was performed with 80% of the horizontal force applied to the beam while 20% of the horizontal force was applied to foundation.

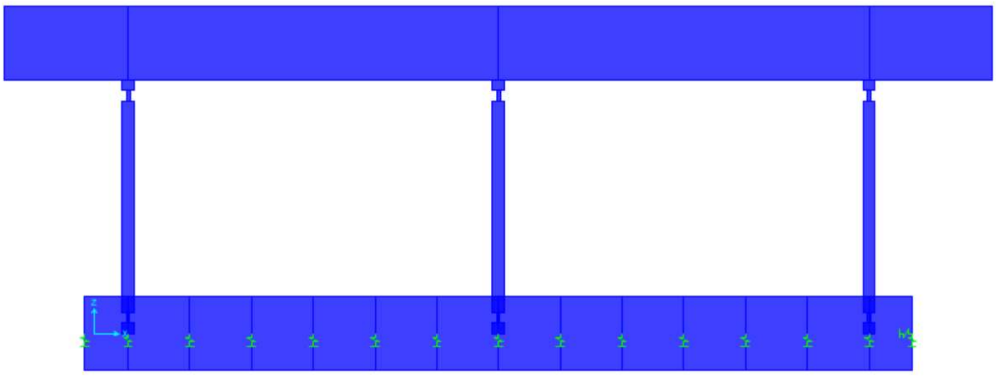

Figure 6: Numerical model with springs under foundation

## 5 RESULTS

In this chapter, results from the experimental research are compared to the results from the numerical models made according to recommendations from the guidelines. It is important to emphasize that numerical models were not calibrated, therefore, this chapter can be interpreted as a blind prediction of the behavior of the experimental model on sand.

One can conclude that results showed in Figure 7 show good match between the experimental results and the numerical models, although the results gained via numerical analysis show lower capacity, which means that they are on the safe side. It is also observed that model with springs determined with FEMA guidelines have lower initial stiffness but it reaches the same capacity as other models, it is important to remember that this model does not have vertical springs but sliding supports and one horizontal spring. Various numerical models provide similar results since the use of the same approaches from the same researchers.

Overall, it is shown that stiffness of the experimentally tested model is lower when compared to numerical models, while the overall capacity of the experimentally tested model is 5%

higher than of numerical models. Also, it is important to notify that code proposed spring stiffnesses are developed for full scale models/structures which can affect the overall results significantly.

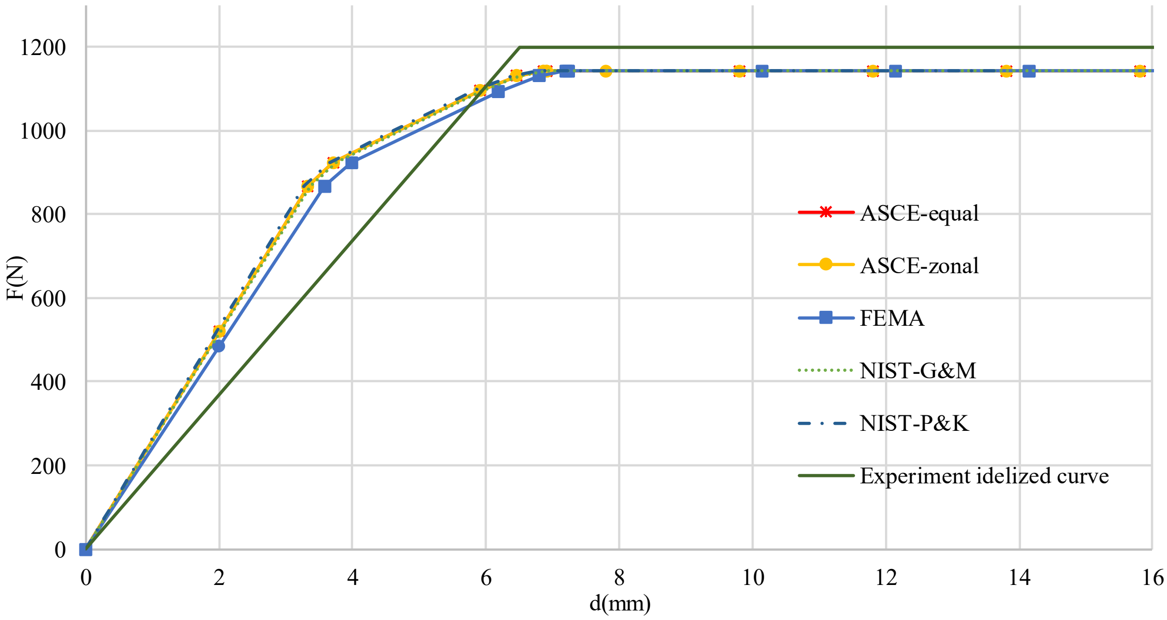


Figure 7: Comparison of the numerically and experimentally gained results

## 6 CONCLUSION

Implementing the soil effects into the seismic design of buildings shows differences in building performance. In engineering practice and academia, it is common to assume that structures are fixed into a non-deformable medium. On the other hand, it is well known that the behavior of structures is affected by the deformability of the media below them. This paper is considering proposed approaches found in NIST, ASCE and FEMA while comparing the numerical results with the results from experimental research. A two-dimensional frame model was modelled in SAP2000 software using frame and area elements with plastic hinges on the places where experimental model was weakened.

When the comparison of the results from the experimental research is observed, first thing that is noticed is difference in initial stiffness of the model and the overall capacity of the experiment. Higher stifness of the numerical models can be the result of use of inadequate spring models for the soil. Further research should be done for the purpose of finding the spring model more suitable for this type of experimental research. Also, tri-linear idealization of the experiment capacity curve should be considered for further comparison of the results.

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