Numerical analysis in SCAD Office of the Soil-Structure Interaction importance

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Abstract. The purpose of the research is to determine the scope of civil engineering design tasks to decide whether it is necessary to take into account the Soil-Structure Interaction (SSI) effects in seismically active regions. The analysis of SSI effects’ significance was carried out by two methods with very close results. It indicates the need to account not only the effect of the soil motion on the structure, but also the reverse effect of the structure oscillations on the soil motion. The presence of the inverse effect introduces changes in the soil motion as compared to the free field motion of the ground surface with the same seismic conditions. This leads to the fact that free field motion accelerograms should be adopted to appropriate stress conditions, the depth of the foundation bottom and modified stiffness of the subgrade.

1. Introduction
The purpose of the research is to determine the scope of civil engineering design tasks and decide whether it is necessary to take into account the Soil-Structure Interaction (SSI) effects in seismically active regions [1]. This check should be recommended for the implementation of the combined asymptotic method of analysing platform models "Structure–Absolutely rigid base plate – Soil" for civil buildings in the structural analysis program SCAD. In the present engineering practice, the combined asymptotic method is commonly used in the design of nuclear power facilities [2].

2. The Facilities of the research
2.1. The analyzed structures
Authors used in the research several monolithic reinforced concrete buildings with a cross-wall system, identical in plan (Figure 1), but with different number of floors (from five to 25). The characteristics of the analyzed structures are presented in Table 1.
Table 1. Characteristics of the analyzed structural models.

| Number of floors | Mass of the building, t | Length of the building slab, m | Width of the building slab, m |
|------------------|------------------------|-------------------------------|-------------------------------|
| 5                | 3620                   |                               |                               |
| 10               | 7250                   |                               |                               |
| 15               | 10880                  | 27.9                          | 16.2                          |
| 20               | 14510                  |                               |                               |
| 25               | 18140                  |                               |                               |

2.2. The studied types of soil

Four types of homogeneous soil half-space are used corresponding to four classes of seismic wave velocity types. The ratios $\delta$ (1) of primary wave velocity $V_p$ to shear wave velocity $V_s$ are taken from Table 1* of the Russian Design Code SP 14.13330.2014 Construction in Seismic Areas.

![General view and the common floor plan of the analysed multi-storey buildings.](image)

Table 2 presents the dynamic soil characteristics, necessary for the analysis. The Young modulus, Poisson’s ratio and shear modulus are calculated from formulas (2)-(4) taken [1]:

$$\delta = \frac{V_p}{V_s} \quad (1);$$

$$E = \rho \cdot V_s^2 \cdot \frac{3 \cdot \delta^2 - 1}{\delta^2 - 1} \quad (2);$$

$$\nu = \frac{\delta^2 - 2}{2 \cdot (\delta^2 - 1)} \quad (3);$$

$$G = \rho \cdot V_s^2 \quad (4).$$

Table 2. Soil characteristics for the homogeneous half-space.

| Type of ground base soil | $V_s$, m/s | $V_p/V_s$ | $\rho$, t/m$^3$ | Young modulus E, kPa | Poisson’s ratio $\nu$ | Shear modulus G, kPa |
|-------------------------|------------|-----------|----------------|----------------------|----------------------|----------------------|
| Soil 1                  | 700        | 1.7       | 2              | 2 421 482            | 0.24                 | 980000               |
| Soil 2                  | 400        | 2.2       | 2              | 876 667              | 0.37                 | 320000               |
| Soil 3                  | 200        | 5.3       | 2              | 237 047              | 0.48                 | 80000                |
| Soil 4                  | 100        | 11        | 2              | 59 833               | 0.50                 | 20000                |
3. Methods of the SSI-effects’ significance analysis

3.1. The first analytical method

The first analytical method was published in the work of the Japanese authors Osawa, Kitagawa and Iri. Later it was described in detail by A. Uzdin [3, 4]. The proposed approach makes it possible to evaluate the reverse influence of the structure on the soil motion as a SSI effect based on the analytic preliminary parameters of the structure and soil. These parameters include dimensionless resonance frequency of the structure $a_0$ (5), dimensionless mass ratio of the structure $m_0$ (6) and the ratio between the horizontal stiffness and the rocking stiffness of the rigid stamp resting on the soil $\chi$ (7):

$$a_0 = \frac{\omega \cdot r}{v_2}; \quad m_0 = \frac{m}{\rho \cdot r^2} \quad (6); \quad \chi = \frac{K_s \cdot h^2}{K_v} \quad (7),$$

where $\omega$ is the dominant frequency of the structure on the rigid foundation; $r = \sqrt{\frac{F}{\pi}}$ is the equivalent radius of the foundation slab, where $F$ – slab area; $\rho$ is soil mass density; $K_s$ and $K_v$ – horizontal and rocking stiffness of the rigid stamp on the soil; $h$ is the distance from the base bottom to structural center of gravity; $v_2$ is the shear wave velocity $V_s$.

According to the first analytical method, one should determine the region in the figure with corresponding parameters $a_0$ and $m_0$ of the Soil-Structure model using the graphs presented in the primary sources (Figure 2). The importance of accounting for the SSI effects depends on the particular region in Figure 2. In the first and in the second regions, the SSI effects should not be considered. In the third and sixth regions, the SSI effects are always significant. In the fourth and fifth regions, SSI effects could be important if $\chi < \chi^*(a_0)$.

![Image](image1.png)

Figure 2. Semiempirical diagrams of the areas with significant and insignificant SSI effects.

The results of the calculation according to the first method are shown in Figure 3. A colored point with a double numerical designation denotes each structural model in the diagram. The first number corresponds to the number of floors, the second number to the soil type. According to this method the SSI effects are not significant for the 15-, 20-, 25-storey buildings with the first soil type and for the 20-, 25-storey buildings with the second soil type. For other cases the SSI effects are significant.

3.2. The second analytical method

According to the second method, regulated by the American Standard for Nuclear Power Facilities ASCE 4-98, the SSI effect is significant if the dominant frequency for the flexible soil under the rigid structural model is not more than two times the dominant frequency of flexible structural model on rigid soil [2]. The formulae for the calculations of the lumped soil springs stiffness are presented in Table 3.
Table 3. Parameters for soil springs and dampers calculation for rectangular foundation slab.

| Structure motions | Equivalent spring constants | Equivalent damping coefficients |
|-------------------|-----------------------------|---------------------------------|
| Horizontal        | $k_x = 2 \cdot (1 + \nu) \cdot G \cdot \beta_x \cdot \sqrt{B \cdot L}$ | $c_x = 0.576 \cdot k_x \cdot R \cdot \sqrt{\rho / G}$ |
|                   | $R = \sqrt{B \cdot L / \pi}$ |  |
| Rocking           | $k_\psi = \frac{G}{1 - \nu} \cdot \beta_\psi \cdot B \cdot L^2$ | $c_\psi = 0.30 \cdot \frac{k_\psi \cdot R \cdot \sqrt{\rho / G}}{1 + B_\psi}$ |
|                   | $R = \frac{\sqrt{B \cdot L^3}}{3 \cdot \pi}$ |  |
| Vertical          | $k_z = \frac{G}{1 - \nu} \cdot \beta_z \cdot B \cdot L^2$ | $c_z = 0.85 \cdot k_z \cdot R \cdot \sqrt{\rho / G}$ |
|                   | $R = \sqrt{B \cdot L / \pi}$ |  |
| Torsion           | $k_t = 16 \cdot G \cdot \frac{R^3}{3}$ | $c_t = \frac{\sqrt{k_t \cdot I_t}}{1 + 2 \cdot I_t / \rho \cdot R^3}$ |
|                   | $R = \frac{\sqrt{B \cdot L \cdot (B^2 + L^2)}}{6 \cdot \pi}$ |  |

Here $\nu$ is the Poisson’s ratio of soil; $G$ is shear modulus; $R$ is the radius of equivalent circular basement; $\rho$ is the mass density of foundation medium; $B_\psi = 3(1-\nu)I_1/8\rho R^3$; $I_0$ is the total mass moment of structural inertia about the rocking axis at the base; $I_t$ is the polar mass moment of structural inertia; $B$ is the width of the basement in the direction of horizontal excitation; $L$ is the length of basement in the direction of horizontal excitation; $\beta_x, \beta_\psi, \beta_z$ are the constants that are functions of the dimensional ratio $L/B$ and are determined by diagrams in Figure 4. The lumped spring stiffness constants calculated for each soil type are presented in Table 4.

The dominant frequencies of rigid structures on flexible soil represented in the model by soil springs could be calculated by formulae in Table 5.

Dominant frequencies of the fixed-base buildings determined by the modal analysis of the structural models in the structural analysis program SCAD are presented in Table 6.
Figure 4. Constants $\beta_x$, $\beta_y$, and $\beta_\psi$ for rectangular foundation slabs.

Table 4. Equivalent lumped spring constants for the middle of rectangular foundation slab.

| Soil springs constants | Soil 1       | Soil 2       | Soil 3       | Soil 4       |
|------------------------|--------------|--------------|--------------|--------------|
| $k_x$, kN/m            | 5.15 E+07    | 1.86 E+07    | 5.04 E+06    | 1.27 E+06    |
| $k_y$, kN/m            | 5.41 E+07    | 1.96 E+07    | 5.29 E+06    | 1.34 E+06    |
| $k_z$, kN/m            | 6.00 E+07    | 2.37 E+07    | 7.22 E+06    | 1.86 E+06    |
| $k_{xy}$, kNm          | 9.38 E+09    | 3.71 E+09    | 1.13 E+09    | 2.90 E+08    |
| $k_{yz}$, kNm          | 4.51 E+09    | 1.78 E+09    | 5.42 E+08    | 1.39 E+08    |

Table 5. Soil dominant frequencies under the rigid structure.

| Ground base motions | Frequency, Hz |
|---------------------|---------------|
| Horizontal $X$      | $f_x = \frac{1}{2 \cdot \pi} \sqrt{\frac{k_x}{m}}$ |
| Horizontal $Y$      | $f_y = \frac{1}{2 \cdot \pi} \sqrt{\frac{k_y}{m}}$ |
| Vertical $Z$        | $f_z = \frac{1}{2 \cdot \pi} \sqrt{\frac{k_z}{m}}$ |

Table 6. Dominant frequencies of the fixed-base multi-storey buildings.

| Number of floors | $f_x$ | $f_y$ | $f_z$ |
|------------------|-------|-------|-------|
| 5                | 9.9   | 11.37 | 34.12 |
| 10               | 4.51  | 4.64  | 21.74 |
| 15               | 2.78  | 2.49  | 12.39 |
| 20               | 1.89  | 1.56  | 9.65  |
| 25               | 1.37  | 1.06  | 7.83  |

The ratios of the dominant frequencies for the analyzed structural models are presented in Table 7. According to these results the ratios for all models do not exceed the level of two for vertical motions; and for the 5-storey building they do not exceed the level of two for all directions of motion. Thus, according to the second analytical method the SSI effects are significant for all cases.
Table 7. The second method results with significant SSI effects (colored by green).

| Number of floors | Soil 1 | Soil 2 | Soil 3 | Soil 4 |
|------------------|--------|--------|--------|--------|
|                  | $f_{x1}$ | $f_{y1}$ | $f_{z1}$ | $f_{x2}$ | $f_{y2}$ | $f_{z2}$ | $f_{x3}$ | $f_{y3}$ | $f_{z3}$ | $f_{x4}$ | $f_{y4}$ | $f_{z4}$ |
| 5                | 1.92   | 1.71   | 0.6    | 1.15   | 1.03   | 0.38   | 0.6    | 0.54   | 0.21   | 0.3    | 0.27   | 0.11   |
| 10               | 2.97   | 2.96   | 0.67   | 1.79   | 1.78   | 0.42   | 0.93   | 0.93   | 0.23   | 0.47   | 0.47   | 0.12   |
| 15               | 3.94   | 4.51   | 0.95   | 2.37   | 2.71   | 0.6    | 1.23   | 1.41   | 0.33   | 0.62   | 0.71   | 0.17   |
| 20               | 5.02   | 6.23   | 1.06   | 3.02   | 3.75   | 0.67   | 1.57   | 1.95   | 0.37   | 0.79   | 0.98   | 0.19   |
| 25               | 6.19   | 8.2    | 1.17   | 3.72   | 4.93   | 0.74   | 1.94   | 2.56   | 0.41   | 0.97   | 1.29   | 0.21   |

4. Comparative analysis of the two methods’ results

The comparison of the calculation results in two methods is presented in Table 8. For the first method, the signs "+" and "-" denote the significance and insignificance of the SSI effects. For the second method, the Table 8 contains the ratios of the horizontal dominant frequencies of rigid structures on soil springs to the dominant frequencies of fixed-base flexible structures.

Horizontal motions for the multi-storey buildings in two methods show very close results. This fact demonstrates that the Japanese authors made the major emphasis on horizontal motions only, with vertical motion excluded from their consideration. If one considers the SSI-effects essential using the threshold value of ratio $\frac{f_u}{f_{x0}}$ at the level of three (instead of two in the ASCE) for the second method, the results would be identical for both methods (see the cells in Table 8 marked by blue color and by bold slant text). It means that the Japanese authors’ criteria of the SSI effect significance is more conservative than in the ASCE 4-98 method.

5. Conclusion

Twenty structural models with different number of floors and on four homogeneous soil half-spaces were considered. Two analytical methods gave similar conclusions about the importance of the SSI effect significance for 12 models or in 60% of all cases. Moreover, the analysis shows very close results for 15 models or in 75% of all cases assuming the threshold value of the ratio $\frac{f_u}{f_{x0}}$ at the level of three (instead of two) for the second ASCE 4-98 method. It indicates the necessity to account for the reverse influence of the structure oscillations on the soil motion for civil buildings as it is done for nuclear industry structures.

The reverse influence introduces changes in the motion of the soil under the foundation slab as compared to the free field motion of the free soil surface at the same seismic conditions [1]. This leads to the fact that accelerograms for 60% of considered models must be changed from the free field movement accelerograms. Modified accelerograms should consider appropriate stress conditions, the depth of the foundation bottom and reinforced stiffness of the soil [2, 5].

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### Table 8. Comparison of the results for both methods (significant SSI effects are colored green).

| Number of floors | Soil 1 | Soil 2 | Soil 3 | Soil 4 |
|------------------|--------|--------|--------|--------|
|                  | $a_0,m_0$ | $f_{x1}$, $f_{y1}$ | $a_0,m_0$ | $f_{x2}$, $f_{y2}$ | $a_0,m_0$ | $f_{x3}$, $f_{y3}$ | $a_0,m_0$ | $f_{x4}$, $f_{y4}$ |
| 5                | +   | 1.92, 1.71 | +   | 1.15, 1.03 | +   | 0.6, 0.54 | +   | 0.3, 0.27 |
| 10               | +   | 2.97, 2.96 | +   | 1.79, 1.78 | +   | 0.93, 0.93 | +   | 0.47, 0.47 |
| 15               | -   | 3.94, 4.51 | +   | 2.37, 2.71 | +   | 1.23, 1.41 | +   | 0.62, 0.71 |
| 20               | -   | 5.02, 6.23 | -   | 3.02, 3.75 | +   | 1.57, 1.95 | +   | 0.79, 0.98 |
| 25               | -   | 6.19, 8.2  | -   | 3.72, 4.93 | +   | 1.94, 2.56 | +   | 0.97, 1.29 |

### References

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