Research on the relationship between the building displacements, thickness and soil type under seismic conditions

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Abstract. The problem of protecting buildings and structures from seismic effects has been troubling the scientists’ minds from different countries for many years. Various engineering structures, damping devices, organizational solutions are proposed, with the help of which scientists and builders try to reduce the destructive seismic effect on buildings and structures. This paper presents an analysis of how the displacement of a structure changed with a change in the thickness of a layer of a particular soil, how the efforts in piles changed. The results can be recommended when making design decisions for high-rise construction.

Introduction
There has been a rapid development of high-rise construction all over the world recently. This is especially true for the countries with a high population density, many of which are located in seismically dangerous areas. It is this circumstance that directs researchers to additional analysis and assessment of soil conditions in the seismic influence zones, to study the dependence of soil thickness on the seismic effects’ characteristics, on the soil interaction and pile foundation during movements of the earth’s crust.

Prior achievements and publications
The influence of dynamic effects on the Earth’s crust and soils has been studied by many researchers. In particular, the works of F.F. Aptikaev [1,2], in which the author analyzed the effect of ground conditions on seismic hazard are widely known. A number of researchers have worked to study the soil bearing capacity loss under the influence of dynamic effects from earthquakes, the soil nonlinear behavior under seismic effects [3,4,5,6,7,8], the surface seismic waves propagation in the soils [9].

The numerical models obtained as the research result made it possible to solve many problems of engineering seismology: to obtain data on the soil layers behavior in situ with strong seismic effects; establish the soil behavior patterns depending on their composition, water saturation and depth at seismic effects of varying intensity in order to predict the soil response during future earthquakes.

Other scientists investigated the various methods for calculating foundations and bases use, their interaction under the seismic components influence [10,11,12, 13,14].

In other words, one can cite many various studies examples of the dependence of the seismic effects influence on the soils’ properties and their relationship with foundations.

A great contribution to the structures and soils behavior study under the influence of seismic forces on them, in addition to the authors mentioned above, was made by Nikolaev A.B., Ayzenberg Ya.M., Berzhinsky Yu.A., Korchinsky I.L., Ter-Martirosyan A.Z. Voznesensky E.A., Funikova V.V., Vasilchkov V.V., Van Haybin, Trofimchuk A.N., Kolyukh Yu. I., San Ling Tun and others.

When analyzing the works of the listed authors, it is clear that a lot of attention was paid to the soil various properties study during seismic effects. However, the dependence question of the structural elements and forces in the foundations (piles) displacements on the soil foundation layer thickness is little studied. The first attempt to study this issue was made by a group of authors in 2017 in St. Petersburg Polytechnic University [15]. Taking into account the relevance and great interest in this issue, the research in this area was continued.
Formulating goals and setting the work objectives
The purpose of this study is to find the high-rise building movement dependence on a pile foundation on the soil thickness and its type in a seismic zone. The SCAD software package was used as the software for the calculation tasks. To achieve this goal, a 3D model of a high-rise building on a pile foundation was created; in the CROSS program, a base of various ground sites was created; a dynamic load, simulating a seismic effect was applied to the building. It was necessary to make the necessary calculations, analyze their results and on their basis derive the necessary mathematical dependencies.

The essence of the study

Initial data
A model of an 18-story building on a pile foundation was presented as a study object. The calculation was carried out in the SCAD Office 11.5 software package using the Lanczos method. The loads on the building and their combinations were determined in accordance with BC 20 13330 2011 and BC 14.13330.2011.

The main loads in the calculation were the loads from the own building weight and its elements, snow and wind loads, soil pressure on the structure from a rolling vehicle. Additionally, the pulsation component of the wind load was introduced into the calculation. The temperature climatic impacts on the building and the dynamic effects from the equipment were not taken into account. For the calculation, combinations of basic loads with seismic components along the X and Y axes, as well as with the seismic load directed to the X axis at an angle of 45°, were created. Combinations of loading were performed taking into account the coefficients of combinations determined in accordance with BC 14.13330.2011. So, for constant loads, the specified coefficient value was 0.9; for temporary - 0.8; for short-term - 0.5.

Examples of such combinations are presented in Table 1.
The designations L1, L2, ... L12 refer to the specific types of basic loads; under the designations L13, L14, L15 - seismic components.

| Number | Formula |
|--------|---------|
| 1      | (L1)*0.9+(L2)*0.9+(L3)*0.9+(L4)*0.9+(L5)*0.8+(L6)*0.9+(L7)*0.5+(L8)*0.5+ +*(L11)*0.5+(L12)*0.9+(L13)*0.5 |
| 2      | (L1)*0.9+(L2)*0.9+(L3)*0.9+(L4)*0.9+(L5)*0.8+(L6)*0.9+(L7)*0.5+(L8)*0.5+ +*(L11)*0.5+(L12)*0.9+(L14)*0.5 |
| 3      | (L1)*0.9+(L2)*0.9+(L3)*0.9+(L4)*0.9+(L5)*0.8+(L6)*0.9+(L7)*0.5+(L8)*0.5+ +*(L11)*0.5+(L12)*0.9+(L14)*0.5 |

A four-layer foundation composed of homogeneous soils (sand, sandy loam, loam and clay) was considered as a soil base. During the calculation, the thickness of the soil layers ranged from one to nine meters, in various combinations with each other. Examples of three combinations of soil bases and the results of the calculated movements are shown in Table 2.

| №  | Soils   | Layer thickness [m] | Moves along Z [m] | Moves along Y [m] | Moves along X [m] |
|----|---------|---------------------|-------------------|-------------------|-------------------|
| 1  | Sand    | 5                   | Max = -0.25       | Max = 2.12        | Max = 0.10        |
|    | Sandy loam | 5                   | Min = 0.01        |                   |                   |
|    | Loam    | 9                   |                   |                   |                   |
|    | Clay    | 1                   |                   |                   |                   |
| 2  | Sand    | 5                   | Max = -0.22       | Max = 1.91        | Max = 0.10        |
|    | Sandy loam | 5                   | Min = 0.03        |                   |                   |
|    | Loam    | 8                   |                   |                   |                   |
|    | Clay    | 2                   |                   |                   |                   |
The results analysis of and the mathematical dependencies construction

According to the calculations results, graphical dependences of the displacement magnitude on the thickness of a specific soil layer, which are presented in Figures 1, 2, 3, and 4 have been constructed.

Analyzing the graphs, we find that the displacements linearly depend on the soil layer thickness.

| Layer      | Thickness, m | Move, m | Max   | Min   |
|------------|--------------|---------|-------|-------|
| Sand       | 5            | -0.22   | 1.81  | 0.09  |
| Sandy loam | 5            | 0.02    |       |       |
| Loam       | 7            |         |       |       |
| Clay       | 3            |         |       |       |

**Figure 1.** Graph of the relationship between the clay layer thickness and the maximum displacements

**Figure 2.** Graph of relationship between sand thickness and maximum displacements

**Figure 3.** Graph of relationship between loam layer thickness and maximum displacements
Figure 4. The graph of the relationship between the sandy layer thickness and maximum movements

Using the approximation method, the linear regression equations were compiled for each soil type. For clay, the equation is

\[ x_i = -0.15 y_i + 2.24 \]  
(1)

where \( x_i \) is the maximum displacement, \( y_i \) is the soil layer thickness. For other soils, the following dependencies were derived:

- for sand
  \[ x_i = 0.06 y_i + 1.17 \]  
(2)

- for loam
  \[ x_i = -0.13 y_i + 2.11 \]  
(3)

- for sandy loam
  \[ x_i = -0.05 y_i + 1.69 \]  
(4)

The results approbation

The obtained dependences were tested when calculating the 16-storey building projected in Kaspiysk and compared with the analytical calculation results. The comparison showed that the building movement dependence on the corresponding soil layer thickness is practically described by the dependencies presented.

Summary

Based on the study, the authors consider the obtained mathematical dependencies to be able to be used in the design of buildings and structures for various purposes using SCAD PC.

The study presented a homogeneous soil composition study. In the future, using this technique, it is advisable to study inhomogeneous soils, as well as soils treated with various binders (organic and inorganic) in order to reduce the construction sites movement in seismically dangerous areas.

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