Comparative analysis of the dynamic stability of a multi-storey building with different base arrangements

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Abstract. The article presents the results of studies by the numerical method of pile and slab foundation with a reinforced base by the method of deep soil mixing (DSM) under the influence of seismic loads using the LIRA-SAPR software package, which implements the finite element method. The parameters of the computer model are presented, which make it possible to obtain the calculation results. A comparative analysis of the calculation results is carried out. In the course of the study, it was revealed that the use of a slab foundation with a reinforced base by the deep soil mixing method (DSM) is more effective than a pile foundation under seismic loads.

1. Introduction

In connection with the increase in the development of new territories, there are problems of earthquake-resistant construction, one of which is aimed at obtaining an effective structure of foundations and foundations to resist the design seismic loads. In this regard, this study is devoted to a comparative analysis of the dynamic stability with a pile foundation and with a slab with a reinforced foundation using the deep soil mixing method (DSM).

For the design of an earthquake-resistant building, it is important to assess the loads that are transferred to the foundation during an earthquake. Murali Krishna A. et al. [1] showed that these loads depend on the seismic loads acting on the superstructure during an earthquake. Seismic loads are horizontal forces caused by the impact of an earthquake. Due to seismic loads, complex movements and deformations occur in buildings and structures. Studies carried out by Chylbak A. A. [2] show that under the action of horizontal forces deformations occur: bending, displacement at different levels of the structure, overturning, tilting, torsion, vibrations. As is known from SP 14.13330.2018, the torsion vibration mode increases the seismic load on the building. Seismic loads cause various damages in load-bearing structures.

Studies by Nurieva D. M. [3], Il'ichev V. A. et al. [4], Zekhniev F. F. et al. [5], Ter-Martirosyan A. Z. [6] show that pile foundations are usually used for various types of multi-storey civil and industrial structures, heavy energy structures, bridges. The design of pile foundations should ensure the effective functioning of various structures, taking into account high seismic loads. Recently, as noted in the works of Subramaniam P. and Banerjee S. [7], Yoobanpot N. et al. [8], the technology of transforming the building properties of the foundation by soil mixing is used to increase seismic stability. In the work of Yamashita K. et al. [9] it is noted that for earthquake-resistant design of pile foundations it is necessary to rely on the data of field geotechnical monitoring, and the studies of Albusoda B. S. [10]
and Dehghanbanadaki A. [11] show the importance of numerical modeling in solving such geotechnical problems.

Deep soil mixing technology (DSM) (figure 1) is one of the varieties of drilling methods and, as noted in the work of Bell A. and Kirsch K. [12], is widely used throughout the world.

The essence of the deep soil mixing method consists in crushing the soil without pulling it to the surface when the drilling tool is immersed and mixing with a special tip consisting of transverse blades and a special cutting tool, soil with a binder solution introduced under pressure through the drill rod during its immersion and extraction. As a result, as noted in the works of Bellato D. et al. [13], Ekmen A. B. et al. [14], a soil-cement element of increased strength is formed, as a rule, of a cylindrical shape with a diameter of mainly from 0.4 to 2.5 m and a length of up to 30 m, and in the presence of special equipment, according to Dou H. and Wang Y. [15], it is possible to stir up to a depth of 70 m from the working platform.

![Figure 1](image.jpg)  
**Figure 1.** Technological scheme for the production of works on technology of soil mixing.

2. Materials and methods
To solve this problem, the LIRA-SAPR software package was used. A 9-storey building was modeled with a frame structural system with dimensions in plan of 24×24 m, a grid of columns of 6 m and a floor height of 3 m with a seismicity of 8 points. Two types of foundations were also modeled to compare the effectiveness: a pile foundation with driven round piles with a diameter of 0.3 m, a length of 10 m and a pile pitch of 2 m (figure 2 (a)) and a slab foundation with a reinforced base using the deep soil mixing method (DSM) (figure 2 (b)).
LIRA-SAPR software allows modeling piles in two ways: 1) the only one-node FE57; 2) chains of vertical bar elements with one-node finite elements of type 57. Since when modeling by method 1 it is not possible to take into account the rigid attachment of the pile to the foundation slab and the mutual influence of the piles, method 2 was used for this task. The piles were modeled using a chain of vertical bar elements, which are connected by one-node finite elements FE57. Rod elements are needed to calculate the stiffness of the pile, and FE57 - the stiffness of the sub grade. FE57 is a single-node finite element with a set of 6 stiffness characteristics or «springs», which are calculated according to the location of the finite element in the soil model (figure 3).

Figure 2. Design scheme of the building, pile foundation (a) and slab with a reinforced base by deep soil mixing (DSM) (b).

Figure 3. Design model of the pile foundation in LIRA-SAPR.
The slab foundation was modeled using lamellar finite elements, and the reinforced foundation was taken into account by setting the reduced modulus of elasticity of the reinforced soils.

The bearing capacity of the piles is calculated in accordance with SP 24.13330.2011. The depth of the compressible strata $H_c$ is taken in accordance with SP 22.13330.2011.

LIRA-SAPR implements 3 methods for calculating the stiffness coefficient of the base $C_1$:
1) based on the averaged values of Young's modulus $E$ and Poisson's ratio $\nu$;
2) according to the Winkler formula;
3) the averaged values of $E$ and $\nu$ are also used, but with a correction factor $u$ to take into account the increase in the Young's modulus of the soil along the depth.

The seismic load was set in two directions (along the global X and Y axes of the design model). The coefficients for the calculation were assigned in accordance with table 5.3-5.5 (SP 14.13330.2018). According to clause 5.19 of SP 14.13330.2018, the calculated seismicity of 8 points corresponds to the acceleration of the ground $A$ equal to 2 m/s$^2$.

When calculating a building for dynamic seismic action using the Static Load Consideration command, a mass matrix was generated. The load combination coefficient for the collection of masses was taken from table 5.2 (SP 14.13330.2018).

3. Results
In the course of numerical modeling of the design scheme of the building on 2 types of foundations, the following results were obtained for the maximum horizontal displacement of the building structures under seismic action:
- pile foundation – 29.6 mm (figure 4).
- slab foundation with a reinforced base by the deep soil mixing method (DSM) – 24.3 mm (figure 5).

**Figure 4.** Distribution of displacements along X (G) for the option of the pile foundation.
Figure 5. Distribution of displacements along X (G) for slab foundation and DSM base option.

Comparing the two options, it was found that with a seismicity of 8 points for the same building, the pile foundation is inferior to the slab foundation with a reinforced foundation using the deep soil mixing method (DSM). This technology has another advantage over the pile foundation - the use of a smaller volume of cement.

4. Conclusion
Ultimately, it can be established that a comparative analysis of the calculation results for a 9-storey building with a frame structural system with dimensions in terms of 24×24 m, a grid of columns of 6 m and a floor height of 3 m with a seismicity of 8 points shows that with a dynamic impact from an earthquake it is more effective use a slab foundation with a reinforced foundation using the deep soil mixing method (DSM) than a pile foundation.

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