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Soil-structure interaction: theoretical research, in-situ observations, and practical applications

M.M. Sabri [1] ✉, ***K.G. Shashkin*** [2]

[1] *Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russian Federation*

[2] *PI Georeconstruction, St. Petersburg, Russian Federation*

✉ *mohanad.m.sabri@gmail.com*

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Abstract. This research paper presents a comprehensive investigation on soil-structure interaction, combining theoretical research and in-situ observations. Detailed calculations and a thorough comparison of the results with long-term settlement observations are provided, accompanied by the validation of the proposed elasto-visco-plastic soil model through rigorous calculations. Real-world examples showcasing the application of design methods incorporating soil-structure interaction calculations in civil and industrial engineering, as well as in the reinforcement and restoration of historical buildings, are also presented. The study reveals that neglecting the spatial behavior of soil leads to significant underestimation of stresses in structures. For buildings on spread footings, the underestimation can range from 150% to 400%, while for buildings on pile foundations, it can be as high as 200% to 900%. Furthermore, an innovative architectural solution employed in a high-rise building successfully mitigated settlement issues by utilizing longer piles. The calculated settlement was reduced to 60 mm, and the actual settlement observed three years after construction was only 32 mm, indicating the effectiveness of the implemented solution. By emphasizing the importance of soil-structure interaction calculations, this research fosters a unified approach among various stakeholders involved in construction design. The findings and methodologies presented in this paper hold great potential to significantly enhance the field of geotechnical engineering, enabling more accurate and effective design approaches for various structures and applications.

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1. Introduction

The impacts of soil-structure interaction on calculations have been extensively studied and validated by the behavior of structures and soils [1-13]. When a rigid plate is loaded, contact pressure contours emerge in the deformed half-space. The Boussinesq analytical solution, which is widely recognized, indicates that these contours are parabolic with asymptotes running along the edges of the plate, assuming the plate is entirely rigid and circular [14-16] (Fig. 1):

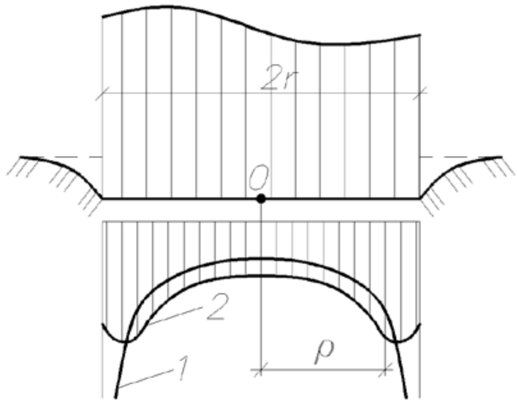
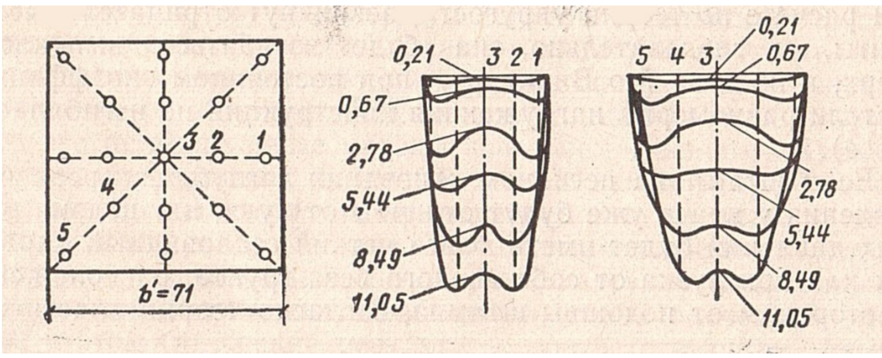


Figure 1. Contact pressure contours in the deformed half-space under a plate:
1 – according to the analytical solutions, 2 – in reality considering the development of plastic deformations.

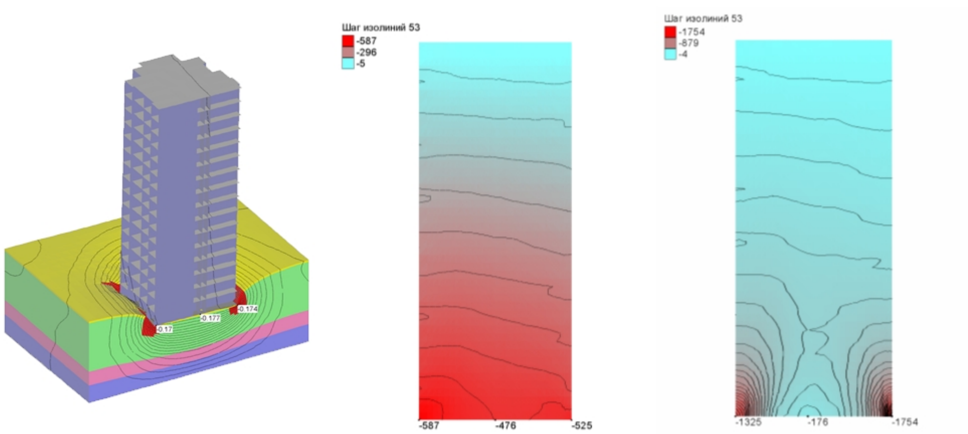
In reality, the contact contours are typically saddle-shaped (contours 2 in Fig. 1, experimental values in Fig. 2).



a. b. c.

Figure 2. Experimental diagrams of reactive pressures: under a square plate 71×71 cm on the surface of sand soil at pressures 0.2–8 kgs/cm^2 (from 20 to 800 kPa) [17, 18]:
a – layout of pressure gauges; b – contours along the middle axis;
c –contours along the diagonal [19].

The same contours of vertical forces form within the plate, reflecting the contract contours under the plate in the deformed half-space. The values of reactive forces in the plate depend on the rigidity of the deformed half-space. It is also apparent that while considering a real structure of a final rigidity instead of the rigid plate, the contact contours will also depend on the rigidity of this structure (Fig. 3).



a. b. c.

Figure 3. The results of calculation of a building on a slab foundation with subsoil:
a – calculation model (cross-section), the areas of limit state are marked in red;
b – linear forces (kN/m) in a transversal wall at calculation on inflexible soil;
c – forces considering of spatial soil behavior.

Although there is clear evidence of the regularities in soil-structure interaction, differential pressure in the subsoil of rigid structures is not always considered in design practice, raising the question of whether it is necessary to consider this feature in structural design.

2. Methods

2.1. Idealized models of reinforced concrete buildings

In order to investigate the effects of soil-structure interaction, idealized models of reinforced concrete buildings were used, with different structural schemes including transversal bearing walls at a spacing of 3 and 6 meters, longitudinal and transversal bearing walls, and longitudinal bearing walls. The use of idealized models enabled to obtain of the fundamental regularities of soil-structure interaction without being distracted by the details of the structural scheme (openings, changes in the spacing of bearing walls etc.). To compare the results, the calculations for each building on elastoplastic soil were compared with the results of a corresponding calculation on a completely inflexible subsoil (on rigid supports), which is equivalent to the loading of a building on a subsoil per loaded area, as commonly accepted in design practice. This comparison was highly informative as it ultimately identified the studied effect, which was completely absent when considering a structure on rigid supports. Figure 4 shows a comparison of stresses in the walls of the building on rigid supports and a flexible subsoil with medium compressibility (with a strain modulus of approximately 10 MPa).

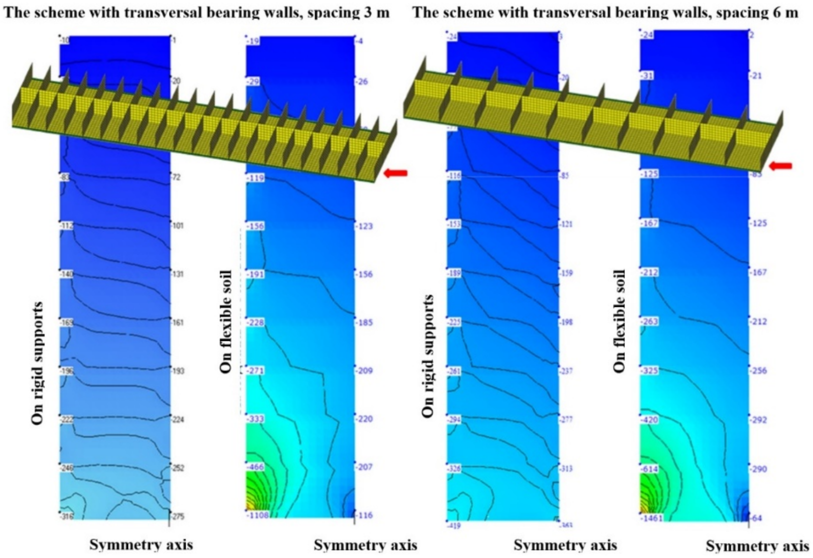


Figure 4. Distribution of vertical forces in a face wall of the building (kN) at various structural schemes.

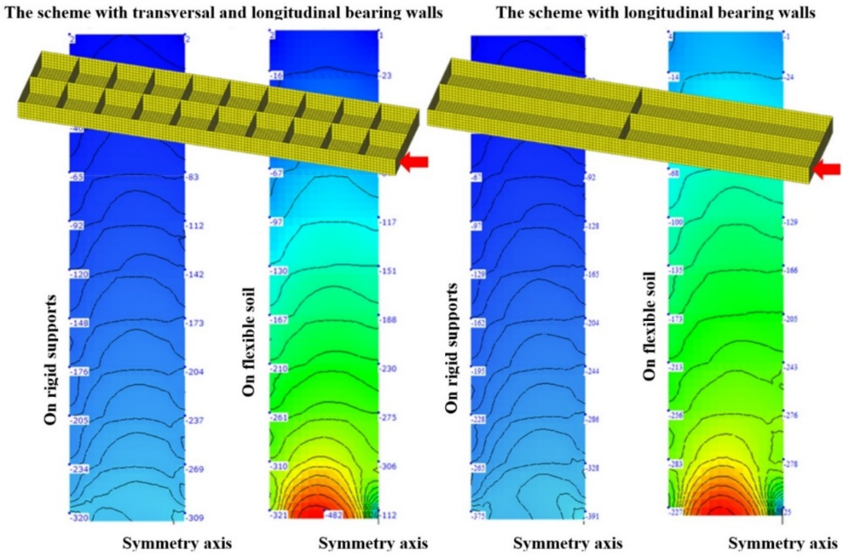


Figure 5. The contours of distribution of vertical forces (kN) in a transversal face wall of the building at calculation on nonlinear deformed soil made of soils of medium deformability, and KSSI contour.

2.2. Account of nonlinear soil behavior in time, account of nonlinear properties of structural materials

Based on the analysis of behavior models used for solving problems related to soil-structure interaction, models with double or independent strain hardening at volumetric and shape-changing deformations are considered the most promising. It has been demonstrated that strains in buildings and structures are not only caused by the consolidation process but also by the process of shape-changing, which is often the deciding factor in practical situations [20]. To accurately predict changes in the stress-strain behavior of soil during loading, models with independent descriptions of the behavior of soil during consolidation and shape-changing are necessary. A model with independent strain hardening has been verified through a series of in situ investigations of building strain development [21-23].

The central concept behind creating a visco-plastic model of soil behavior is to develop an independent description of the reversible deformations area, also known as the strain hardening area, for both consolidation and shape-changing. In this model, the relationships between the shear strain $\gamma_p(p,q)$ and volumetric strain $\varepsilon_{vp}(p,q)$ are determined based on laboratory soil tests and can be graphically represented by contours in p–q coordinates (Fig. 7). As the limit stress approaches, strains increase, and the contours of $\gamma_p(p,q)$ align along the Coulomb law line.

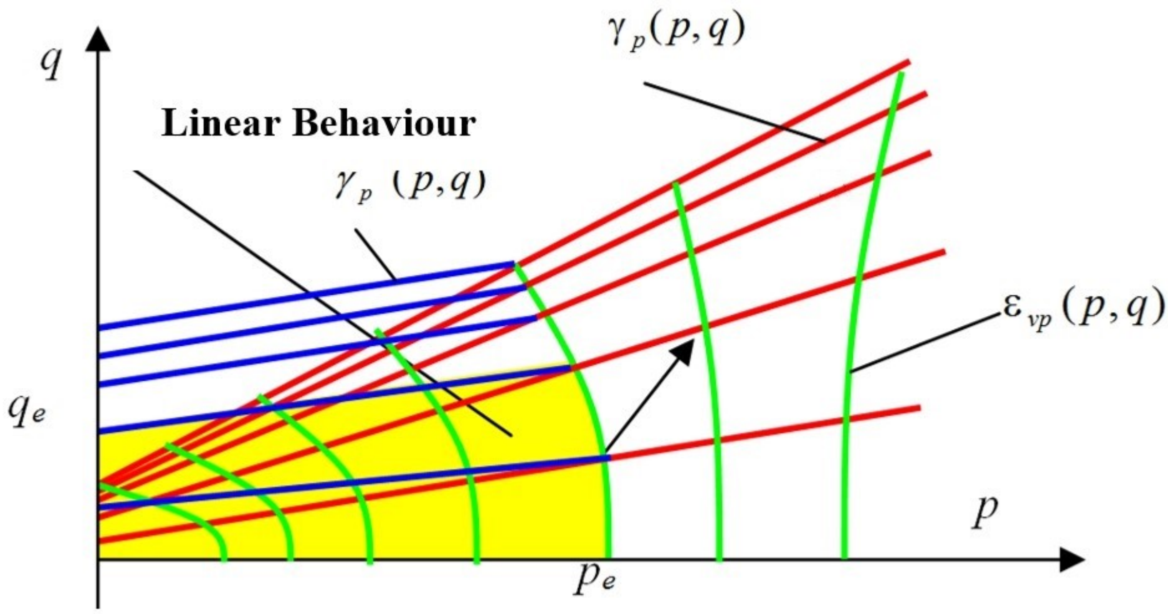


Figure 8. The scheme of making an elastoplastic model with independent strain hardening.

The approach described here involves defining the complete set of dependencies between shear $\gamma_p(p,q)$ and volumetric strains $\varepsilon_{vp}(p,q)$ and varying values of stress deviator. These dependencies can be represented as contours in p-q coordinates, with the contours of $\gamma_p(p,q)$ concentrating along the Coulomb law line as strains increase, approaching the limit stress. Points above the limit line of Coulomb law correspond to stress states that are impossible for the soil milieu and should not be considered in the model. The vector of plastic deformation for a given increment of stresses is then defined by the set of $\gamma_p(p,q)$ and $\varepsilon_{vp}(p,q)$ dependencies. This approach does not require any theoretical assumptions about the shape of a "tent" or other mathematical abstractions, allowing the maximum approximation of the model behavior to experimental results. Any differences between the model and experiment are primarily due to inaccuracies in approximating the $\gamma_p(p,q)$ and $\varepsilon_{vp}(p,q)$ functions.

The limitations of existing models in describing soil behavior over time and predicting the strains of buildings and structures are acknowledged. Specifically, there is a lack of models that can accurately describe the development of shear strains in time. Most models assume immediate development of shear strains, which is inconsistent with the accumulated construction experience. Therefore, there is a need to develop more advanced models that can better capture soil behavior over time and provide more accurate predictions of strain development.

The Creep Model is a method of modeling the development of creeping deformations over time. It relates the strains caused by creeping in shear and secondary consolidation as two projections of a vector that is orthogonal to the tent surface in the Cam Clay model. However, the tent surface and the associated law of plastic flow are mathematical abstractions that may not be applicable to describing the actual soil behavior. As a result, it is uncertain whether using these abstractions will lead to success in describing shear creeping based on the dependency for compression.

The proposed model used the simplest linear dependency: viscosity decreases according to the linear law with an increase of shear stress and approaches null at reaching the strength limit:

$$\eta(\tau) = \eta_0 \frac{\tau_{\lim} - \tau}{\tau_{\lim}}. \tag{1}$$

The model incorporates a linear relationship between the rate of development of shear strains and acting stresses, which aligns well with previous research [24]. This enables the model to integrate different soil behaviors, where slow strain development occurs at small shear stresses and quick failure occurs at stresses approaching the strength limit. As the strength limit approaches, the shear viscosity resistance decreases to zero, leading to soil failure.

To validate the proposed model, a database of long-term observations of settlements of buildings and structures was compiled and analyzed (Fig. 9).

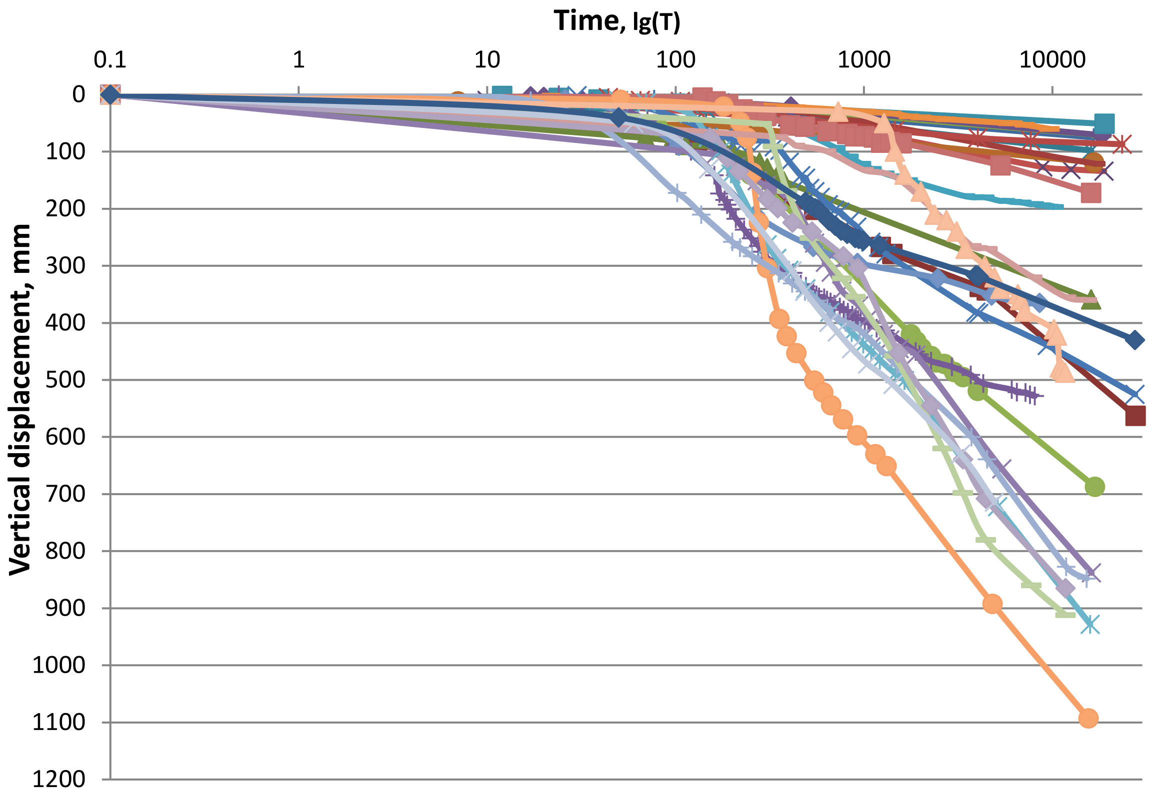


Figure 9. The results of long-term observations of 30 buildings on soft soils (duration of observations 23–77 years [25]).

3. Results and Discussion

3.1. The results of the Numerical modeling using the proposed soil-structure interaction ideology

The ratio between a force in a point of structure at the flexible soil solution and a force in the same point in the rigid support solution is called "an indicator of the effect of soil-structure interaction, denoted as KSSI. Fig. 5 displays the KSSI graphs for various structural schemes of the building on medium compressive soil. Its shows that the stresses in structures are evidently affected by the soil-structure rigidity ratio. Fig. 6 and 7 exhibit the KSSI dependencies on the soil-structure rigidity ratio for different structural schemes and various types of foundations.

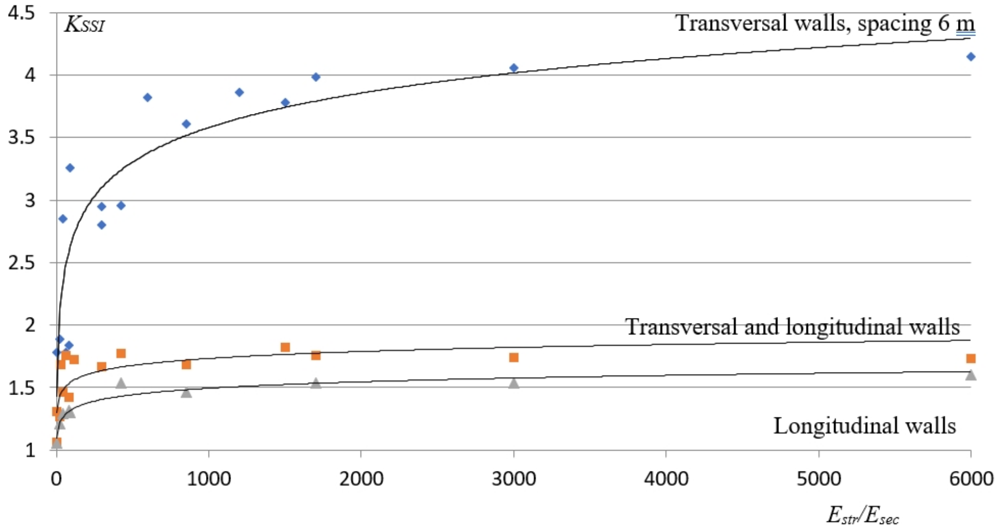


Figure 6. The dependency of an indicator of non-linearly deformed soil-structure interaction effect on their ridigity ratio for different structural schemes.

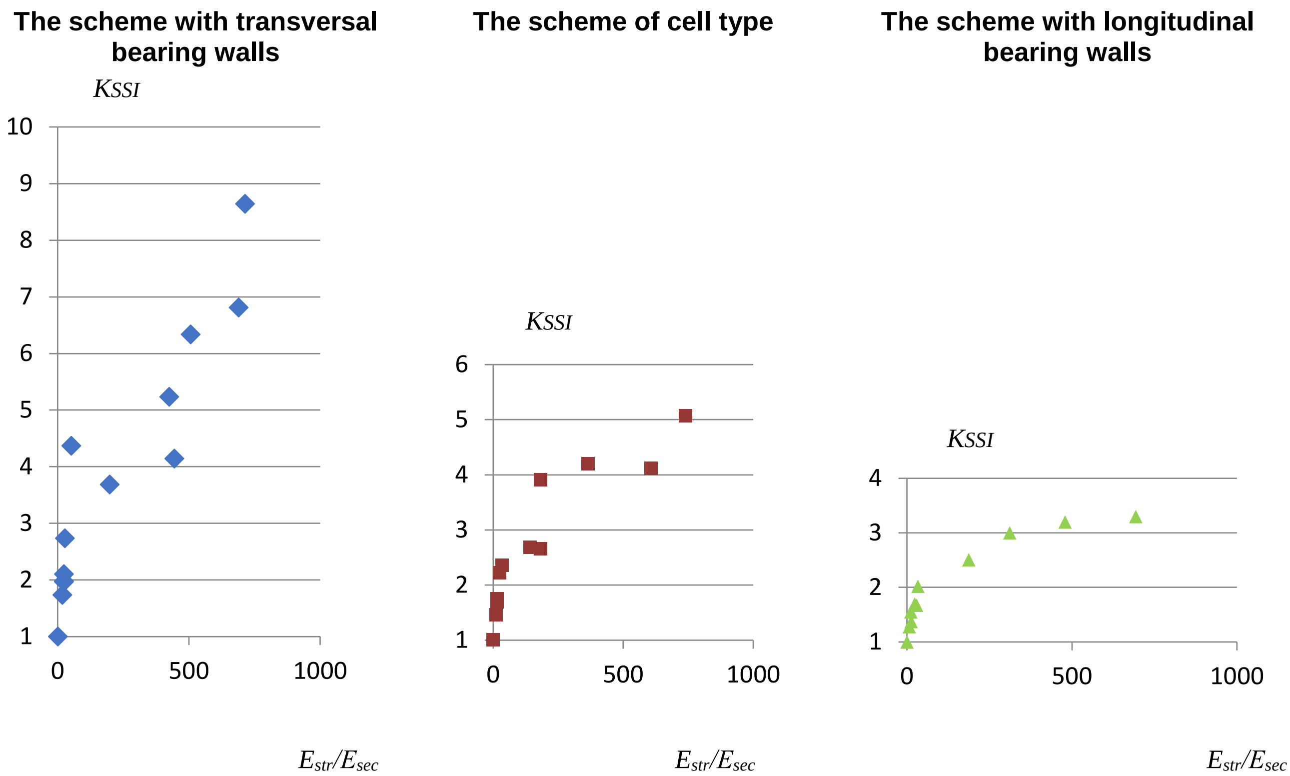


Figure 7. The graphs of dependency of an indicator of soil-structure interaction effect for the building on pile foundation and non-linearly deformed soil on their ratios for various structural schemes of buildings.

The results of numerical experiments indicate a significant underestimation of stresses in structures when the spatial behavior of soil is not considered. The underestimation can range from 150 to 400% for buildings on spread footings, while for buildings on pile foundations, it can be as high as 200–900%. Despite the importance of this issue, both in Russia and abroad, it is often ignored in design practice. One reason for this is the division of experts involved in structural and geotechnical calculations, which results in using different software suites that do not interact well. Furthermore, practical design experience highlights the importance of accounting for soil-structure interaction to design more durable and cost-effective structures. Despite this, doubts remain about the accuracy of soil calculations, which hinders the adoption of soil-structure interaction calculations. To address these doubts, extensive work has been done to compare calculated and observed strain values, discussed in detail below.

3.2. Comparison of the calculated results according to different methods and observation results

Fig. 9 demonstrates that considering buildings on soft soils, the notion of "final settlement" loses its sense as settlements develop as per logarithmical law, which does not have an asymptote. Therefore, a clear scientific setting of the task of comparison of calculations and observations requires a comparison of settlements in a certain time moment. Fig. 10 compares results according to the simplified method of strata summing (set in the Russian regulations) and nonlinear calculations according to the abovementioned model with results of long-term observations. The figure shows that the accuracy of geotechnical calculations using nonlinear models increases significantly.

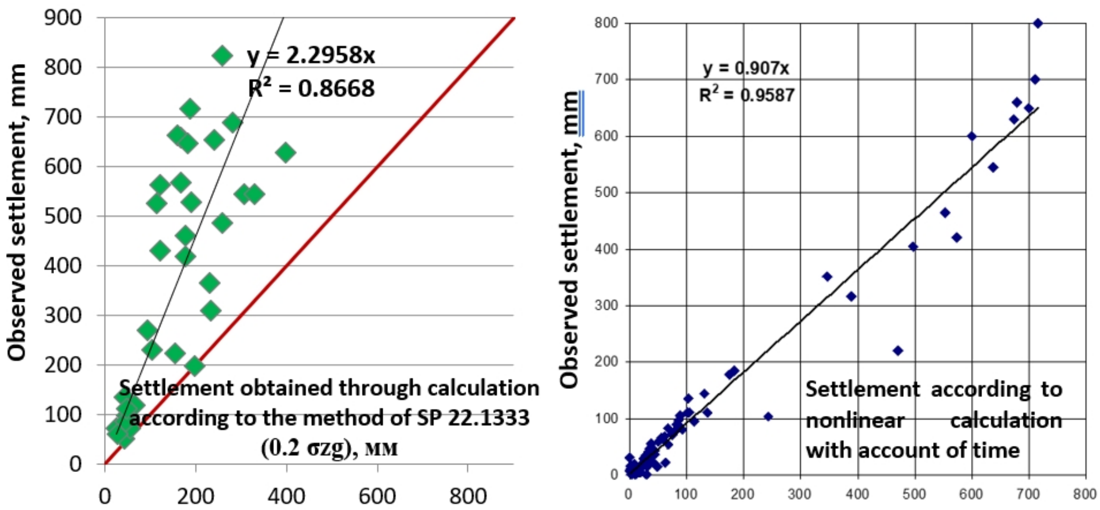


Figure 10. Comparison of the results of calculations according to different methods and observation results.

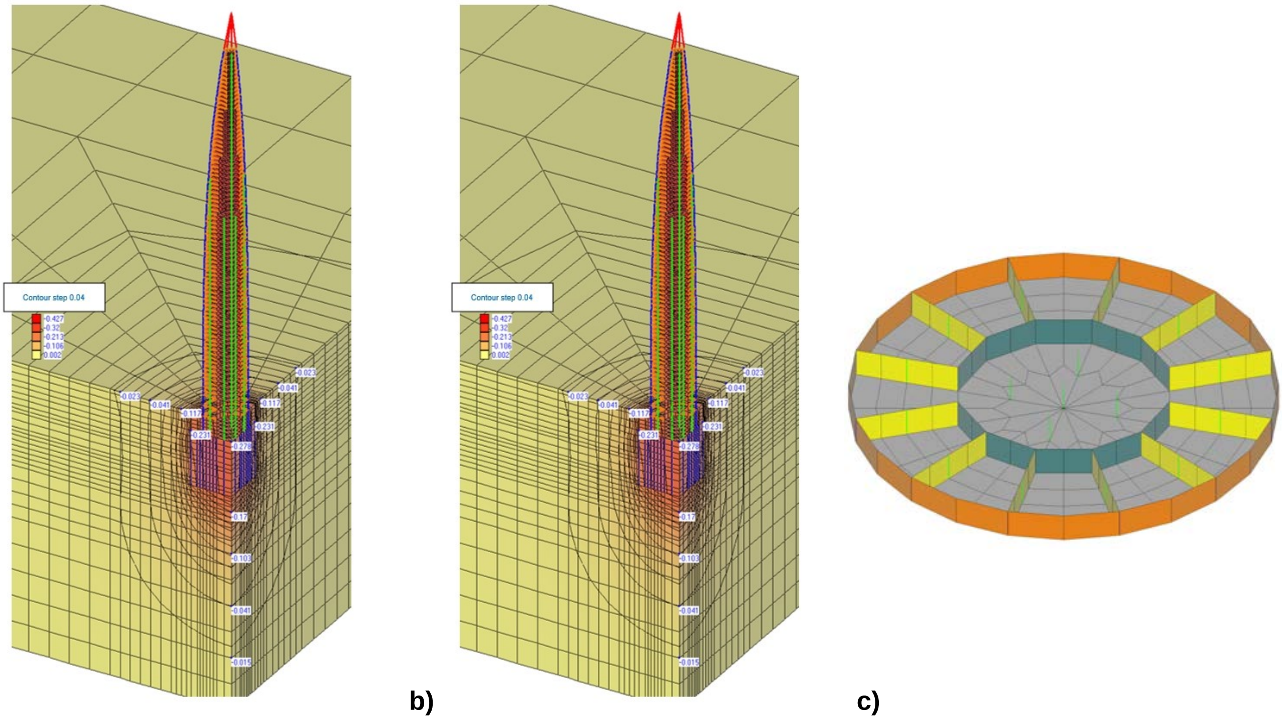
With the correct account of soil deformations, there is a problem of the correct account of structural rigidity since the values of forces in soil-structure interaction calculations largely depend on a rigidity ratio. There is a need to consider the long-term creeping of concrete and cracking for reinforced concrete structures. N.A. Evseev [26] has elaborated on convenient methods of accounting for the rigidity of RC structures in soil-structure interaction calculations.

3.3. Application of the design ideology considering the soil-structure behavior

3.3.1. Design of the unique high-rise building

The account of soil-structure behavior is essential for both usual and unique high-rise buildings. An example of a unique high-rise building constructed in difficult soil conditions in St. Petersburg is considered. At the pre-design stage, soil-structure interaction calculations were performed for the unique building for different configurations of its underground floor (Fig. 11). As a result, a structural scheme was proposed, which minimized settlements and tilts and formed the basis of the architectural solution (Fig. 12). The proposal was to increase the area of building spread on soil and simultaneously deepen the underground part, and construct rigid radial walls to provide transfer of pressure throughout the foundation area.

The concept, which was accepted as the basis of the architectural solution, allowed minimizing settlement of the high-rise building (Fig. 13). Increasing the pile length provided reduced the calculated settlement to about 60 mm, according to the observation results, the actual settlement three years after completion of the construction was 32 mm. At the same time, soil-structure interaction calculations allowed considering the development of forces in radial walls of the underground part and ensuring the strength of these structures.



a) b) c)

Figure 11. Pre-design calculations of the high-rise building on dispersed soils in St. Petersburg: a – the settlement at the underground part diameter of 55 m (the maximum value 64 cm); b – the settlement at the underground part diameter of 80 m (the maximum value 28 cm), c – the plan of the underground floor with radial walls proposed at pre-design stage.

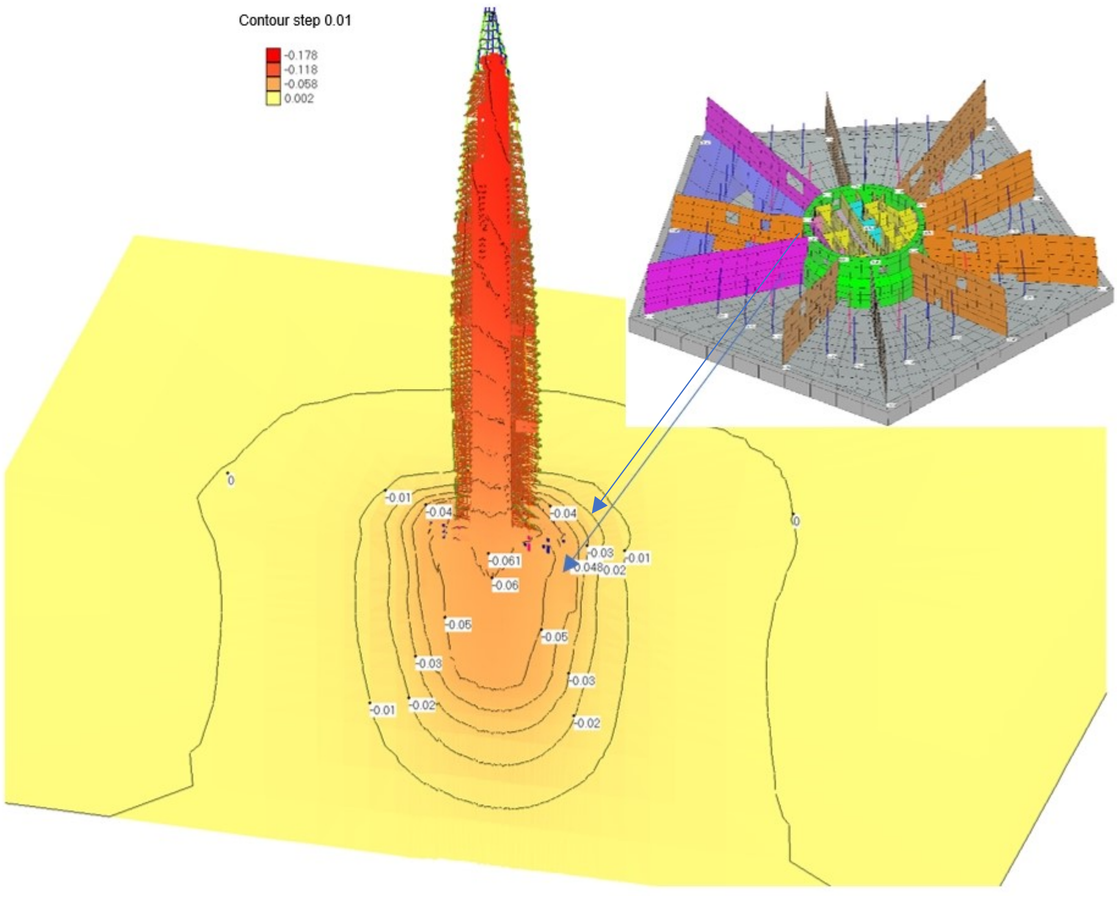


Figure 13. Calculation of settlements of the high-rise building, m (in the top right corner, there is a fragment of the calculation model for the configuration of the underground part accepted in the design).

3.3.2. Account of soil-structure interaction in industrial construction

In contrast to civil engineering, where traditional structural schemes are used for most buildings (as discussed in detail in part 1), complex shapes are more common in industrial construction structures due to the requirements of technological processes. In these cases, adequate consideration of soil behavior is necessary to determine the forces acting on superstructures accurately. For example, an 80-meter-high silo tower for production (Fig. 14) experiences the same loads as a 200-meter-high skyscraper, while a clinker brick warehouse (Fig. 15) applies almost the same pressure to the soil as the 500-meter-high building discussed earlier. In the latter case, a unique technical solution was implemented involving cutting structures with numerous deformation joints to allow the structures to adapt to the significant soil deformations that could not be minimized using long piles.

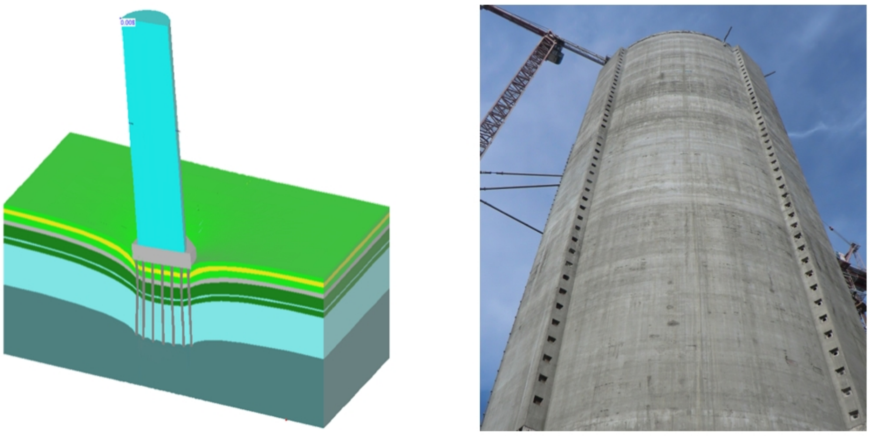


Figure 14. The calculation model (the exaggerated strain model at the calculation for wind action) and view of the erected structure of the silo tower for ready production, the cement plant in Novorossiysk.

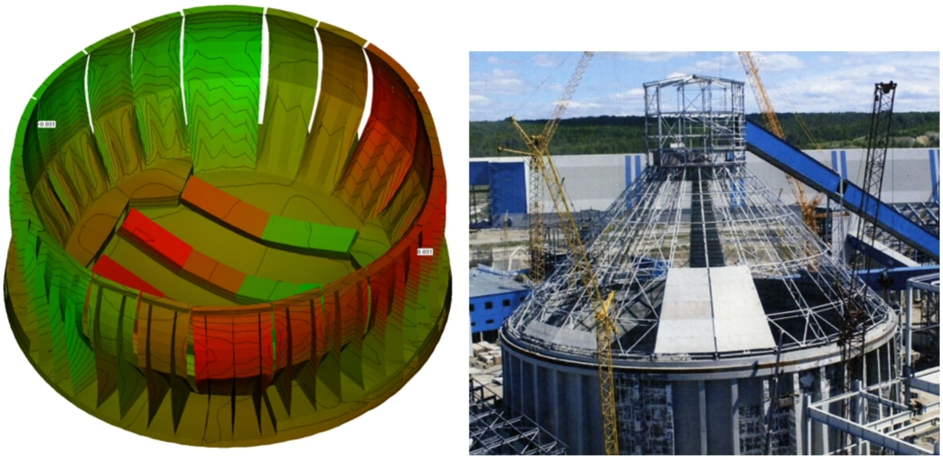
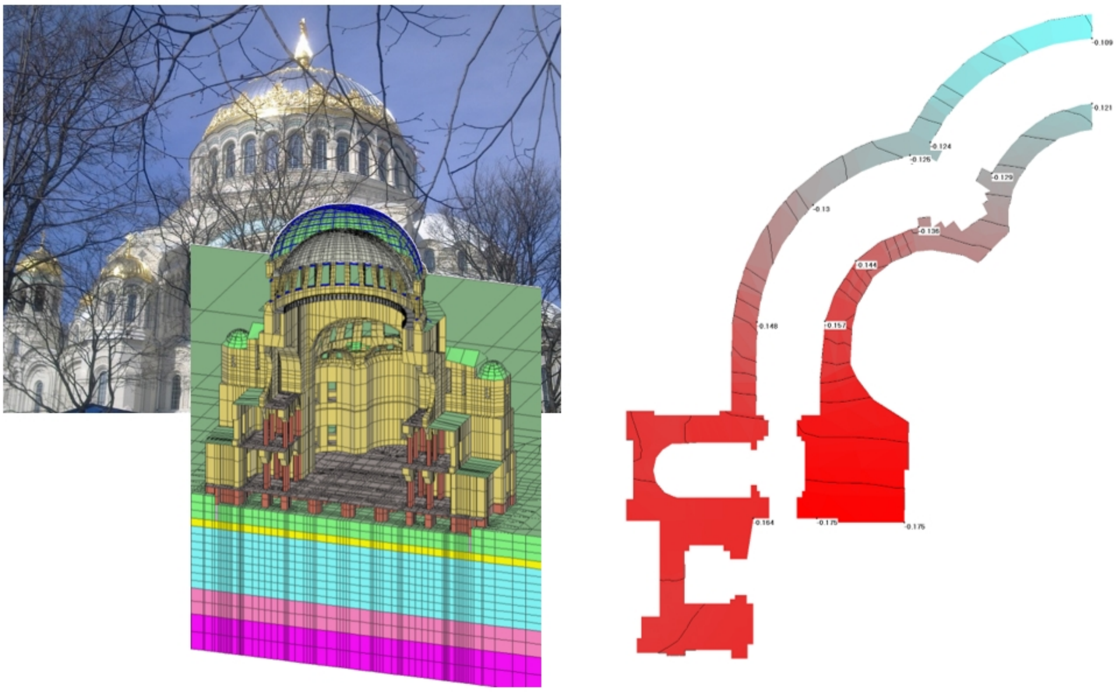


Figure 15. The strain model (in a larger scale) and view of the erected structure of the clinker warehouse, the cement plant in Novorossiysk.

3.3.3. Soil-structure interaction calculation at the analysis of causes of deformation of historical buildings

The consideration of soil-structure interaction also proves to be beneficial for diagnosing the causes of defects in historical buildings and selecting the most effective options for strengthening foundations and structures. The analysis of the strains of the Marine Cathedral in Kronshtadt, for instance, revealed characteristic settlement features for cross and cupola temples, where the four central pillars, on which the dome rests, experienced the largest settlement (Fig. 16), while the surrounding structures were less deformed. Based on the structure calculation, tensile areas prone to cracking were identified. These were found to be the areas where cracks had occurred (Fig. 17), allowing for unequivocal conclusions about the reasons for the development of defects. The clearly stated reason for the development of defects allowed for substantiating the lack of necessity to reinforce foundations and avoid the dangerous influence of technology on the building structures.



a) b)

Figure 16. Calculation of Kronshtadt Marine Cathedral:
a – photo and calculation model (cross-section);
b – settlement contours in one-fourth of the building plan.

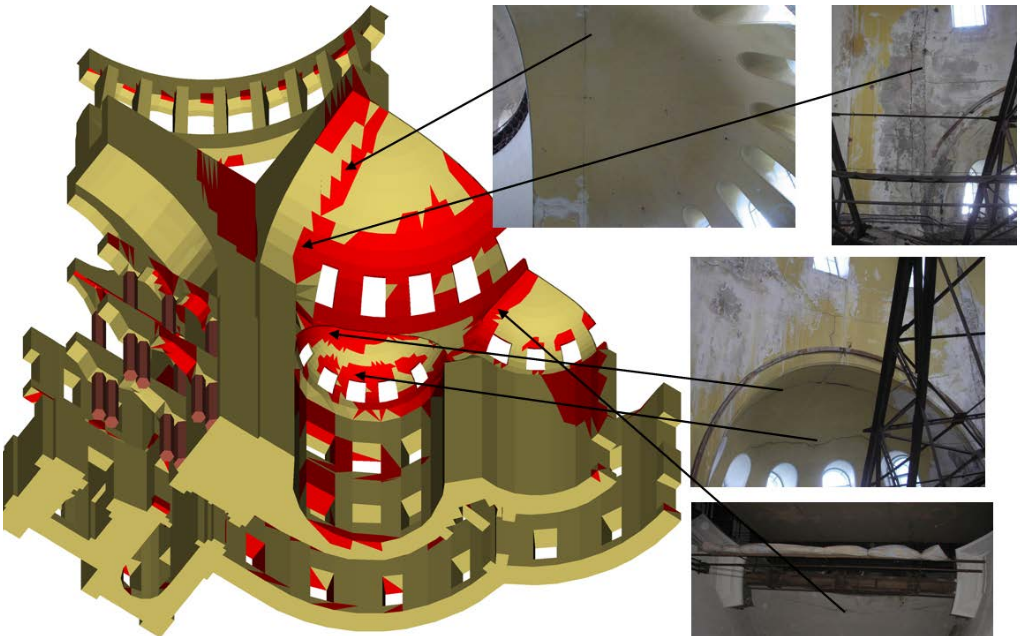


Figure 17. Matching of the expected areas of cracking according to the calculation and the examination results.

4. Conclusions

The paper highlights the importance of considering soil-structure interaction in construction design, particularly for high-rise buildings, industrial structures, and historical monuments. Based on the calculation analysis, the main findings of the research are:

1. Soil-structure interaction calculations are essential for both usual and unique high-rise buildings, industrial construction structures, and historical buildings. These calculations help correctly define forces in superstructures and diagnose causes of defects in historical buildings.

2. The results of numerical experiments indicate a significant underestimation of stresses in structures when the spatial behavior of soil is not considered. The underestimation can range from 150 to 400% for buildings on spread footings, while for buildings on pile foundations, it can be as high as 200–900%.

3. Based on the information provided, the architectural solution implemented in the high-rise building successfully minimized settlement using longer piles. The calculated settlement was reduced to 60 mm, and the actual settlement three years after construction was only 32 mm, indicating that the solution was effective.

4. Adequate consideration of soil behavior is necessary for industrial construction structures with complex shapes due to the requirements of technological processes. The results of calculation of an 80-meter-high silo tower and a clinker brick warehouse shows that such structures can experience similar loads and pressures on the soil as much taller buildings in civil engineering.

5. The calculation model of soils and structures plays a unifying role, interconnecting geological data, foundation engineering details, and features of structural behavior.

6. Reliable investigation data and application of nonlinear models in soil calculations provide the accuracy required for calculation of structures.

7. The calculation of structures considers expected and differential settlements, which increase the reliability of structures and exclude additional costs in foundation construction.

8. Soil-structure interaction calculations provide a reliable tool for diagnostics of causes of development of strains and defects in historical structures and rational designating measures to strengthen foundations and structures.

9. Using soil-structure interaction calculations results in a single ideology of interaction of different participants of construction design.

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Information about authors:

Mohanad Sabri*, PhD in Technical Sciences*
ORCID: https://orcid.org/0000-0003-3154-8207
E-mail: mohanad.m.sabri@gmail.com

Konstantin Shashkin*, PhD in Technical Sciences*
E-mail: cshashkin@yandex.ru

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