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Contact interaction between foundation structures and subsoil and its effect on the stiffness characteristics of structural frames in high-rise buildings

Abstract. The increasing proportion of high-rise buildings in dense urban development requires a reliable assessment of contact interaction between foundation structures and subsoil. For such buildings, serviceability and structural reliability are governed not only by absolute settlements, but also by differential settlements, angular distortion and their effect on the spatial behaviour of the structural frame. The aim of this study is to develop a consistent engineering procedure for assessing the subsoil–foundation–building system in high-rise construction. The study is based on a comparative analysis of classical, two-parameter, semi-continuum and continuum subsoil models, including the Winkler, Pasternak, Filonenko-Borodich and Vlasov models, as well as spatial finite element formulations. A unified notation system is used to describe settlements, contact pressure, angular distortion and additional axial forces caused by differential foundation deformation. It is shown that differential settlements and angular distortion are the key engineering indicators for high-rise buildings, since they directly affect the redistribution of forces in columns, walls and other vertical load-bearing elements. A staged modelling procedure is proposed, in which preliminary assessment is followed by refined analysis and subsequent spatial verification of the entire system. An integral suitability index is used for preliminary comparison of raft, pile and piled-raft foundation systems. The practical value of the study lies in formalising the transition from simplified analytical models to detailed spatial analysis and reducing the risk of design decisions in which the structural consequences of differential settlements are underestimated.

Keywords: differential settlements; angular distortion; deformation compatibility; piled-raft foundation; contact pressure; soil–structure interaction

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Introduction.

For high-rise buildings, contact interaction between foundation structures and subsoil is a key factor in ensuring serviceability and, in certain cases, the overall reliability of the load-bearing structural system. In contrast to low-rise buildings, where the design assessment is often governed mainly by the bearing capacity of the subsoil, high-rise buildings are more sensitive to differential settlements, angular distortion and the associated redistribution of internal forces in the structural frame.

The deformation behaviour of the foundation system directly affects the support conditions of columns, walls and other vertical load-bearing elements. Therefore, the assessment of a high-rise building cannot be limited to the isolated verification of the foundation or subsoil. It must also consider the deformation compatibility of the subsoil–foundation–building system and the structural consequences of differential foundation deformation.

This makes it necessary to use a consistent modelling procedure that links the selected subsoil model, the predicted settlement field, contact pressure distribution and angular distortion with the resulting additional axial forces in the structural frame. Such an approach is particularly important for selecting and justifying raft, pile and piled-raft foundation systems under complex engineering-geological conditions.

Literature Review / State of the Art

Recent studies published in 2019–2025 show that the selection of a subsoil model and a foundation system for high-rise buildings is increasingly based on an integrated assessment of the subsoil–foundation–building system. In a numerical study of a 20-storey building, it was shown that a piled-raft foundation can significantly reduce the seismic response of the superstructure, although this effect depends on the excavation geometry and embedment conditions [1]. A study of a high-rise building resting on a finned pile mat confirmed that proper consideration of soil–structure interaction changes the predicted internal forces and displacements in comparison with a fixed-base model [2]. A case study on the deviation rectification of a high-rise building with a piled-raft foundation demonstrated the critical role of settlement monitoring and staged correction of the foundation system [3]. Additional studies have also shown that, for high-rise frame-wall systems, soil–structure interaction affects not only force parameters but also deformation indicators, especially under soft subsoil conditions [4].

For the period 2024–2025, an important development is the transition towards performance-based assessment in dense urban environments. The use of combined piled-raft foundations together with spatial modelling of construction stages makes it possible to control both the settlement of a new high-rise building and its influence on adjacent structures [5]. Modified Vlasov-type models may serve as an effective intermediate level between simplified two-parameter models and full continuum analysis [6]. For core-wall and piled-raft foundation systems, it has also been confirmed that settlement prediction and force redistribution cannot be assessed completely without considering the combined behaviour of the foundation and the superstructure [7]. Long-term field measurements of combined piled-raft foundations further support the need to combine computational models with monitoring data during the service life of a structure [8].

Thus, the current engineering approach is not limited to selecting a single computational model. It is based on a controlled multi-level procedure: preliminary verification using simplified models, refinement using two-parameter or semi-continuum formulations, and final assessment using spatial finite element models. A general methodological framework for this transition from simplified models to continuum formulations is presented in [9].

Classical engineering approaches to the design of high-rise buildings, presented in [10–12], remain an important methodological basis for interpreting numerical results obtained using modern computational software. In particular, the approaches described in [11] are relevant for analysing structural frame deformations caused by differential settlements and for interpreting the results of numerical modelling.

At the same time, the literature review reveals a methodological gap. Most applied studies provide detailed finite element results, whereas the transition between different levels of model complexity and the rules for selecting parameters for intermediate formulations remain insufficiently formalised. This gap is especially important for high-rise buildings, where differential settlements of the foundation system may cause additional axial forces in the vertical load-bearing elements of the structural frame.

Aim and Objectives

The aim of this study is to develop a consistent engineering procedure for assessing contact interaction in the subsoil–foundation–building system for high-rise buildings, taking into account subsoil models, regulatory approaches and the structural consequences of differential settlements.

To achieve this aim, the following objectives were addressed: 1) to systematise subsoil models and define their applicability limits; 2) to harmonise the notation used for settlements, contact pressure and angular distortion; 3) to formulate the analytical basis of the contact problem; 4) to compare the relevant provisions of DBN, Eurocodes and JGJ 3-2010; 5) to substantiate a practical procedure for selecting foundation systems based on deformation compatibility criteria.

Materials and Methods

The methodological basis of the study includes a comparative analysis of subsoil models, verification of the consistency of the governing equations, and interpretation of the results from the standpoint of the serviceability limit state (SLS) and the ultimate limit state (ULS). In this study, the variation in the stiffness characteristics of the structural frame is considered not as an abstract change in the integral stiffness of the system, but as a consequence of specific structural factors: the configuration of the underground part, the presence or absence of stiff walls and diaphragms, the characteristics of joints and connections, and the spatial interaction between vertical load-bearing elements and the foundation system. This structural interpretation makes it possible to relate the results of contact interaction analysis to real design decisions and to the subsequent assessment of the stiffness behaviour of the structural frame.

Unlike a purely descriptive comparison, this study applies a criterion-based «model–verification–decision» approach, which directly links the calculation results with the selection of the foundation system.

One of the typical sources of errors in applied calculations is the inconsistent use of terminology and notation found in regulatory and scientific sources. For this reason, the notation used in this paper is harmonised before formulating the contact interaction problem. Table 1 presents the correspondence between the symbols used in Ukrainian regulatory documents, the notation adopted in this study and the variants commonly found in the literature.

Table 1 – Correspondence of notation used in different sources

Notation according to Ukrainian regulatory documents (DBN, DSTU)	Notation adopted in this study	Variants used in the literature	Typical context	Explanation used in this paper
s	$w(x, y)$	s, u_z, δ	Settlement, vertical displacement	Field of vertical displacements of the foundation base
p, σ_z	$q(x, y)$	p, σ_z, r	Contact reaction of the subsoil	Normal contact pressure at the foundation–subsoil interface
C_z	k_s	k, C_z	Winkler model	Coefficient of subgrade reaction, representing local subsoil stiffness
C_1	k_p	k_1, C_1	Pasternak model	Compression parameter of the subsoil in a two-parameter formulation
C_2	G_p	k_2, t	Pasternak model	Shear interaction parameter in the foundation plane
k, t	k_v, t_v	k, t, α, β	Vlasov model	Generalised compression and shear interaction parameters of a semi-continuum subsoil
Δs	Δs	Δw, δ_s	Differential settlements	Difference between maximum and minimum settlement
i = Δs/L	θ	i, β	Tilt / angular distortion	Generalised angular indicator of foundation deformation

In contact interaction problems, the following subsoil models are distinguished:

1) Winkler model, in which the subsoil is modelled as independent vertical springs without shear interaction between adjacent zones:

$$q(x, y) = k_s w(x, y), \tag{1}$$

where q(x, y) is the contact pressure; w(x, y) is the subsoil settlement; k_s is the coefficient of subgrade reaction;

2) Pasternak model, in which shear interaction between adjacent zones of the subsoil is added to the local Winkler reaction:

$$q(x, y) = k_p w(x, y) - G_p \nabla^2 w(x, y), \tag{2}$$

where k_p is the elastic compression parameter of the subsoil; G_p is the shear interaction parameter; ∇^2 is the Laplace operator; $q(x, y)$ is the contact pressure; $w(x, y)$ is the field of vertical displacements (settlements) of the foundation slab;

3) Filonenko-Borodich model, in which the subsoil reaction is defined non-locally, taking into account the characteristic length of mutual interaction:

$$(1 - l^2\nabla^2)q(x, y) = k_f, w(x, y), \tag{3}$$

where l is the characteristic interaction length; k_f is the compression coefficient in the Filonenko-Borodich model; $q(x, y)$ is the contact pressure; $w(x, y)$ is the field of vertical displacements (settlements) of the foundation slab;

4) Vlasov model, which represents a semi-continuum description of the subsoil, taking into account deformations through the depth of the compressed soil layer:

$$D\nabla^4 w + k_v w - 2\,t_v \nabla^2 w = p(x, y), \tag{4}$$

where $D = \frac{E_f h_f^3}{12(1-\nu_f^2)}$ is the cylindrical stiffness of the slab; k_v, t_v are the generalised subsoil parameters in the Vlasov model; E_f, h_f, ν_f are the modulus of elasticity, thickness and Poisson's ratio of the foundation slab, respectively; $w(x, y)$ is the field of vertical displacements (settlements); $p(x, y)$ is the external load;

5) Continuum models (elasticity theory and the finite element method), in which the soil is considered as a continuum with a spatial stress–strain state:

$$\nabla \cdot \sigma + b = 0, \tag{5}$$

$$\sigma = C : \varepsilon, \tag{6}$$

$$\varepsilon = \frac{1}{2}(\nabla u + \nabla u^T), \tag{7}$$

$$K(u)u = F, \tag{8}$$

where σ is the stress tensor; ε is the strain tensor; u is the displacement vector; b is the body force vector; C is the matrix/tensor of elastic properties; K is the stiffness matrix of the system; F is the load vector; the expression $K(u)\ u = F$ is the result of spatial discretisation of the governing elasticity equations using the finite element method.

In high-rise design practice, continuum models should be considered not only in a linear elastic formulation, but also in a nonlinear elastoplastic formulation of the subsoil. This approach is particularly important for multilayered subsoil conditions, local stress concentration zones, significant differential deformation and cases where a linear elastic model does not provide sufficient accuracy in representing the actual stress–strain state of the subsoil–foundation–building system.

In the practical calculation sequence, the Winkler, Pasternak and Vlasov models may be used for the preliminary and refined assessment of foundation alternatives, whereas the final verification of the stress–strain state of the subsoil–foundation–building system should be performed using spatial finite element models.

For high-rise buildings, such refined spatial analysis should take construction staging and the staged application of loads into account, since the stiffness of the system develops progressively during construction. In this formulation, the subsoil–foundation–building system is considered as an evolving system, while settlements, contact pressures and additional internal forces are assessed with regard to the sequential change in the structural scheme.

Based on the characteristics of the models considered above, their integral comparison is presented in Table 2.

Table 2 – Comparison of subsoil models

Model	Physical concept	Mathematical complexity	Accuracy	Field of application	Advantages	Limitations
Winkler model	Local reaction without shear interaction	Low	Low / medium	Preliminary calculation	Simplicity and calculation speed	Neglects spatial redistribution
Pasternak model	Local reaction and shear interaction	Low / medium	Medium	Practical foundation calculations	Improved assessment of differential settlements	Requires determination of two parameters
Filonenko-Borodich model	Two-parameter interaction	Medium	Medium	Locally complex zones	More physically justified pressure distribution	Difficult parameter identification
Vlasov model	Semi-continuum description	Medium / high	Increased	Raft foundations with a large area; multilayered subsoil	Accounts for the compressed subsoil layer	Sensitive to parameter identification
Continuum FEM model	Continuous 2D/3D medium	High	High	Final system calculation	Most complete description of subsoil–foundation–building interaction	High modelling cost

To assess the combined behaviour of the subsoil–foundation–building system, a generalised mathematical model of the interaction between the foundation slab and the subsoil is used. This study applies an approach based on classical elastic subsoil models, which make it possible to describe the relationship between loading, deformation of the foundation structure and the reaction of the subsoil.

In the general case, the behaviour of a foundation slab resting on an elastic subsoil may be described by the governing equation for slab bending:

$$D\nabla^4 w(x,y) + q(x,y) = p(x,y), \tag{9}$$

where D is the flexural rigidity of the foundation slab; $w(x, y)$ is the field of vertical displacements (settlements) of the foundation slab; $q(x, y)$ is the contact pressure of the subsoil; $p(x, y)$ is the external load applied to the foundation slab; and ∇^4 is the biharmonic differential operator of slab bending. For a two-parameter Pasternak-type subsoil model, the contact pressure may be expressed as $\mathrm{q(x,y) = k_p(x,y)w(x,y) - G_p\nabla^2 w(x,y)}$ is the compression parameter of the subsoil, G_p is the shear interaction parameter, and ∇^2 is the Laplace operator.

Solving this equation makes it possible to determine the displacement field of the foundation slab and to assess settlements at characteristic points of the system. One of the main parameters characterising the deformation state of the foundation is differential settlement:

$$\Delta\, s = s_{max} - s_{min}, \tag{10}$$

$$\theta \approx \frac{\Delta s}{L}, \tag{11}$$

where s_{max} and s_{min} are the maximum and minimum settlements in the control zone, respectively; Δs is the differential settlement; θ is the angular distortion indicator; and L is the design distance between the control points.

Here, $w(x, y)$ is interpreted as a continuous field of vertical displacements (settlements) of the foundation slab, whereas s_{max} and s_{min} are used for settlements at control points or as generalised design indicators of this field.

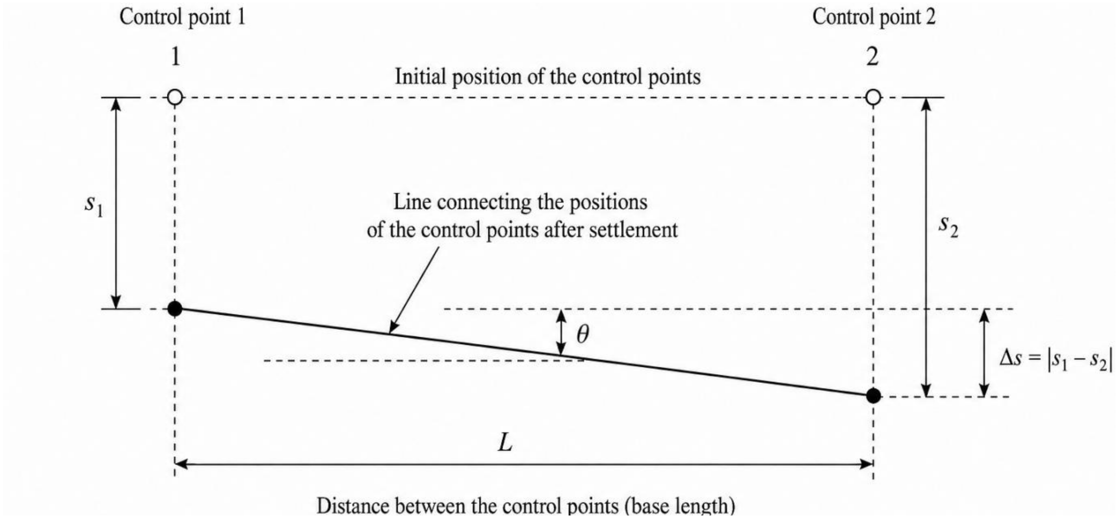

Figure 1 – Engineering scheme for assessing differential settlement and angular distortion of the foundation system

Differential settlement (Δs) and angular distortion (θ) are the main engineering indicators through which the effect of foundation system deformation on the superstructure is generalised. Their geometric meaning is illustrated in Fig. 1, where s_1 and s_2 correspond to settlements at control points, L is the distance between them, and $\theta = \Delta s / L$ characterises the relative distortion of the foundation system.

The parameter Δs characterises differential settlement, whereas θ characterises the angular distortion of the foundation system; an increase in these parameters causes redistribution of forces in the structural frame.

In subsequent analysis, these indicators of differential deformation (Δs, θ) are used as input data for force interpretation in the spatial model of the superstructure. Refined additional forces are determined with regard to the stiffness of the structural frame and the adopted load combinations, which ensures a consistent assessment of the combined behaviour of the subsoil–foundation–building system.

$$N_{add,j} = -\frac{E_j A_j}{h_j}\Delta_j, \tag{12}$$

$$N_{z,j} = N_{z,j}^{(load)} + N_{add,j}, \tag{13}$$

where $N_{add,j}$ is the additional axial force in the j-th vertical element caused by support settlement; $E_j A_j$ is the axial stiffness of the element; h_j is the height (design length) of the element; Δ_j is the vertical displacement of the support node; $N_{z,j}^{(load)}$ is the force due to external loads; and $N_{z,j}$ is the total axial force.

Equations (9)–(13) form a consistent analytical scheme for the transition from the mathematical formulation of the contact interaction problem for a foundation slab resting on subsoil to the engineering assessment of differential settlements, angular distortion and additional internal forces in the vertical elements of the structural frame. Equations (12) and (13) show that kinematic displacements of supports may generate additional internal forces even without any change in the external load.

In the subsequent regulatory interpretation of JGJ 3-2010, the notation N_j is used for the same physical effect as $N_{add,j}$ in the general formulation of the problem, namely the additional axial force caused by differential support settlement. Therefore, the relationships presented above provide an analytical basis for comparing the approaches of DBN, Eurocodes and Chinese standards in terms of the contact, deformation and force assessment of the subsoil–foundation–building system.

Results

To specify the regulatory framework relevant to Ukrainian engineering practice, this study considers DBN V.2.1-10:2018 Bases and Foundations of Buildings and Structures. General Provisions [13], DBN V.1.1-45:2017 Buildings and Structures in Complex Engineering-Geological Conditions. General Provisions [14], DBN V.1.1-46:2017 Engineering Protection of Territories, Buildings and Structures against Landslides and Collapses. General Provisions [15], DBN V.2.2-41:2019 High-Rise Buildings. Basic Provisions [16], DBN V.1.2-2:2006 Loads and Actions. Design Standards [17], DBN A.1.1-94:2010 Design of Building Structures according to Eurocodes. Basic Provisions [18], DSTU-N B EN 1990:2008 Eurocode. Basis of Structural Design [19], DSTU-N B EN 1997-2:2010 Eurocode 7. Geotechnical Design. Part 2: Ground Investigation and Testing [20], DSTU-N B EN 1998-1:2010 Eurocode 8. Design of Structures for Earthquake Resistance. Part 1: General Rules, Seismic Actions and Rules for Buildings [21], DSTU-N B EN 1997-1:2010 Eurocode 7. Geotechnical Design. Part 1: General Rules [22], DSTU-N B EN 1998-5:2012 Eurocode 8. Design of Structures for Earthquake Resistance. Part 5: Foundations, Retaining Structures and Geotechnical Aspects [23], as well as the Chinese standards JGJ 3-2010 Technical Specification for Concrete Structures of Tall Buildings [24] and GB 50010-2010 Code for Design of Concrete Structures [25].

For Ukrainian engineering practice, it is appropriate to combine the mandatory design verification required by the current DBN standards or Eurocodes with the applied tools provided in JGJ 3-2010 for construction staging, control of differential settlements and verification of additional forces in vertical load-bearing elements.

This approach enables a transition from the regulatory control of subsoil behaviour to the assessment of the stress–strain state of the structural frame.

The adaptation of three elements of Chinese engineering practice is considered particularly useful: 1) mandatory staged analysis taking into account the actual construction sequence; 2) verification of additional forces in the structural frame caused by settlements at the nodes of the lower storeys; 3) active geotechnical monitoring for updating the computational model during construction. Such an approach reduces the gap between design predictions and the observed behaviour of the system in situ.

A comparative analysis of the regulatory approaches is presented in Table 3.

Table 3 – Comparative analysis of regulatory approaches

Regulatory framework	Strengths	Limitations	Typical focus	Engineering implication for design
DBN V.2.1-10:2018; DBN V.1.1-45:2017; DBN V.1.1-46:2017	Clear regulatory certainty for Ukraine; direct link with expert review	Lower flexibility for non-standard geotechnical scenarios	Control of limit states and deformation serviceability	Basic mandatory decision-making framework
DSTU-N B EN 1997-1:2010; DSTU-N B EN 1998-5:2012	Design according to ULS/SLS (ultimate and serviceability limit states); consistency of design checks	Requires careful determination of parameters in accordance with national standards and their annexes	Reliability throughout the life cycle; consistency of design situations	Appropriate for in-depth verification of complex solutions
JGJ 3-2010; GB 50010-2010	Strong applied focus on high-rise buildings, construction staging and force effects of settlements	Limited direct compatibility with the Ukrainian regulatory review procedure	Influence of differential settlements on the structural frame; monitoring and correction	Useful as methodological support for DBN-based design of high-rise buildings in high-rise building design

In the section of JGJ 3-2010 [24] devoted to high-rise buildings, differential settlement is considered specifically as a source of additional force effects on the structural frame. The JGJ approach combines limitation of differential settlements, direct calculation of additional axial forces in vertical elements, and structural measures when control thresholds are exceeded.

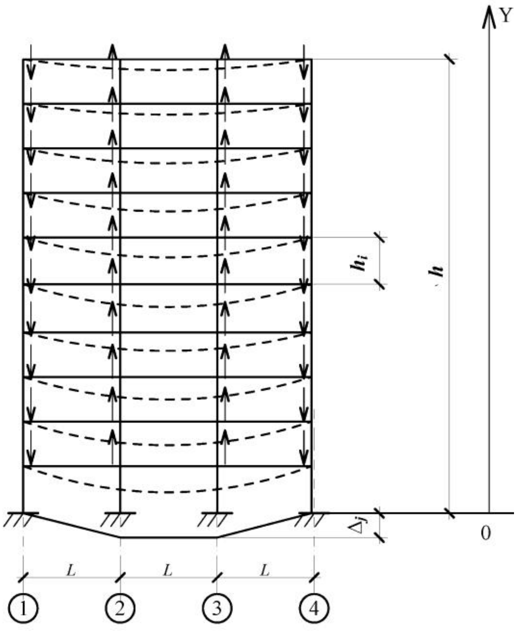

Figure 2 – Generalised deformation scheme of a high-rise building under differential support settlements

For unambiguous interpretation in this subsection, the relationships are divided into two groups. The first group, which directly corresponds to the provisions of JGJ 3-2010, includes relationships (14) and (15). The second group comprises formulas (16)–(18), presented in this paper as an engineering interpretation of the regulatory provisions of JGJ 3-2010. These interpretative formulas are used solely to analytically explain the mechanism of force redistribution and do not replace the direct regulatory relationships of JGJ 3-2010.

For high-rise buildings, this formulation is fundamental, since even when absolute settlements are acceptable, differential deformation changes the support conditions of the structural frame and causes secondary redistribution of forces between load-bearing elements. The geometric interpretation of the indicators of differential settlement *Δs* and angular distortion θ is shown in Fig. 1. The generalised deformation scheme of a high-rise building is shown in Fig. 2, and the design model of a vertical element subjected to support settlement in the regulatory interpretation of JGJ 3-2010 is shown in Fig. 3.

When determining additional forces in vertical elements, for the j-th vertical element subjected to support settlement Δj, JGJ 3-2010 uses the following deformation compatibility relationship:

$$\frac{R_j h_1}{E_j A_j} = \Delta_j, \qquad (14)$$

where R_j is the force that arises in the element due to support displacement; h_1 is the height of the first storey; E_jA_j is the axial stiffness of the element; Δ_j is the settlement of the support node. In the general model, the notation h_j is used for the height of the j-th vertical element, whereas in JGJ 3-2010 h_1 is used as the characteristic height of the element. Subsoil settlement imposes deformation on the vertical element, and the magnitude of the additional force is determined by its axial stiffness.

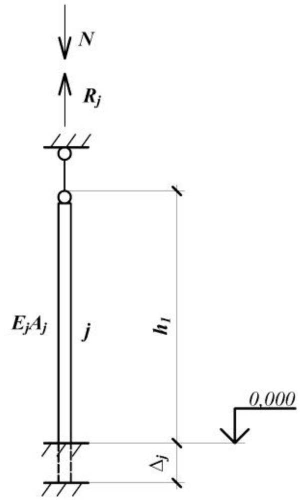

Figure 3 – Design scheme of a vertical element subjected to support settlement according to JGJ 3-2010

The additional force N_j arising in the element is expressed as follows:

$$N_j = -R_j = \frac{E_jA_j}{h_1}\Delta_j, \qquad (15)$$

where the minus sign reflects the orientation of the axial force adopted in the design scheme. In terms of the general formulation, N_j corresponds to the additional axial force $N_{add,j}$ with due regard to the sign convention of the specific computational model.

The total axial force in the vertical element is determined as:

$$N_{z,j} = N_{z,j}^{(load)} - N_j, \qquad (16)$$

where $N_{z,j}^{(load)}$ is the design force caused by external loads without consideration of settlement effects; $N_{z,j}$ is the total force including the effect of differential settlement.

The load-bearing capacity of vertical elements should therefore be verified not only for the force caused by external loads, but for the total force including settlement effects. In the general formulation, this basic axial force corresponds to $N_{(load)}$, while the difference in notation is due to the transition to the regulatory interpretation of JGJ.

For deformation assessment and the combination of effects, JGJ uses a design expression applied to evaluate the influence of settlements in combination with the main loads:

$$\Delta s_{ij} = |s_i - s_j|, \qquad (17)$$

$$\theta_{ij} \approx \frac{\Delta s_{ij}}{L_{ij}}, \qquad (18)$$

where s_i, s_j are settlements at two control points; L_{ij} is the distance between them; Δs_{ij} is the local differential settlement; θ_{ij} is the angular distortion. Physically, these parameters characterise a hazardous deformation gradient that generates additional forces in the structural frame. In this context, Δs and θ are used as integral indicators of differential foundation deformation, whereas Δs_{ij} and θ_{ij} are used as local indicators for individual elements or nodes of the structural frame.

Within the engineering interpretation of the provisions of JGJ 3-2010, exceeding a local differential settlement Δs_{ij} of approximately 1 cm should be regarded not as a universal regulatory limit, but as a practical indicator of the need for an additional verification of the force effects in the structural frame. In such a case, a refined calculation should be performed and, where necessary, structural measures should be considered, including verification or strengthening of the lower-storey elements. The final decision should not be based solely on exceeding this indicative value, but on a consistent assessment of deformation compatibility and additional internal forces in the subsoil–foundation–building system.

The practical value of this approach lies in the transition from settlement prediction to the verification of load-bearing elements and the adoption of design decisions. It makes it possible to identify cases in which settlements that are acceptable according to geotechnical criteria may become critical for the structural frame due to additional axial forces.

Compared with DBN and Eurocodes, JGJ 3-2010 [24] more explicitly formalises frame-oriented verification of additional forces caused by differential settlements. For the general verification of load combinations, ASCE/SEI 7-22 [26] may be considered as an additional international reference.

The analysis of the results shows that a design decision should be adopted according to the following sequence: «subsoil model → q, w, Δs, θ → force effects in the structural frame → selection of the foundation type». The transition from the Winkler model to the Pasternak, Vlasov and continuum finite element models increases the reliability of predicting contact pressures, differential settlements and additional forces. Simplified models are appropriate for preliminary selection, whereas spatial finite element analysis should be used for the final justification of the foundation system. For piled-raft systems, this conclusion is consistent with the study [27], which demonstrates the sensitivity of differential settlements to raft stiffness, pile configuration and loading.

For a unified interpretation of the results, it is appropriate to use the integral suitability index:

$$\eta = max\left\{\frac{q_{max}}{q_{allow}}, \frac{\Delta s}{\Delta s_{allow}}, \frac{\theta}{\theta_{allow}}\right\}, \qquad (19)$$

where η is an integral indicator for the preliminary assessment of the state of the subsoil–foundation–building system. It simultaneously accounts for limitations related to contact pressures and deformation compatibility. This index does not replace a full regulatory design check; it is used for engineering comparison of scenarios and for selecting alternatives for subsequent detailed verification. q_{max} is the design maximum contact pressure; q_{allow} is the allowable contact pressure; Δs_{allow} is the allowable differential settlement; θ_{allow} is the allowable angular distortion.

For the preliminary engineering assessment of alternatives, when $\eta > 1$, refinement of the computational model, modification of the foundation type or revision of the structural solution is required.

The engineering decision should follow a multi-level procedure combining preliminary Winkler-based analysis, refinement using the Pasternak or Vlasov models, spatial finite element analysis, regulatory interpretation according to DBN, Eurocodes and JGJ 3-2010, and selection of the foundation type based on contact, deformation compatibility and structural force-state criteria. The generalised procedure is presented in Fig. 4.

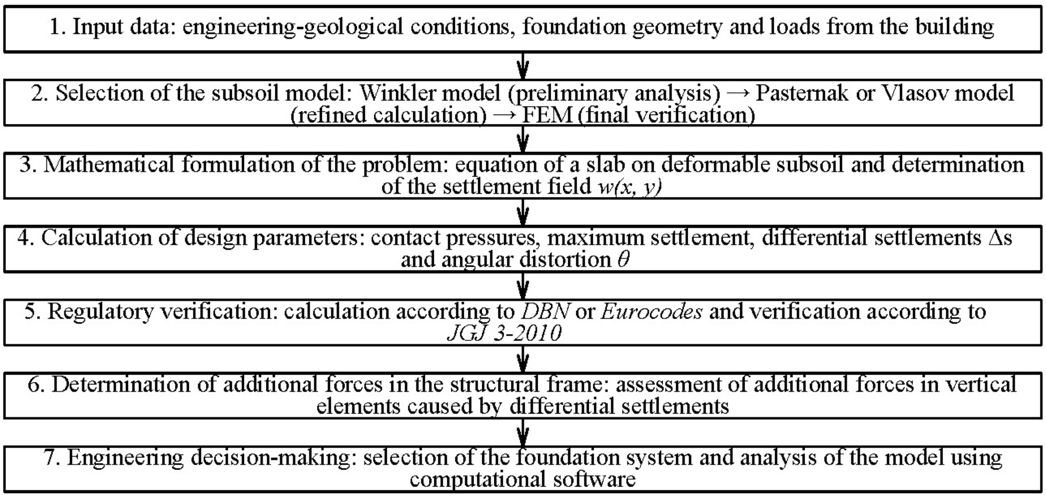

Figure 4 – Procedure for assessing contact interaction in the subsoil–foundation–building system for high-rise buildings

The obtained results are consistent with numerical and applied studies [1, 2, 3, 5, 7], which confirm the need for an integrated assessment of the subsoil–foundation–building system. Therefore, the design decision should rely on a coordinated evaluation of contact pressure, deformation compatibility and force effects, rather than on the isolated control of a single indicator.

Conclusions

This study systematises approaches to modelling contact interaction in the subsoil–foundation–building system, formulates a generalised mathematical formulation of the problem, and demonstrates the relationship between differential foundation settlements and additional axial forces in the vertical elements of the structural frame. For high-rise buildings, the effectiveness of the foundation system is governed not only by absolute settlement, but primarily by differential settlement and the associated force effects.

The one-parameter Winkler model is suitable for preliminary analysis, but is insufficient for final design decisions under complex conditions. The Pasternak, Filonenko-Borodich and Vlasov models improve the physical adequacy of prediction by accounting for the spatial redistribution of subsoil reaction. Continuum finite element models are a necessary stage of final assessment for critical high-rise structures, particularly in cases involving construction staging and heterogeneous subsoil conditions.

The comparative analysis of DBN, Eurocodes and Chinese standards shows their conceptual compatibility despite differences in regulatory structure. In Ukrainian practice, Chinese engineering approaches may be considered as a methodological supplement for staged analysis, assessment of settlement-induced additional forces and geotechnical monitoring, provided that the mandatory DBN-based design procedure is maintained.

The practical result of the study is a methodologically consistent procedure for selecting a subsoil model and foundation system. This procedure combines analytical and numerical interpretation of the influence of differential settlements on the stress–strain state of the structural frame of a high-rise building, thereby improving the reliability of design decisions and reducing the risk of subsequent design corrections.

Further research should develop a cyclic «model–monitoring–model updating» procedure and verify it through numerical and field studies.

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Контактна взаємодія фундаментних конструкцій з основою та її вплив на жорсткісні характеристики каркасу висотних будівель

Аннотація. Зростання частки висотних будівель у щільній міській забудові потребує надійної оцінки контактної взаємодії фундаментних конструкцій із ґрунтовою основою. Для таких будівель експлуатаційна придатність і конструктивна надійність визначаються не лише абсолютними осіданнями, а й нерівномірними осіданнями, кутовою деформацією та їхнім впливом на просторову роботу несучого каркаса. Метою дослідження є розроблення узгодженої інженерної процедури оцінювання системи «основа – фундамент – будівля» у висотному будівництві. Дослідження ґрунтується на порівняльному аналізі класичних, двопараметричних, напівконтинуальних і континуальних моделей ґрунтової основи, зокрема моделей Вінклера, Пастернака, Філоненка-Бородича та Власова, а також просторових скінченно-елементних постановок. Для опису осідань, контактного тиску, кутової деформації та додаткових поздовжніх зусиль, спричинених нерівномірною деформацією фундаментів, використано уніфіковану систему позначень. Показано, що нерівномірні осідання та кутова деформація є ключовими інженерними показниками для висотних будівель, оскільки вони безпосередньо впливають на перерозподіл зусиль у колонах, стінах та інших вертикальних несучих елементах. Запропоновано поетапну процедуру моделювання, у якій попередня оцінка доповнюється уточненим аналізом і подальшою просторовою перевіркою всієї системи. Для попереднього порівняння плитних, пальових і плитно-пальових фундаментних рішень використано інтегральний індекс придатності. Практична цінність дослідження полягає у формалізації переходу від спрощених аналітичних моделей до детального просторового аналізу та зниженні ризику прийняття проєктних рішень, у яких недооцінюються конструктивні наслідки нерівномірних осідань.

Ключові слова: нерівномірні осідання; кутова деформація; деформаційна сумісність; плитно-пальовий фундамент; контактний тиск; взаємодія основи і споруди.

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