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IMPACT OF STRESS–STRAIN STATE EVALUATION METHOD IN RAFT FOUNDATION ANALYSIS

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The article presents a comparison of stresses in a soil base under a rectangular raft foundation obtained by the analytical corner points method and finite element numerical simulation for elastic–linear and elastic–plastic soil models (with the Mohr–Coulomb failure criterion). The aim of the study is to refine the influence coefficients used in the corner points method, to identify quantitative and qualitative differences between the approaches, and to outline the boundaries of their correct application. The comparison revealed significant discrepancies not only in the values of contact stresses but also in the shape of their distribution surface. Preliminary discrepancy coefficients for the studied case have been determined.

Keywords: raft foundation, soil base, stress-strain state, corner points method, numerical simulation, FEM, linear-elastic model, Mohr–Coulomb model.

1. Introduction

The design of raft foundations relies on the accurate assessment of the soil-structure interaction (SSI), particularly on the reliable determination of contact stresses. The choice of calculation method directly affects the results of bearing capacity evaluation and the prediction of soil deformations. Analytical approaches [1,3,4], such as the corner points method [1], are traditionally widely used in engineering practice due to their simplicity and relatively low labor intensity. However, these methods are based on simplified assumptions regarding the stress–strain state of the soil, which can lead to errors under specific conditions, such as non-uniform loading, complex geometry, or heterogeneous soil composition.

Modern numerical methods, particularly finite element modeling (FEM), allow for a more detailed consideration of soil behavior, including elastic–plastic properties and realistic boundary conditions [2, 5]. Nevertheless, they require significant computational resources, expertise in specialized software, and comprehensive input data on soil properties.

Therefore, a comparative study of the results obtained using the analytical corner points method and numerical simulation is relevant both for verifying the accuracy and applicability limits of traditional approaches and for refining influence coefficients to adapt calculation methods to current engineering requirements. Understanding the quantitative and qualitative differences between these methods will enable engineers to make informed decisions when selecting a calculation approach depending on the design conditions, while also optimizing the balance between accuracy, available resources, and calculation time.

2. Relevance of the Study

Accurate determination of contact stresses in the soil base is essential for the reliable design of raft foundations. Traditional analytical methods, such as the corner points method, offer simplicity but are based on simplified assumptions, which may lead to errors under complex engineering conditions. Numerical FEM provides a more realistic representation of soil behavior but requires considerable resources. Comparing these approaches is relevant for defining their applicability limits and improving calculation accuracy.

3. Methods for estimating stresses under the foundation

At present, four groups of methods are available for determining stresses in soil foundations:

a) Analytical methods:

- Boussinesq method – the classical solution of the elastic half-space problem for point and distributed loads; applicable to ideally elastic soils.

- Corner Points Method – a simplified engineering approach for determining stresses beneath rectangular foundations; convenient in practical calculations but based on simplified assumptions.
- Elasticity-based methods (Flamant, Westergaard, Boussinesq-Brusson, etc.) – provide more accurate solutions for specific loading conditions and soil structures.

b) Semi-empirical methods, which combine theoretical models with experimental data (e.g., formulas incorporating subgrade reaction coefficients). These are employed in national and international design codes for evaluating bearing capacity and settlements.

c) Numerical simulation:

- Finite Element Method (FEM) – enables simulation of complex geometries, heterogeneous soils, as well as nonlinear and plastic soil behavior.
- Finite Difference Method (FDM) and Boundary Element Method (BEM) – less widely used but effective for specific engineering problems.
- Soil models may include linear-elastic, elastic–plastic (Mohr–Coulomb, Drucker–Prager), hyperelastic, and others.

d) In situ experimental methods:

- Field load tests – direct measurement of settlements and stresses under trial loading of a foundation slab.
- Pressuremeter and dilatometer tests – determination of soil parameters subsequently applied in stress–strain analyses.

Analytical methods allow a quick and straightforward estimation of stress distribution in soils, though with limited accuracy.

4. Analytical approach to calculating stresses under a raft foundation

The corner points method is one of the most common simplified engineering approaches for determining contact stresses under rectangular foundations. Its principle is based on analytical relationships derived from the solution of the elastic half-space problem Boussinesq solution (1) for a finite rectangular loaded area, using the superposition of effects from each of the corner points (2)

$$\sigma_z = \frac{3Pz^2}{2\pi\left(r^2+z^2\right)^{5/2}}, \tag{1}$$

where σ_z — vertical stress at a point located at depth z; P - magnitude of point load; r - horizontal distance from the load application point to the point of interest; z - depth of the calculation point.

$$\sigma_z = \frac{q}{4\pi}\left[\varphi(x_1,y_1)+\varphi(x_2,y_2)-\varphi(x_1,y_2)-\varphi(x_2,y_1)\right], \tag{2}$$

where

$$\varphi(x,y) = \arctan\left(\frac{xy}{zR}\right)+\frac{xyz}{R\left(z^2+x^2+y^2\right)} \tag{3}$$

and

$$R=\sqrt{x^2+y^2+z^2}. \tag{4}$$

Here q - intensity of distributed load; x_1, x_2, y_1, y_2 - coordinates of the loaded area corners.

The feasibility of applying this method is determined by several factors:

– Calculation efficiency – it enables a rapid estimation of stress distribution without the need for complex numerical simulation.

– Minimal input data requirements – only the geometric parameters of the foundation, the load magnitude, and the soil deformation modulus are required.

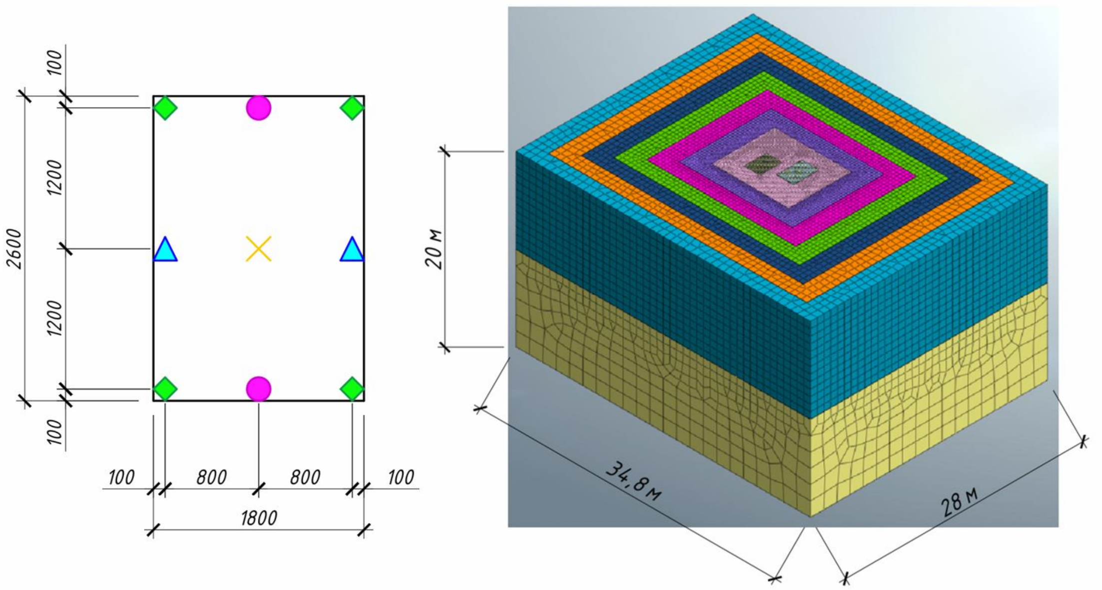
– Analytical transparency – the calculation scheme is straightforward and easily verifiable, which is important for engineering project reviews.

– Effectiveness under standard conditions – the method provides acceptable accuracy for cases where the foundation has a simple geometry (rectangular slab), the load is uniformly distributed, and the soil can be considered homogeneous and isotropic.

For preliminary design tasks, when a quick assessment of the feasibility of a design solution is required, the corner points method is economically and temporally efficient. It can also serve as a tool for verifying numerical simulation results, detecting anomalous values, or identifying significant errors in input data.

However, the method has limitations related to model idealization and the inability to account for complex boundary conditions, soil heterogeneity, and non-uniform load distribution. Therefore, its application is most justified for problems with regular geometry, uniform loading, and homogeneous soil structure, as well as in cases where any loss of accuracy can be compensated by a design safety margin.

For the study, a foundation was selected in the form of a monolithic reinforced concrete slab with dimensions of 1.8×2.6 m and a thickness of 0.3 m (Fig. 1(a)). The foundation was subjected to a uniformly distributed pressure of 200 kPa. The supporting soil was modeled as medium sand with an elastic modulus E=30 MPa and unit weight γ=17 kN/m^3.



(a) (b)

Fig.1. Elements of SSI model for numerical simulation in Midas GTS NX: (a) – raft foundation plan with test points; (b) – FE model

Stresses were determined at characteristic points selected for the analysis (Fig. 1(a)). As a result of the calculations, stress distribution diagrams of the additional pressure σ_{zp} were constructed down to a depth of 9.9 m, corresponding to 5.5 times the foundation width (Figs. 4–7).

The maximum stresses occur beneath the central zone of the slab (204 kPa), while the minimum stresses are observed in the corner zones (126 kPa). Starting from a depth of about 3 m, the stress values become nearly uniform.

5. Numerical simulation to determine stresses under the foundation footing

Numerical simulation, particularly the Finite Element Method, is a modern tool for analyzing SSI. It allows for consideration of complex foundation geometries, actual geological conditions with stratification and nonlinear soil behavior, as well as accurate load distribution, including dynamic and non-uniform effects.

FEM enables a detailed analysis of the stress–strain state of the soil mass, assessment of the interaction between all elements of the system (soil–foundation–superstructure), and prediction of long-term behavior, taking into account creep, consolidation, and cyclic loading.

This approach facilitates comparison and optimization of structural design alternatives and integration with geotechnical monitoring, which makes it possible to validate models with field data and develop digital twins for real-time observation.

For the study, a rectangular raft foundation was selected with dimensions of 2.6×1.8 m and a thickness of 0.3 m, where the aspect ratio is η=1.44. Stress distribution was analyzed in characteristic zones of the foundation chosen for the study: corners, midpoints of the side edges - left/right, center, midpoints of the edges - top/bottom (Fig. 1(a)). Numerical simulation was carried out using the software package *Midas GTS NX*, applying solid finite elements to simulate the soil mass and shell elements to model the foundation slab. The dimensions of the soil block included in the computational model were 28×34.8×20 m (Fig. 1(b)).

The FEM mesh has variable triangulation in both plan and depth, ranging from 0.2 m beneath the foundation to 2.8 m at the bottom boundary of the computational domain.

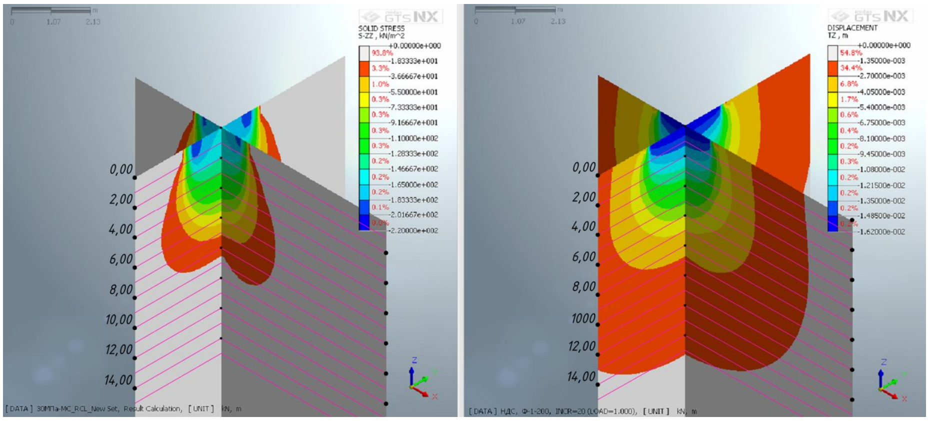
The study of SSI was carried out in two modeling approaches:

1. Elastic soil behavior law (model parameters: elastic modulus E=30 MPa, unit weight γ=18 kN/m^3, Poisson's ratio ν=0.3).
2. Elasto-plastic soil behavior law with the Mohr–Coulomb failure criterion (model parameters: elastic modulus E=30 MPa, unit weight γ=18 kN/m^3, Poisson's ratio ν=0.3, cohesion c=1kPa, internal friction angle φ=35°, dilation angle ψ=10°).

The foundation slab was modeled with shell elements characterized by an elastic modulus E=30 GPa, Poisson's ratio ν=0.2, and concrete unit weight γ=25 kN/m^3.

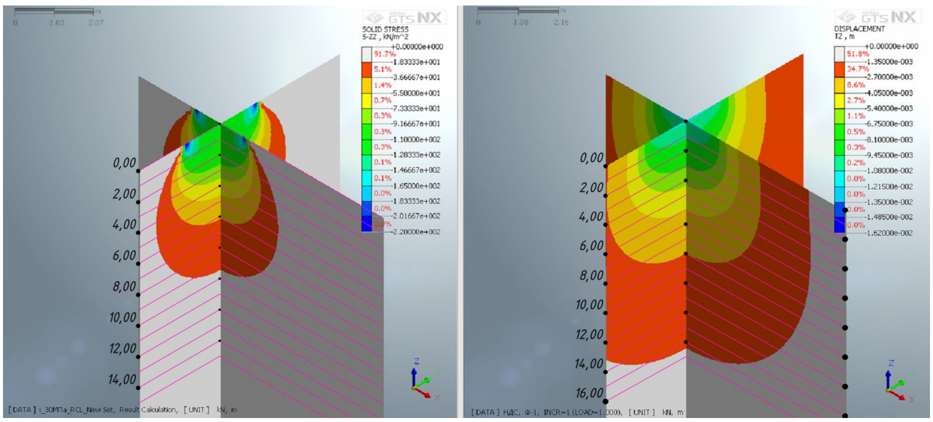
At the surface between the slab shell elements and the soil solid elements, interface elements were introduced with the following stiffness parameters: normal stiffness K_n=6.35*10^5 kN/m^3 and shear stiffness K_t=57.7*10^3 kN/m^3. If the soil mass exhibits nonlinear properties, additional interface parameters are applied: cohesion c=0.5 kPa and internal friction angle φ=19.3°.

The results of the SSI analysis using the linear elastic soil model are presented in Fig. 2, while the results obtained considering the nonlinear soil behavior are shown in Fig. 3.



(a) (b)

Fig. 2. Results of SSI analysis (X,Y-direction slice plane), linear elastic model: (a) - stresses (kPa); (b) - displacements (mm)



(a) (b)

Fig. 3. Results of SSI analysis (X,Y-direction slice plane), Mohr–Coulomb model: (a) - stresses (kPa); (b) - displacements (mm)

A comparison of stresses in the soil mass (Figs. 2(a), 3(a)) shows that the elasto-plastic model with the Mohr–Coulomb failure criterion produces higher stress values than the purely elastic model. It should also be noted that the shape of the additional stress zone in the soil mass differs: in the elastic model, stresses form a more spherical distribution, i.e., they dissipate over a wider area.

The analysis of soil deformations (Figs. 2(b), 3(b)) demonstrates that the elastic soil model results in smaller deformations compared to the Mohr–Coulomb elasto-plastic model. In the following sections of this paper, a more detailed comparison of soil stresses and deformations will be performed depending on the calculation method.

6. Influence of the method for calculating stresses in the base of a raft foundation

The analysis of calculation results within this study was carried out for selected zones within the foundation area: corner, top/bottom edge, left/right edge, and central zone (Fig. 1(a)). At these points, stresses and deformations in the soil mass were evaluated with depth.

6.1. Stresses in the soil mass under the foundation

In the corner zones of the slab, at a depth of 0.1 m, the vertical stresses were found to be 272.97 kPa when using the elasto-plastic model with the Mohr–Coulomb failure criterion; 270.25 kPa when using the elastic soil model; and 125.95 kPa according to the analytical Corner Points Method (Fig. 4).

Also, it should be noted that at depths of approximately 2.2 m and below, the stresses obtained from numerical simulation converge to nearly identical values, regardless of the material properties assigned to the soil finite elements. On average, the stresses calculated analytically are about 2.2 times lower compared to those obtained from numerical simulation.

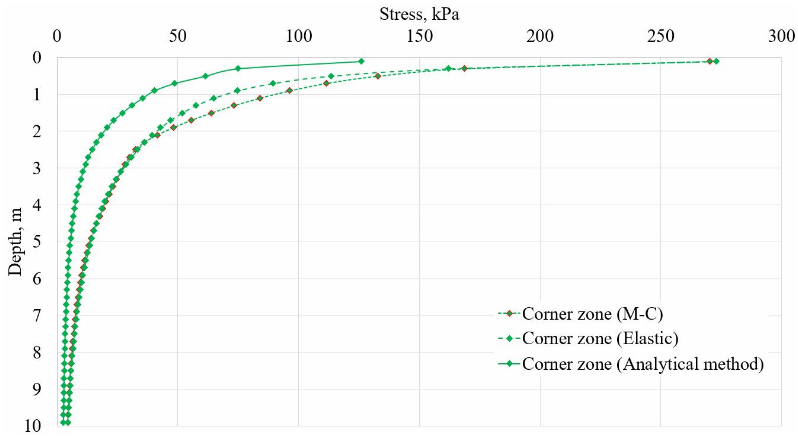


Fig. 4. Stresses in the corner zones

In the top/bottom edge zones of the slab, at a depth of 0.1 m below the foundation base, the vertical stresses were 213.18 kPa when using the elasto-plastic model with the Mohr–Coulomb failure criterion; 200.23 kPa for the elastic soil model; and 159.36 kPa according to the Corner Points Method (Fig. 5). It should be noted that in this zone, the stresses show good correlation starting from a depth of 4 m and below, regardless of the modeling approach (failure criterion). On average, the stresses obtained analytically are 2.6 times lower compared to those from numerical simulation.

In the side zones (left/right) beneath the foundation, at a depth of 0.1 m, the stresses were: 205.02 kPa for the Mohr–Coulomb elasto-plastic model; 193.42 kPa for the elastic soil model; and 159.57 kPa according to the Corner Points Method (Fig. 6). The same trend of good stress correlation at depths of 4 m and below is observed here, similar to the top/bottom case. On average, the stresses from analytical calculations are 2.6 times lower compared to numerical simulation.

In the central zone beneath the foundation, at a depth of 0.1 m, the stresses ranged as follows: 204.39 kPa from analytical calculation (Corner Points Method); 164.61 kPa for the Mohr–Coulomb elasto-plastic model; and 110.62 kPa for the elastic soil model (Fig. 7). An interesting trend was observed: up to a depth of 1 m, stresses in the central zone remain almost unchanged, while below 1 m they dissipate significantly. In the top zone (up to 1 m depth), analytical stresses are 1.2…1.8 times higher, but on average (with increasing depth), analytical stresses are 2.85 times lower compared to numerical simulation.

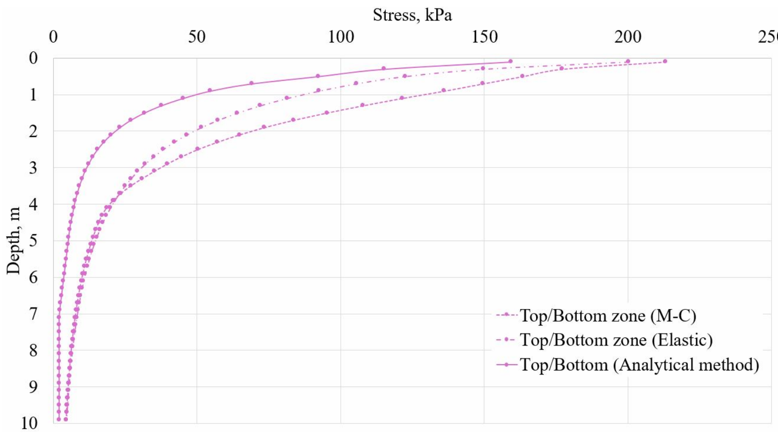


Fig. 5. Stresses in the top/bottom zones

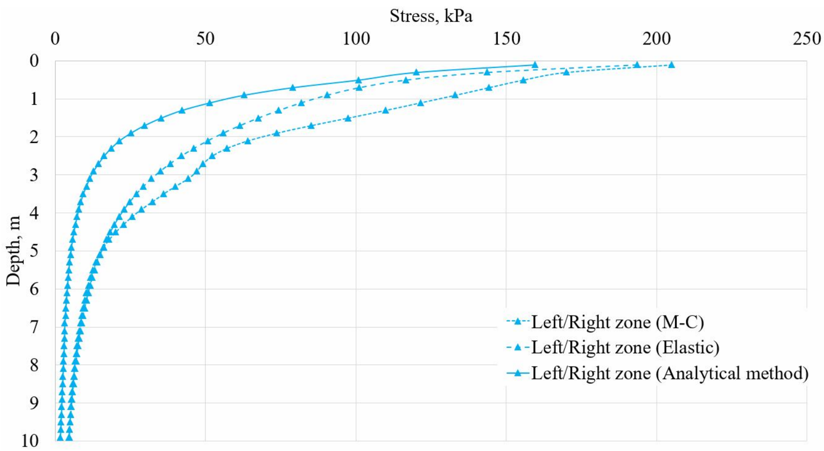


Fig. 6. Stresses in the left/right zones

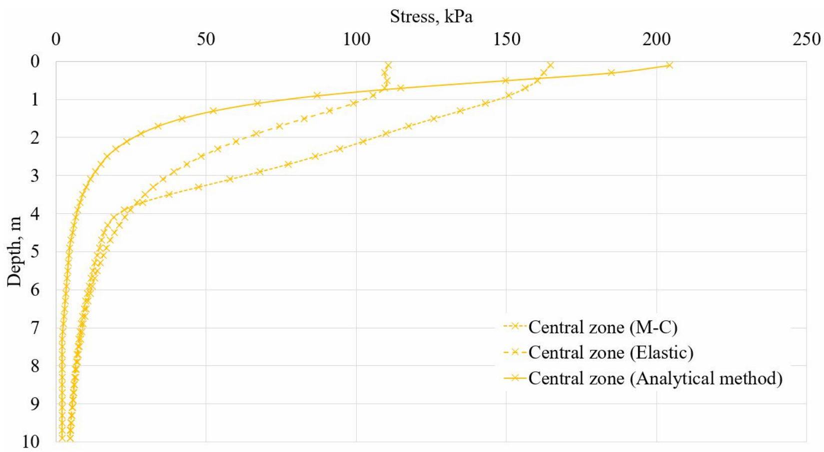
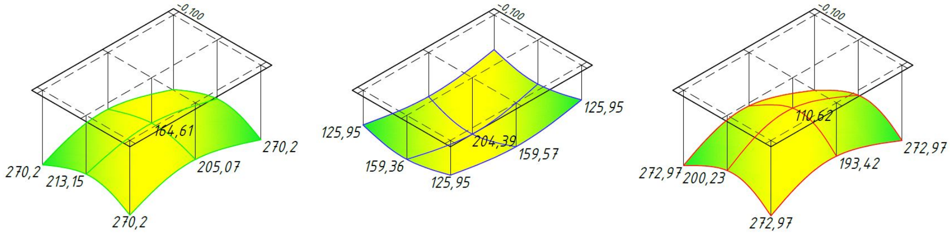


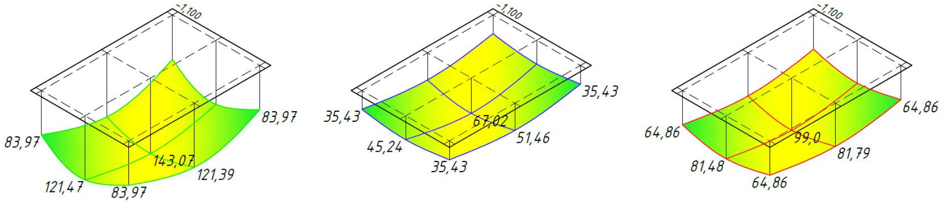
Fig. 7. Stresses in the central zone

Thus, the quantitative analysis of stresses in the soil mass was performed and presented above. For the qualitative analysis, stress surfaces were constructed at the following depths: 0.1 m (Fig. 8), 1.1 m (Fig. 9), 3.1 m (Fig. 10), 5.1 m (Fig. 11), 7.1 m (Fig. 12), and 9.9 m (Fig. 13).



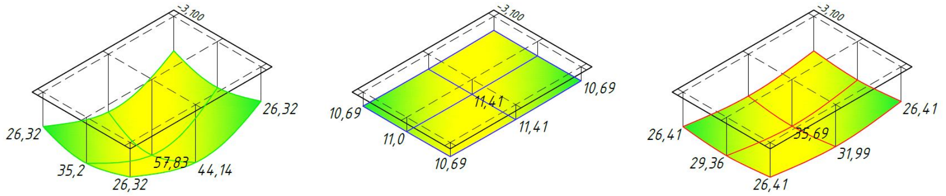
(a) (b) (c)

Fig. 8. Stress distribution surface on the depth 0,1 m:
(a) – Mohr–Coulomb model; (b) – analytical corner points method; (c) – linear elastic model



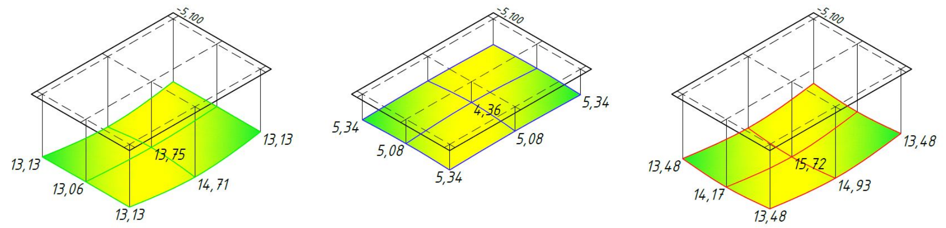
(a) (b) (c)

Fig. 9. Stress distribution surface on the depth 1,1 m:
(a) – Mohr–Coulomb model; (b) – analytical corner points method; (c) – linear elastic model



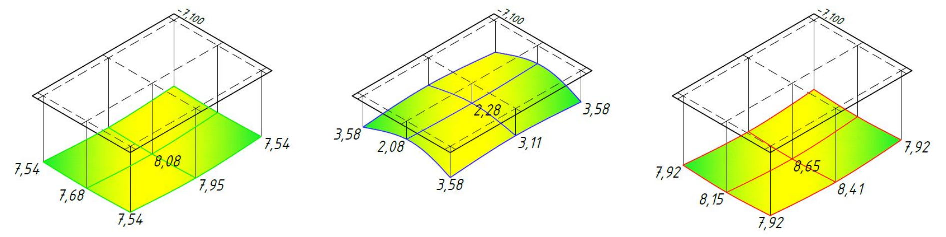
(a) (b) (c)

Fig. 10. Stress distribution surface on the depth 3,1 m:
(a) – Mohr–Coulomb model; (b) – analytical corner points method; (c) – linear elastic model



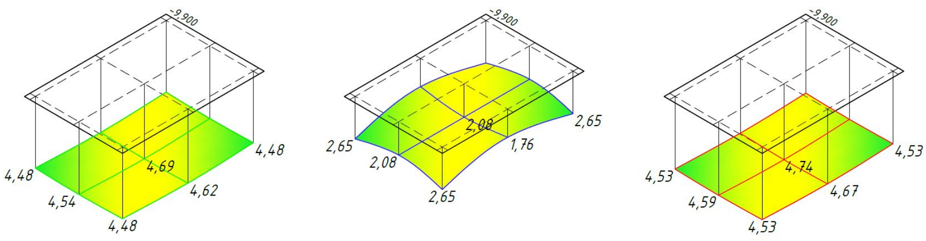
(a) (b) (c)

Fig. 11. Stress distribution surface on the depth 5,1 m:
(a) – Mohr–Coulomb model; (b) – analytical corner points method; (c) – linear elastic model



(a) (b) (c)

Fig. 12. Stress distribution surface on the depth 7,1 m:
(a) – Mohr–Coulomb model; (b) – analytical corner points method; (c) – linear elastic model



(a) (b) (c)

Fig. 13. Stress distribution surface on the depth 9,9 m:
(a) – Mohr–Coulomb model; (b) – analytical corner points method; (c) – linear elastic model

It can be observed that the stress surfaces obtained by analytical calculations (Figs. 8(b)–13(b)), starting from a depth of 3.1 m, exhibit an almost flat shape, i.e., stress values at any point within the foundation contour become nearly equal. It was also found that with increasing depth, stresses in the corner zones obtained by analytical calculation (Corner Points Method) become dominant in magnitude, whereas such a phenomenon is absent in the numerical simulation results.

Based on the quantitative stress analysis in the soil mass, at the foundation zones selected for the study, a comparison between numerical simulation and the analytical approach allowed for determining the stress differences and deriving a discrepancy coefficient (Fig. 14).

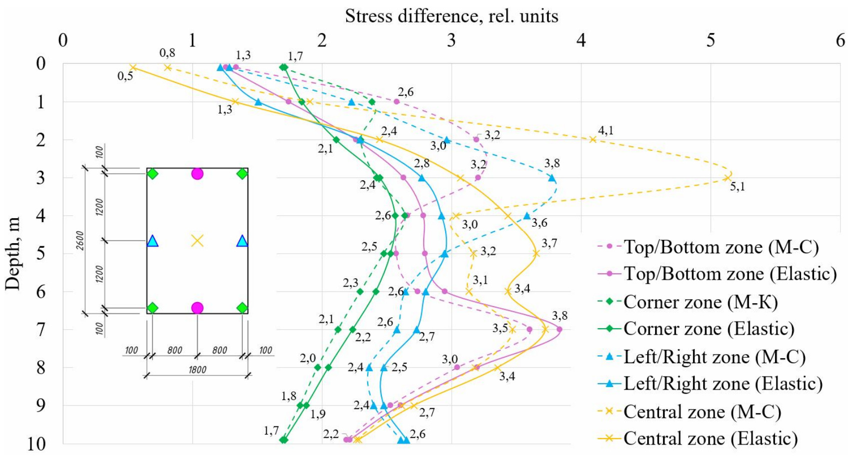


Fig. 14. Discrepancy coefficients for stresses in the studied zones (comparison with corner points method results)

6.2. Vertical soil displacements under the foundation

Soil deformations in the central zone beneath the foundation varied with depth in the range from 16.13 mm to 0.87 mm when using the elasto-plastic model with the Mohr–Coulomb failure criterion; from 11.03 mm to 0.85 mm for the soil mass with elastic properties; and from 6.36 mm to 0.01 mm according to the analytical calculation using the Corner Points Method (Fig. 15). It was found that the settlement of the slab according to the analytical calculation is 7.25 times smaller compared to numerical simulation. It should be noted that the deformation curves of the soil medium at any studied point are almost identical in shape; therefore, the graphs for subsequent points are not presented, and the discussion proceeds directly to the qualitative analysis.

The qualitative analysis was carried out by constructing surfaces of vertical displacements at depths of 0.1 m (Fig. 16), 1.1 m (Fig. 17), 3.1 m (Fig. 18), 5.1 m (Fig. 19), 7.1 m (Fig. 20), and 9.9 m (Fig. 21).

Figures 16–21 illustrate how the settlement surface of the soil changes with depth. At a distance of 0.1 m from the foundation base (Fig. 16), the surface obtained from the analytical calculations exhibits a more curved shape compared to the surfaces obtained from numerical simulation results.

It can also be observed that soil deformations obtained through analytical calculations are several times smaller than those derived from numerical simulation. When comparing the Mohr–Coulomb soil mass model with the analytical approach, the difference in deformations averages about 6.5 times. For the soil mass with elastic properties, the difference is approximately 6.3 times. A quantitative comparison of deformations is presented in Fig. 22.

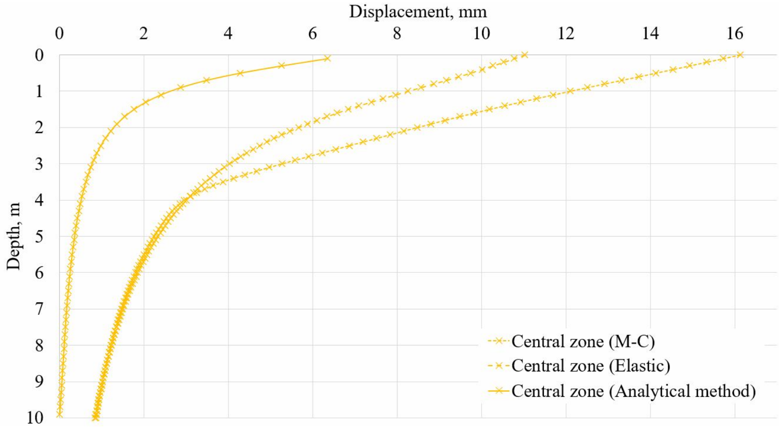
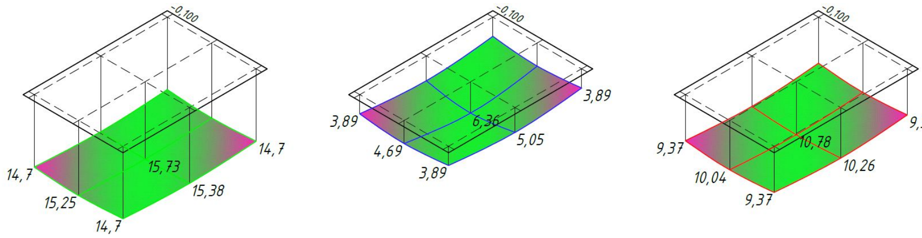
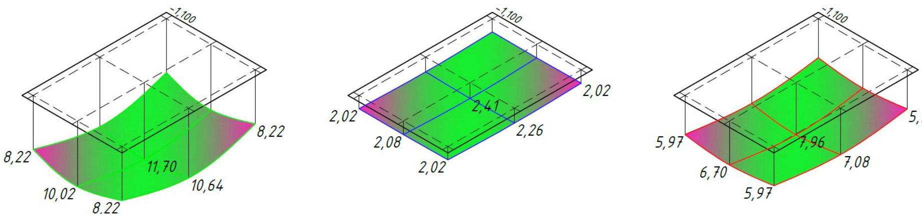


Fig. 15. Displacements in the central zone



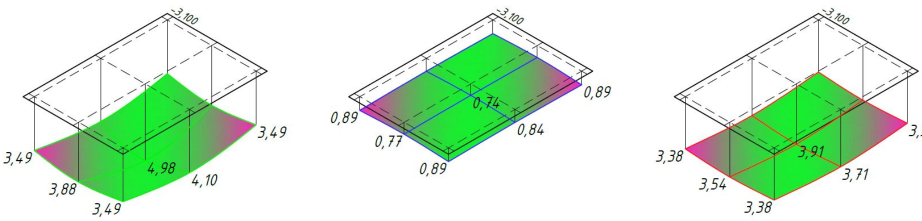
(a) (b) (c)

Fig.16. Settlement surface on the depth 0,1 m:
(a) – Mohr–Coulomb model; (b) – analytical corner points method; (c) – linear elastic model



(a) (b) (c)

Fig.17. Settlement surface on the depth 1,1 m:
(a) – Mohr–Coulomb model; (b) – analytical corner points method; (c) – linear elastic model



(a) (b) (c)

Fig.18. Settlement surface on the depth 3,1 m:
(a) – Mohr–Coulomb model; (b) – analytical corner points method; (c) – linear elastic model

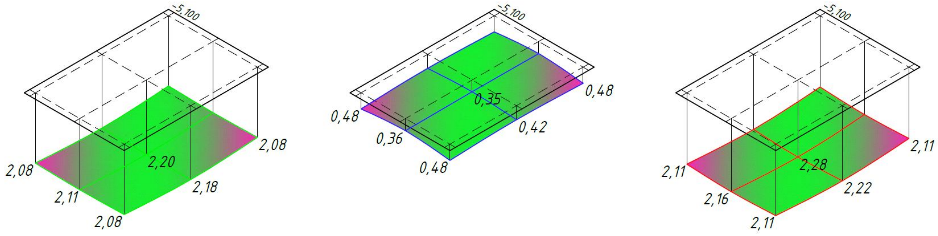


Fig.19. Settlement surface on the depth 5,1 m:
(a) – Mohr–Coulomb model; (b) – analytical corner points method; (c) – linear elastic model

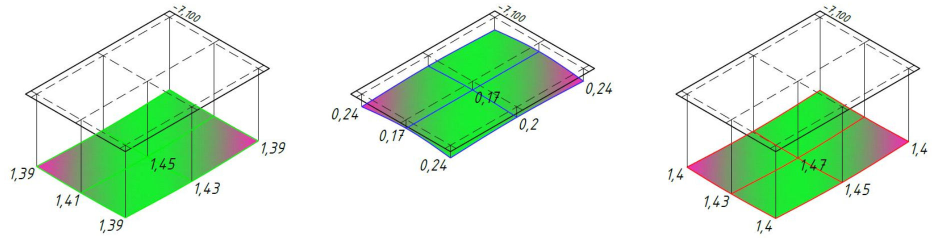


Fig.20. Settlement surface on the depth 7,1 m:
(a) – Mohr–Coulomb model; (b) – analytical corner points method; (c) – linear elastic model

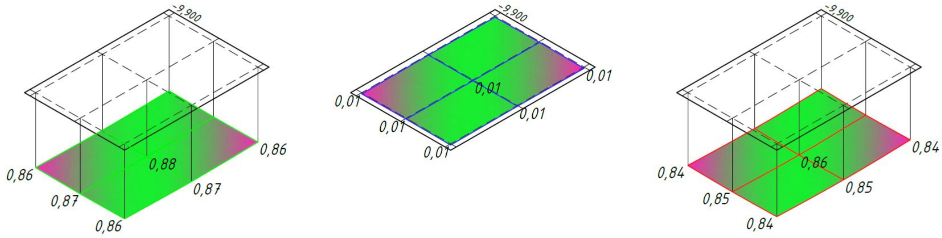


Fig.21. Settlement surface on the depth 9,9 m:
(a) – Mohr–Coulomb model; (b) – analytical corner points method; (c) – linear elastic model

The discrepancy coefficients (Fig. 22) are presented up to a depth of 9 m. This decision was made because, at greater depths, the deformations obtained from analytical calculations are very small, resulting in excessively large coefficients (in the range of 60–93 times), which would distort the scale of the graph.

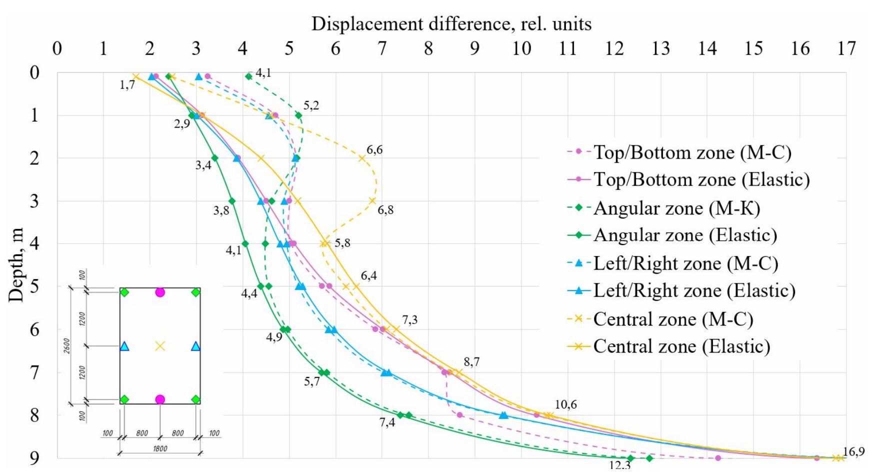


Fig. 22. Discrepancy coefficients for displacements in the studied zones (comparison with corner points method results)

7. Conclusions

This paper presents a comparative analysis of the results of determining contact stresses in the soil base under a rectangular raft foundation obtained using the analytical corner points method and finite element numerical simulation for two approaches to describing soil behavior: an elastic–linear model and an elastic–plastic model with the Mohr–Coulomb failure criterion. The main objective of the study is to refine the influence coefficients used in the corner points method, identify quantitative and qualitative differences between the results obtained by different methods, and determine the scope of applicability of each method in engineering practice.

Within the study, contact stress distribution surfaces were constructed for each approach, enabling not only point-by-point comparison of stress magnitudes but also assessment of the spatial pattern of stress variation beneath the slab. It was found that the shape of the contact stress distribution surface obtained by the analytical method differs significantly from that produced by numerical simulation, particularly in the edge zones of the foundation. Discrepancy coefficients were determined for the analyzed case, which can be used to further adjust the influence coefficients in analytical calculations:

1. It was found that the stresses determined using the analytical approach (Corner Points Method) are underestimated: the top/bottom zone of the foundation – by an average factor of 2.63; the corner zone – by 2.15 on average; the right/left zone – by 2.55 on average; the central zone – by 2.85 on average.
2. It was shown that the stresses from analytical calculations, obtained using the stress influence factor α, which is tabulated and depends on the foundation geometry and the depth of stress evaluation, provide a misleading representation of stress distribution within the foundation contour. These stress influence factors require refinement.
3. It was found that the deformations determined using the analytical approach are significantly underestimated: the top/bottom zone of the foundation – by an average factor of 6.69; the corner zone – by 5.52 on average; the right/left zone – by 6.55 on average; the central zone – by 7.27 on average.

The results confirm that even for relatively simple geometry and loading conditions, discrepancies between the methods can have a substantial impact on the assessment of bearing capacity and the uniformity of soil foundation performance. The proposed approach lays the groundwork for further comprehensive studies of the influence of geometric parameters of the foundation, type and magnitude of loading, and the physical–mechanical properties of the soil on the consistency of results obtained from analytical and numerical calculation methods.

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ДОСЛІДЖЕННЯ ВПЛИВУ МЕТОДУ РОЗРАХУНКУ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ОСНОВИ ПЛИТНОГО ФУНДАМЕНТУ

Точне визначення контактних напружень у ґрунтовій основі є ключовим для надійного проектування плитних фундаментів. Традиційні аналітичні методи, зокрема метод кутових точок, мають переваги простоти, але ґрунтуються на спрощених припущеннях, що може зумовлювати похибки у складних інженерних умовах. Числове моделювання методом скінченних елементів дозволяє враховувати більш реалістичну поведінку ґрунту, проте потребує значних ресурсів. Порівняння цих підходів є актуальним для визначення меж їх застосування та підвищення точності розрахунків.

У статті представлено результати порівняння визначення напружень у ґрунтовій основі під плитним фундаментом прямокутної форми, отриманих за аналітичним методом кутових точок та шляхом числового моделювання у середовищі скінчено-елементного аналізу для пружно-лінійної та пружно-пластичної моделі з використанням критерію міцності Кулона–Мора. Метою дослідження є уточнення коефіцієнтів впливу, що застосовуються в методі кутових точок, а також виявлення кількісних і якісних розбіжностей між підходами та окреслення меж їх коректного застосування. Порівняння показало суттєві відмінності не лише у величинах контактних напружень, але й у формі поверхні їх розподілу. Попередньо визначено коефіцієнти розбіжності для дослідженого випадку.

Отримані результати підтверджують, що навіть для відносно простої геометрії та умов навантаження розбіжності між методами можуть мати істотний вплив на оцінку несучої здатності та рівномірності роботи ґрунтової основи. Запропонований підхід створює передумови для подальшого комплексного дослідження впливу геометричних параметрів фундаменту, виду та величини навантаження, а також фізико-механічних властивостей ґрунту на узгодженість результатів аналітичних та числових методів розрахунку.

Ключові слова: плитний фундамент, ґрунтова основа, напружено-деформований стан, метод кутових точок, чисельне моделювання, МСЕ, лінійно-пружна модель, модель Кулона-Мора.

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IMPACT OF STRESS–STRAIN STATE EVALUATION METHOD IN RAFT FOUNDATION ANALYSIS

Accurate determination of contact stresses in the soil base is essential for the reliable design of raft foundations. Traditional analytical methods, such as the corner points method, offer simplicity but are based on simplified assumptions, which may lead to errors under complex engineering conditions. Numerical finite element modeling provides a more realistic representation of soil behavior but requires considerable resources. Comparing these approaches is relevant for defining their applicability limits and improving calculation accuracy.

The article presents a comparison of stresses in a soil base under a rectangular raft foundation obtained by the analytical corner points method and finite element numerical modeling for elastic–linear and elastic–plastic soil model with the Mohr–Coulomb failure criterion. The aim of the study is to refine the influence coefficients used in the corner points method, to identify quantitative and qualitative differences between the approaches, and to outline the boundaries of their correct application. The comparison revealed significant discrepancies not only in the values of contact stresses but also in the shape of their distribution surface. Preliminary discrepancy coefficients for the studied case have been determined.

The results confirm that even for relatively simple geometry and loading conditions, discrepancies between the methods can have a substantial impact on the assessment of bearing capacity and the uniformity of soil foundation performance. The proposed approach lays the groundwork for further comprehensive studies of the influence of geometric parameters of the foundation, type and magnitude of loading, and the physical–mechanical properties of the soil on the consistency of results obtained from analytical and numerical calculation methods.

Keywords: raft foundation, soil base, stress-strain state, corner points method, numerical simulation, FEM, linear-elastic model, Mohr–Coulomb model.

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Виконано порівняння визначення напружень у ґрунтовій основі під плитним фундаментом прямокутної форми, отриманих за аналітичним методом кутових точок та шляхом числового моделювання у середовищі скінчено-елементного аналізу для пружно-лінійної та пружно-пластичної моделей з використанням критерію міцності Кулона–Мора.
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