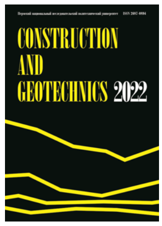
Численное моделирование взаимодействия подземной части здания с грунтовым основанием при образовании карстовой полости на примере строительства административно-делового центра / А.З. Тер-Мартиросян, Р.Х. Черкесов, И.О. Исаев, Н.А. Филаретов, Ю.В. Ванина // Construction and Geotechnics. – 2023. – Т. 14, № 3. – С. 80–91. DOI: 10.15593/2224-9826/2023.3.08

Ter-Martirosyan A.Z., Cherkesov R.H., Isaev I.O., Filaretov N.A., Vanina Yu.V. Numerical modeling of the interaction of the underground part of the building with the soil basis due to formation of a karst cavity on the example of the construction of an administrative and business center. *Construction and Geotechnics*. 2023. Vol. 14. No. 3. Pp. 80-91. DOI: 10.15593/2224-9826/2023.3.08

пермский политех

CONSTRUCTION AND GEOTECHNICS
Т. 14, № 3, 2023
http://vestnik.pstu.ru/arhit/about/inf/



DOI: 10.15593/2224-9826/2023.3.08
УДК 624.159

COMPUTER MODELING OF THE INTERACTION OF THE BUILDING UNDERGROUND PART WITH THE SOIL FOUNDATION DURING THE KARST CAVITY FORMATION ON THE EXAMPLE OF THE ADMINISTRATIVE AND BUSINESS CENTER CONSTRUCTION

A.Z. Ter-Martirosyan[1], R.H. Cherkesov[2], I.O. Isaev[3], N.A. Filaretov[3], Yu.V. Vanina[2]

[1]National Research Moscow State University, Moscow, Russian Federation
[2]Institute Mosinzhproekt, Moscow, Russian Federation
[3]Mosinzhproekt, Moscow, Russian Federation

ARTICLE INFO

Received: 18 April 2023
Approved: 16 June 2023
Accepted for publication: 24 July 2023

Keywords:
karst cavity, numerical modeling, piled raft footing, regulations in karst hazard matters, formation of a karst cavity arch, high-rise building, failure type deformations.

ABSTRACT

In restrained urban conditions of Moscow, the accomplishment of complex urban construction projects is complicated by the choice of construction sites, as well as by lack of methods for computer modeling of the interaction of high-rise and unique buildings and structures with the probable formation of karst cavities in the current regulatory documents. The overall profitability of the project is under the great impact of it, therefore a reliable accounting of karts-suffusion processes is a priority issue in designing buildings and structures, especially if it concerns the unique and high-rise ones. The authors analyze the results of the calculations of the forecast assessment of the impact of a karst cavity probable formation on the subsurface parts of building of the administrative and business center construction in flat and spatial formulation. In spatial formulation different positions of the potential karst cavities are considered; their locations were chosen according to standard procedures and were guided by the results of geological and geophysical research. It has been reviewed the formation of arch over a karst cavity in a 2D and 3D formulation in the condition of different location of the karst cavities in plan and by depth of occurrence. It has been made methodological recommendations for determining the predicted bore of the karst cavity, for taking into account the frame stiffness of the aboveground part of the building, for defining the principles of a karst cavity modeling, as well as for the choice of assessment

© **Тер-Мартиросян Армен Завенович** – доктор технических наук, профессор, e-mail: gic-mgsu@mail.ru.
Черкесов Рустам Хасанович – генеральный директор, e-mail: cherkesov.r@mosinzhproekt.ru.
Исаев Илья Олегович – руководитель отдела мероприятий, e-mail: isaevio@mosinzhproekt.ru.
Филаретов Николай Александрович – руководитель направления, e-mail: filaretov.na@mosinzhproekt.ru.
Ванина Юлия Викторовна – ведущий инженер, e-mail: vanina.iuv@mosinzhproekt.ru.

Armen Z. Ter-Martirosyan – Doctor of Technical Sciences, Professor, e-mail: gic-mgsu@mail.ru.
Rustam Kh. Cherkesov – CEO, e-mail: cherkesov.r@mosinzhproekt.ru.
Ilya O. Isaev – Head of the Department, e-mail: isaevio@mosinzhproekt.ru.
Nikolay A. Filaretov – Head of the Impact Assessment, e-mail: filaretov.na@mosinzhproekt.ru.
Yulia V. Vanina – Leading Engineer, e-mail: vanina.iuv@mosinzhproekt.ru.

criteria of stability of cover mass above the potential cavity. The discovered differences in the results of 2D and 3D settings permit to make a conclusion that solving the problem in a flat formulation contributes to the overestimation of karst processes danger and, therefore, to the excess in anti-karst measures included in the project.

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ВЗАИМОДЕЙСТВИЯ ПОДЗЕМНОЙ ЧАСТИ ЗДАНИЯ С ГРУНТОВЫМ ОСНОВАНИЕМ ПРИ ОБРАЗОВАНИИ КАРСТОВОЙ ПОЛОСТИ НА ПРИМЕРЕ СТРОИТЕЛЬСТВА АДМИНИСТРАТИВНО-ДЕЛОВОГО ЦЕНТРА

А.З. Тер-Мартиросян[1], Р.Х. Черкесов[2], И.О. Исаев[3], Н.А. Филаретов[3], Ю.В. Ванина[2]

[1]Национальный исследовательский Московский государственный строительный университет, Москва, Россия
[2]Институт «Мосинжпроект», Москва, Россия
[3]Мосинжпроект, Москва, Россия

О СТАТЬЕ

Получена: 18 апреля 2023
Одобрена: 16 июня 2023
Принята к публикации:
24 июля 2023

Ключевые слова:
карстовая полость, численное моделирование, плитно-свайный фундамент, нормативное регулирование в вопросах карстовой опасности, свод образования карстовой полости, высотное здание, деформации провального типа.

АННОТАЦИЯ

В условиях плотной городской застройки в г. Москве вопрос о реализации сложных градостроительных проектов осложняется выбором площадки строительства, а также отсутствием методик численного моделирования взаимодействия высотных и уникальных зданий и сооружений при вероятном образовании карстовых полостей в действующей нормативной документации. Данное обстоятельство имеет колоссальное влияние на общую рентабельность проекта, поэтому корректность учета карстово-суффозионных процессов является актуальной и приоритетной темой при проектировании зданий и сооружений, особенно уникальных и высотных. Авторами приведен анализ результатов расчетов прогнозной оценки влияния вероятного образования карстовой полости на подземную часть здания административно-делового центра в плоской и пространственной постановке. В пространственной постановке рассмотрено различное положение потенциальной карстовой полости, выбор положения которой осуществлен в соответствии с общепринятыми методиками, при этом руководствуясь результатами геологических и геофизических исследований. Рассмотрено формирование свода над карстовой полостью в двумерной и трехмерной постановке при различных вариантах местоположения карстовой полости в плане и по глубине залегания. Приведены методические рекомендации для определения прогнозируемого диаметра карстовой полости, учету жесткости каркаса надземной части здания, принципам моделирования карстовой полости, а также выбору критерия оценки устойчивости покрывающей толщи над потенциальной полостью. Выявленные различия в полученных результатах трехмерного и двумерного расчетов позволяют сделать вывод о том, что решение задачи в плоской постановке приводит к переоценке опасности карстовых процессов и, как следствие, к заложению в проекте избыточных противокарстовых мероприятий.

Introduction

The formation of karst hazards and corresponding risks occurs in most territories of Moscow; in their geological structures there are massifs of carbonate rocks of Carboniferous age, usually occurring at a depth of several dozens of meters from the surface of the earth. The greatest cavernous porosity of carbonate rock massifs to a depth of 80–85 m from their roof is generally in the ancient interred river valleys of Moscow and its tributaries that are not topographical, as well as in out of condition tectonic zones of increased rock fracturing.

However, in restrained urban conditions of Moscow, the accomplishment of complex urban construction projects is constrained by the choice of construction sites. In some cases, the construction possibilities are limited with actual regulations due to the high risks of an emergency.

According to the Set of Rules 267.1325800.2016 "High-rise buildings and complexes. Design Rules" construction of high-rise buildings in areas with recorded and documented karts-suffusion processes it is not allowed without special anti-karst measures (structural, geotechnical, waterproof, etc.). It has a great impact on the overall profitability of the project, so the consideration of karst-suffusion processes is a relevant and priority problem in the process of designing buildings and structures, especially unique and high-rise ones.

The efforts of consideration the karst cavities formation in the foundations of buildings and structures as well as the assessment of the karst-suffusion danger of a construction site by the methods of mathematical modeling were carried out by the following researchers: Gotman N.Z. [1–3], Kovalev [4], Podolsky [5]. Subsequently, the proposed methods were more or less reflected in Set of Rules 499.1325800.2021 "Engineering protection of territories, buildings and structures from karst-suffusion processes" which included recommendations for determining the parameters of karst deformations by numerical methods.

At the same time, the studies carried out at different times remained underdeveloped in terms of recommendations for numerical modeling, especially in a 3D formulation. Research papers and regulations do not highlight the questions related to the frame stiffness, to the principles of modeling a karst cavity, and there is no clear assessment of the cover mass stability above the potential cavity. Generally, the solution comes down to an axisymmetric problem, not allowing to take into account properly the irregularity in the foundation load, the edge effects (particularly in the case of complex geometry of the construction site), as well as the variability of the geologic section in the base of the structure. Moreover, some foreign scientists also point out the lack of regulatory regulations in terms of karst hazard of new construction territories, as well as buildings and structures already in operation [6, 7].

Constructing tunnels in China [8–11] engineers and researchers very often face construction problems of karst rocks, especially in case of hydraulic fracture in limestone. This fact caused the need to develop computational models and prerequisites for analytical solutions and numerical modeling of karst cavities for the most complete consideration of the factors which form karst hazard in the construction site.

In this paper using the example of constructing the administrative and business center the case of a karst cavity formation in the foundation base of the high-rise building on a slab-pile foundation is considered. It is examined formation of the arch over a carst cavity in a two-dimensional and three-dimensional formulation with different variants of a karst cavity location in plan and in depth. Methodological recommendations are given to assess the impact of karst hazard on the sediment and bearing capacity of the building foundation structures of increased level of responsibility of KS-3.

Procedure of numerical studies and justification of the accepted calculation model

The designed complex includes 15 architectural blocks with aboveground and underground (basement) parts and one underground block with car parking. Generally, there is a common division into high-rise and low-rise developments: block 9 (Fig. 1, *a*) – 46 storied one with maximum graded elevation of +288,100 m (by the pinnacle) and +248,900 m (by the covering), blocks 7, 8, 10, 11 (Fig. 1, *b*) – low-rise (4, 7 and 10 floors each).

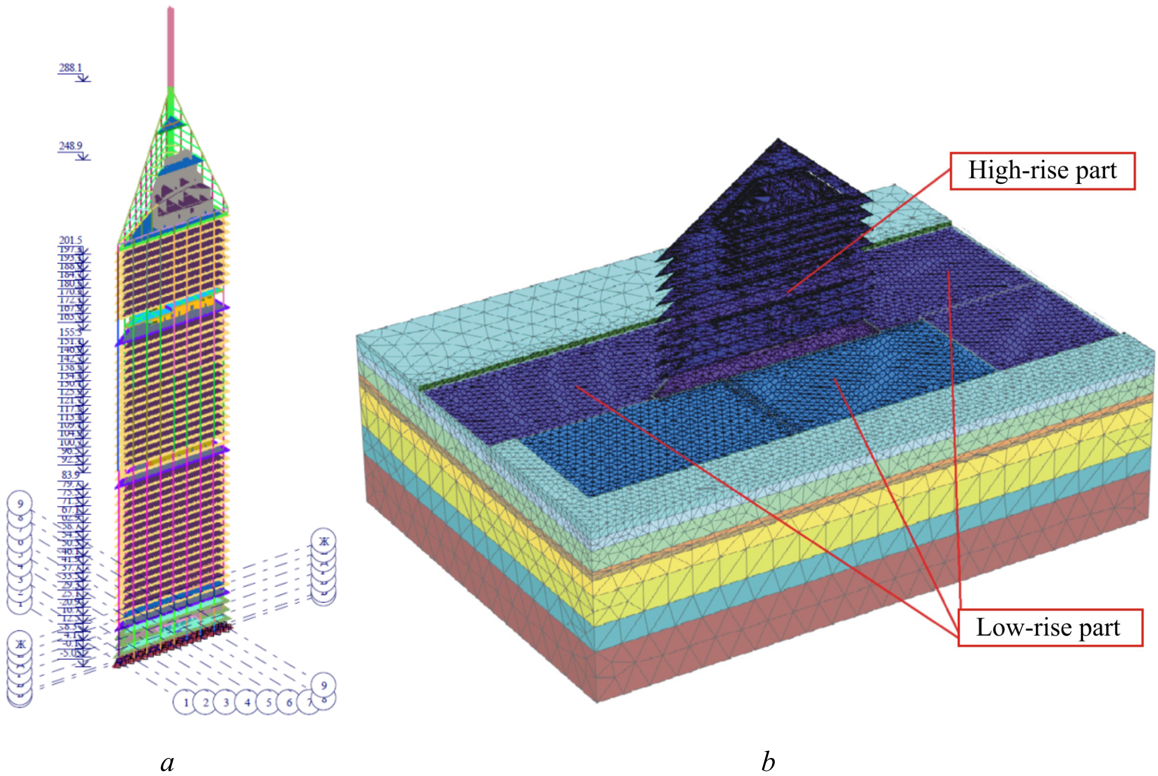
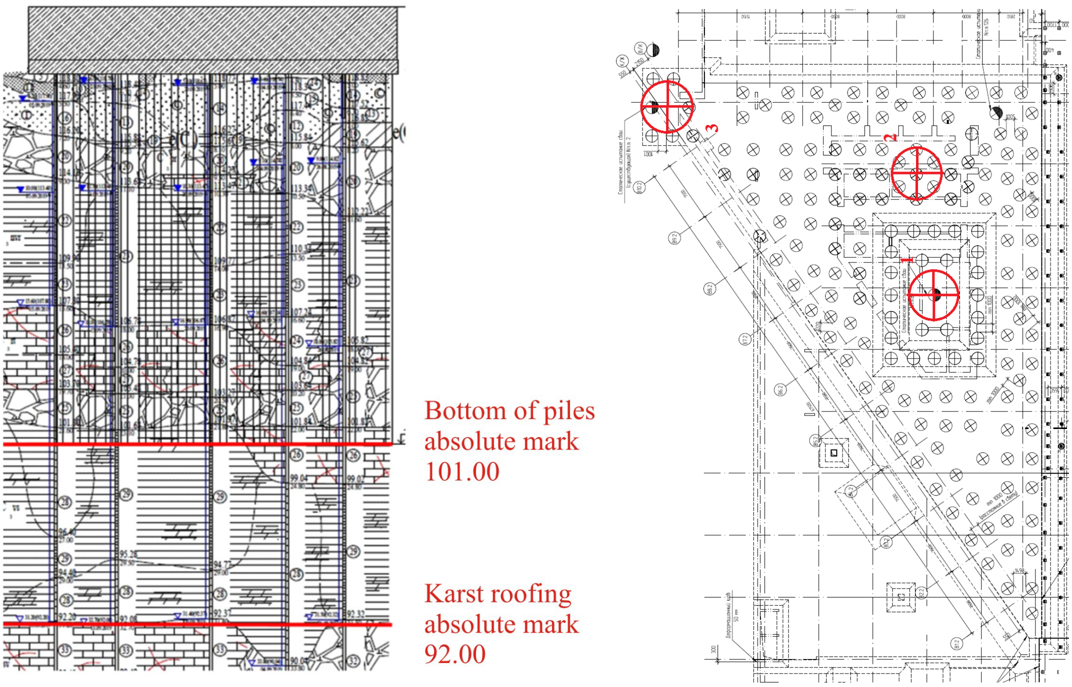


Fig. 1. Calculation models: *a* – complete calculation model of a high-rise building in DC LIRA-SAPR;
b – calculation model in PC PLAXIS 3D with the indication of the high-rise and low-rise parts

Due to the uniqueness of the object under construction (height more than 250 m), as well as due to the complex engineering and geological conditions of the construction site special attention is required when considering the joint operation of the soil foundation with the underground and aboveground parts of the building. The peculiarity of the site under consideration is the danger in terms of the development of karst-suffusion processes.

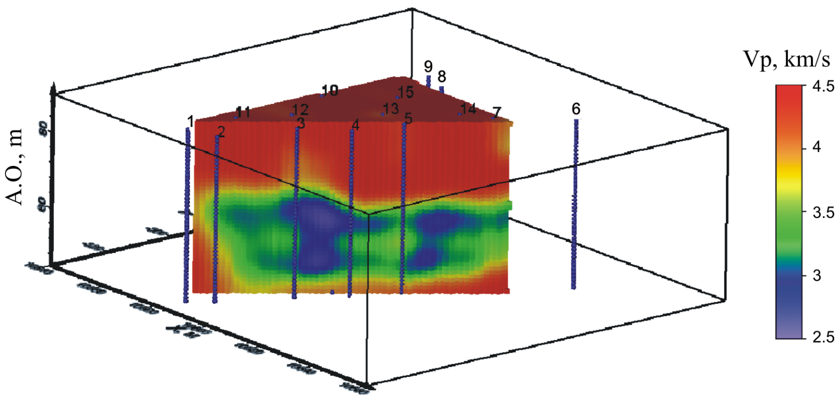
The first stage is devoted to the analysis of the results of engineering, geological and geophysical surveys with the landing of designed structures on engineering and geological profiles. Karst processes under the high-rise building are confined to fractured and destroyed limestones of the carboniferous system, overlying at a depth of more than 35 m (absolute elevation of the roof coating 92.0), covered by semi-solid and hard clays. The depth of the underground part of the building is about 8.0 m; the length of the piles is 18.3 m (absolute elevation of the tip 101.0). A typical engineering and geological profile of landing the high-rise building foundations is given in Fig. 2, *a*. The foundation plan of the calculated and indicated karst cavities is represented in Fig. 2, *b*. A minimal distance from the bottom of the piles to the roof of karst limestone is 6.0 m.

According to engineering and geological surveys, and particularly to the data on the failures of the drilling tools, cavities with a diameter of no more than 2 m were found. In conformity with geophysical survey (GIS: inter-well seismic acoustic sounding, radioactive (gamma) logging, cavernometry, induction logging, standard logging, inclinometry) zones of reduced longitudinal wave velocities (below the absolute elevation of 85.0) have been identified which suggests the presence of cavities up to 5 m in size. The results of the study of the soil mass by the method of inter-well sounding are shown in Fig. 3. The study carried out was in the interval of datum 45.0–90.0.

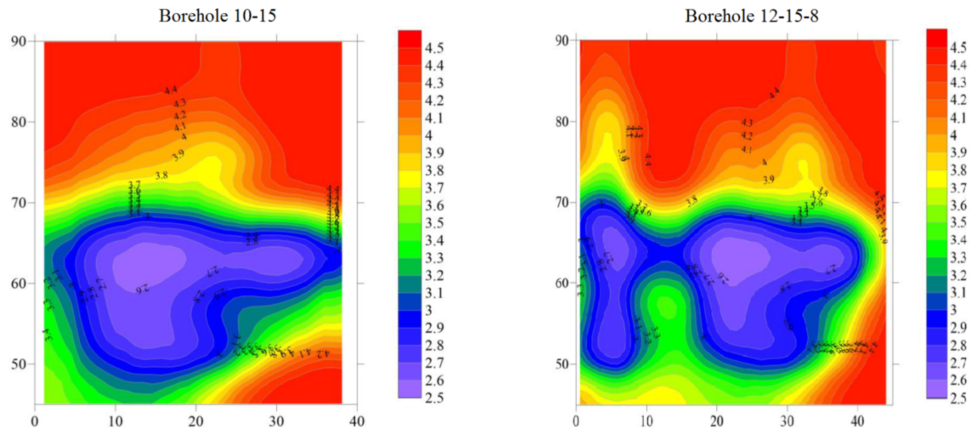


a *b*

Fig. 2. High-rise block No. 9: *a* – basic section of the foundations; *b* – foundation plan of the calculated and indicated karst cavities (variants 1, 2, 3) with a diameter of 4.0 m (absolute elevation 95.00) and 7.0 m (absolute elevation 85.00)



a



b *c*

Fig. 3. Geophysical model of the base of the high-rise complex: *a* – three-dimensional model of the base, *b* – cross-sections for borehole 10-15, *c* – cross-sections for borehole 12-15-8

Further, it is necessary to predict diameter of the karst cavity according to the method given in Set of Rules 499.1325800.2021 "Engineering protection of territories, buildings and structures from karst-suffusion processes". The predicted diameter of the karst cavity was 4.0 m (according to the records of the drilling tool failure) and 7.0 m (according to geophysical research) and was determined with the account of the its dissolution rate $V_{diss} = 0.01$ m/year and the estimated service life of the structure $T = 100$ years:

$$d_{comp} = d_{\text{fact}} + k\, V_{diss}\, T \tag{1}$$

where d_{fact} is the initial size of the karst cavity according to the drilling and geophysical research results.

Considering the fact that it is a structure of the increased level of responsibility (KS-3 class) and the absence of laboratory [12] filtration tests of carbonate rocks, it was made a decision to increase the dissolution rate on $k = 2$. It is explained by the assignment this territory to zones of accelerated denudation of karst limestone [13], due to the location of the construction site in the valley of the Moscow River.

For a joint calculation in PC PLAXIS 3D and PC LIRA-SAPR, two design situations of the karst cavities formation were analyzed:

• in the roof of carbonate rocks (absolute elevation 92.00) with a size of 4 m, in accordance with the data on the failure of drilling tool;

• in the thickness of carbonate rocks (absolute elevation 85.00) with a size of 7 m, in accordance with the data on the failure of drilling tools and geophysical studies.

The position of karst cavities of 4.0 m and 7.0 m in the plan is identical according to Fig. 2, *b*.

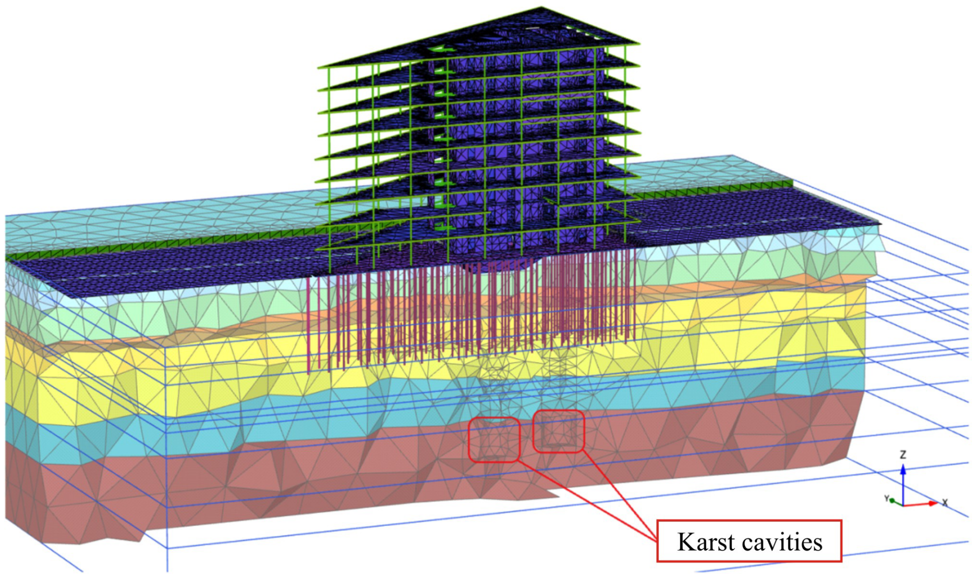


Fig. 4. Geotechnical calculation model. Profile indicating the position of karst cavities

To take into account the rigidity of the upper structure in the PLAXIS 3D PC, structures and loads of the aboveground part of the complex are imported from the LIRA-CAD PC, the height of the aboveground part is reduced iteratively to the minimum possible value so that its change does not significantly affect the calculation results in comparison with the full-scale model in the LIRA-CAD PC. The section according to the finite element model of the PC "PLAXIS 3D" in the zone of simulated karst cavities is shown in Fig. 4.

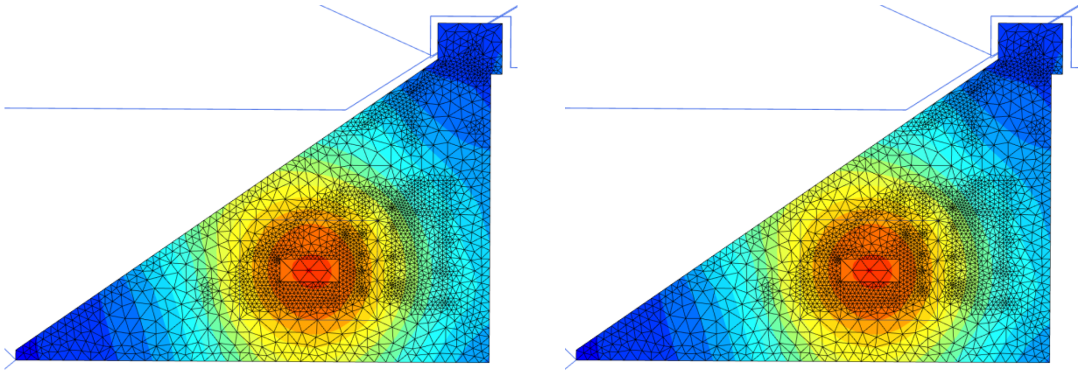
Analysis of the numerical studies results

The results of the joint calculation of the system "soil foundation with karst cavity – underground part of the building – aboveground part of the building" made by PC PLAXIS 3D and PC LIRA-SAPR are presented in Fig. 5–6 in the most unfavorable karst cavity position.

The joint calculation results showed:

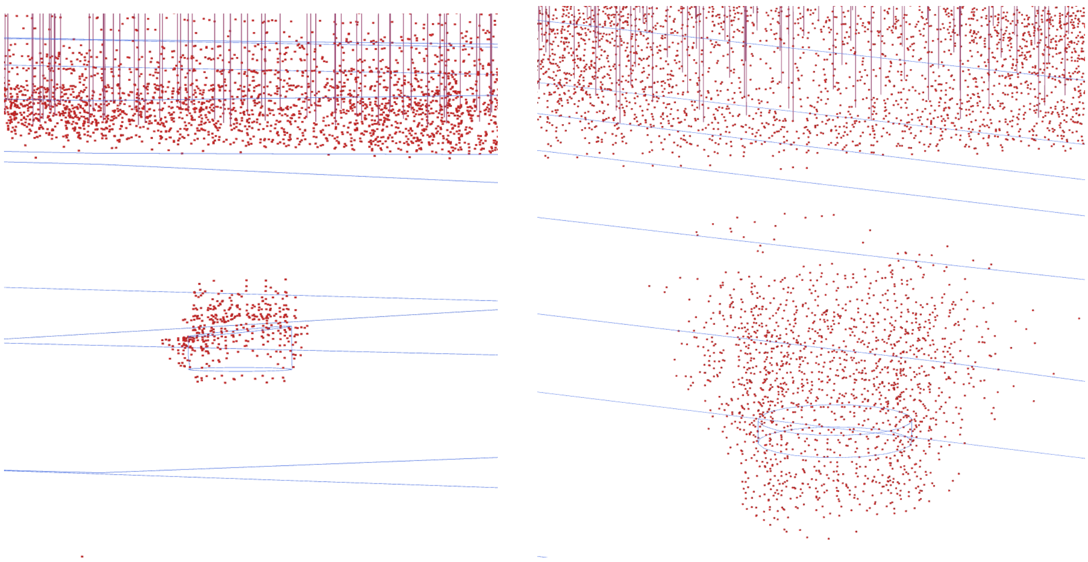
– vertical deformations of the raft foundation during the stage of the karst cavity formation do not exceed 1.0 mm for all design cases;

– the results of calculation in PC LIRA-SAPR based on the bedding value from PC PLAXIS 3D showed there is no need to increase the reinforcement selected for the main combinations of loads.



a *b*

Fig. 5. Isofields of additional vertical displacements of the block 9 foundation at the phase a karst cavity formation: *a* – during karst cavity formation under foundation of 4 m in diameter (variant 1) at absolute elevation 95.00, *b* – during karst cavity formation under foundation of 7 m in diameter (variant 1) at absolute elevation 85.00



a *b*

Fig. 6. Zone of maximum shear deformations located within the area of plastic points' concentration: *a* – for a karst cavity with 4 m diameter (variant 1); *b* – for a karst cavity with 7 m diameter in section no. 1 (variant 1)

The calculation in the flat formulation was also performed in PC PLAXIS 2D to compare the forming geometry of the arch over the karst cavity. The results are shown in Fig. 7.

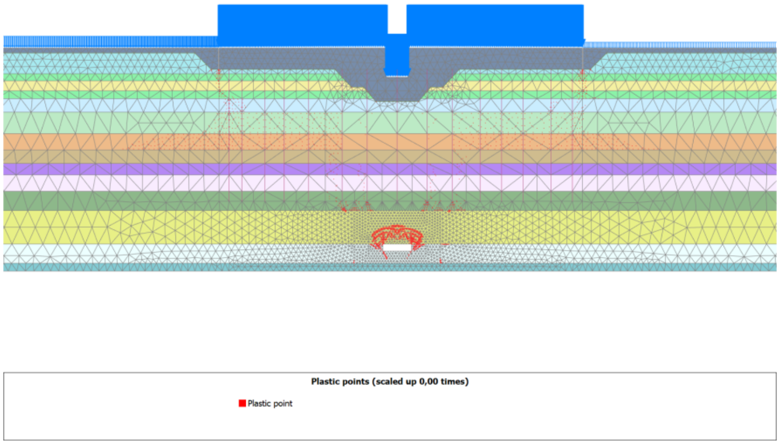


Fig. 7. Zone of maximum shear deformations located within the area of plastic points' concentration for a karst cavity with 4 m in diameter (variant 1)

Fig. 6 and 7 show that according to the 2D results the diameter of the arch over the karst cavity significantly exceeds the 3D results for a similar problem.

The maximum values of the phase displacements of the foundation plate of the high-rise block 9 were 16 mm, which significantly exceeds the results obtained in the three-dimensional formulation.

Isofields of phase vertical displacements of the soil mass during the formation of a karst cavity were also obtained (Fig. 8).

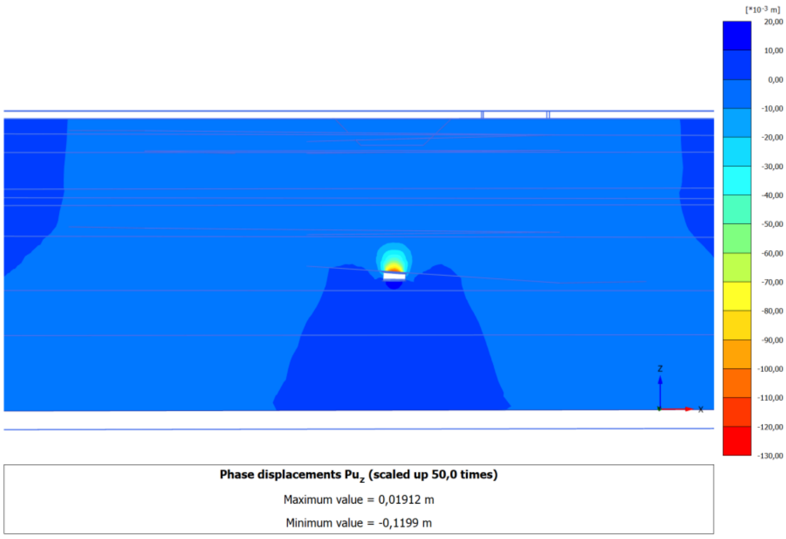


Fig. 8. Isofields of phase vertical displacements of the foundation mass during the karst cavity formation with a diameter of 7 m (variant 1)

Isofields of vertical displacements of the soil foundation while forming a karst cavity first allow us to define the depressed area above the sinkhole, but do not fully characterize the arch formation. Thus, it is recommended to be guided by the schemes of distribution of plastic points in the soil array, characterizing the zone of violation of the strength criterion for the selected soil model.

The critical diameter of the karst cavity, determined by the Troitsky method [14] and consisting in determining the diameter of the karst cavity from the equilibrium condition of a circular-cylindrical column of soil hanging over the karst cavity, was adopted as a criterion for assessing the karst-suffusion hazard of the construction site. The weight of the column in this case is balanced by the total friction acting on its side surface.

For covered karst [15, 16], this method is generally accepted and included in Set of Rules 499.1325800.2021. It is based on the experimental studies of Protodyakonov [17], and developed by Birmbaumer [13], Khomenko [18, 19] and Anikiev [13, 16].

The minimum capacity of the bearing covering thickness (solid clay) at the location of the high-rise part of the complex is 6.0 m. According to the calculation by the Troitsky method, the critical diameter of the karst cavity was 7.0 m. The obtained calculation results mean that when a karst cavity of up to 7.0 m in size is formed in karst rocks under the high-altitude part of the complex, the bearing capacity of the covering thickness will be provided.

Taking into account the fact that for the high-altitude part of the complex, the predicted and accepted estimated diameter of the karst cavity (4.0 m) is less than the critical one according to the Troitsky method (7.0 m), it is concluded that during the estimated life of the structure, sinkhole-type karst deformations are not formed provided there are no cavities in carbonate rocks above the abs. of 85.00 m with a diameter of more than 2 m.

The analytical solution of the problem for a variant of a karst cavity with an estimated diameter of 7.0 m, adopted in the limestone thickness according to the results of geophysical studies, is not considered due to the lack of appropriate methods in the regulatory and scientific literature.

Conclusion

Summarizing the results obtained, the following conclusions can be drawn:

1. Currently, there is not enough research devoted to the development of recommendations for numerical modeling of the interaction of the underground part of buildings and structures with the soil base during the formation of karst cavities, especially in three-dimensional formulation.

2. The results of the joint calculation in the PC "PLAXIS 3D" and PC "LIRA-CAD" showed that the formation of karst cavities determined by the method of SR 499.1325800.2021 according to the data on the failure of the drilling tool (diameter 4 m) and according to geophysical studies of the construction site (diameter 7 m) does not entail the development of vertical movements of the foundation more than 1 mm, as well as significant changes in internal forces in the foundation structures of the high-rise block building.

3. According to the comparative analysis of calculations in the PC "PLAXIS 2D" and PC "PLAXIS 3D" a significant difference in the results was revealed. The height of the arch above the karst cavity, according to the results of a two-dimensional calculation, significantly exceeds the value obtained from the results of a three-dimensional calculation for a similar task. A significant difference in the phase displacements of the foundation plate of the high-rise block 9 was also revealed: less than 1 mm in the three-dimensional formulation and 16 mm in the two-dimensional formulation. The solution of the problem in a flat formulation leads to an overestimation of the danger of karst processes and, as a consequence, to the laying of excessive anti-karst measures in the project. Thus, the calculation of buildings and structures complex in geometry must be carried out in a three-dimensional formulation.

4. Evaluating the geometry of the arch based on the results of mathematical modeling, it is recommended to guide the distribution schemes of plastic points in the soil mass, characterizing the zone of violation of the strength criterion for the selected soil model.

5. If, based on the results of mathematical modeling, a depression zone is detected above the predicted karst cavity, subject to stable arching (the coefficient of stability margin is more than the maximum permissible) in the soils overlapping the cavity, it is recommended to carry out a joint calculation of the projected structure in a geotechnical software package and a computing complex that allows performing a static analysis of the work of load-bearing structures according to various combinations of loads (SCAD, LIRA-CAD). In these calculations it is worth considering the different position of the potential karst cavity, and the choice of position should be carried out in accordance with generally accepted methods [14, 20], being guided by the results of geological and geophysical studies.

6. It is planned to consider further the problem and systematize the calculated data on the example of other unique and high-rise objects.

Финансирование. *Исследование не имело спонсорской поддержки.*
Конфликт интересов. *Авторы заявляют об отсутствии конфликта интересов.*
Вклад авторов. *Все авторы сделали равный вклад в подготовку публикации.*

Библиографический список

1. Готман Н.З, Каюмов М.З. Расчет фундаментов зданий с заглубленной подземной частью на закарстованных территориях// Вестник гражданских инженеров. – 2010. – № 4. – С. 68–72.

2. Готман Н.З., Пантелеев Ю.И. Проектирование противокарстовой защиты автомобильных дорог с использованием геосинтетических материалов и системы сигнализации // Construction and Geotechnics. – 2022. – Т. 13, № 3. – С. 5–14. DOI: 10.15593/2224-9826/2022.3.01

3. Готман Н.З., Евдокимов А.Г. Численные исследования взаимодействия основания и буронабивных свай фундамента мостовой опоры при возникновении карстовых деформаций // Construction and Geotechnics. – 2021. – Т. 12, № 4. – С. 5–18. DOI: 10.15593/2224-9826/2021.4.01

4. Ковалев В.А., Патрикеев А.Б. О расчете параметров карстового провала // Промышленное и гражданское строительство. – 2016. – № 10. – С. 36–41.

5. Подольский В.А., Логачева В.М., Панчуков Н.П. Численный метод моделирования развития деформаций при вероятном образовании карстовых полостей // Известия Тульского государственного университета. Науки о земле. – 2021. – № 1. – С. 283–289.

6. Richardson J.J. Fitting regulatory square pegs into round holes: local land use regulation in karst terrain // Karst Groundwater Contamination and Public Health. Advances in Karst Science. – Springer, Cham. – 2018. DOI: 10.1007/978-3-319-51070-5_29

7. Richardson J. Local land use regulation of karst in the United States. – 2003. – P. 492–501. DOI: 10.1061/40698(2003)45

8. Zhang D., Gao L., Wu J. Mechanism of the rock stratum resisting inrush in filling-type karst tunnels and its application // Arabian Journal of Geosciences. – 2022. – No. 15. DOI: 10.1007/s12517-022-10825-9

9. Semianalytical solution to determine minimum safety thickness of rock resisting water inrush from filling-type karst caves / Z.H. Xu, J. Wu, S.C. Li, B. Zhang, X. Huang // International Journal of Geomechanics. – 2018. – No. 18. DOI: 10.1061/(ASCE)GM.1943-5622.0001071

10. The mechanism and numerical simulation analysis of water bursting in filling karst tunnel / H. Hui, Q. Wang, Z. Yanyan, Z. Chunmei, W. Yize, G. Zeng // Geotechnical and Geological Engineering. – 2018. – No. 36. DOI: 10.1007/s10706-017-0386-6

11. Guo J.-Q., Qiao C.-S. Study on water-inrush mechanism and safe thickness of rock wall of karst tunnel face. Tiedao Xuebao // Journal of the China Railway Society. – 2012. – No. 34. DOI: 105–111. 10.3969/j.issn.1001-8360.2012.03.018

12. Крашенников В.С., Хоменко В.П. Изучение покрывающей толщи, как один из важнейших компонентов инженерных изысканий в районах покрытого карста // Вестник МГСУ. – 2011. – № 5. – С. 113–119.

13. Аникиев А.В. Об использовании модели Бирбаумера в инженерном карстоведении // Сергеевские чтения. Моделирование при решении геоэкологических задач. Вып. 11: Материалы годичной сессии Научного совета РАН по проблемам геоэкологии, инженерной геологии и гидрогеологии 23–24 марта 2009 г. – М.: ГЕОС, 2009. – С 257–262.

14. Толмачев В.В., Троицкий Г.М., Хоменко В.П. Инженерно-строительное освоение закарстованных территорий. – М.: Стройиздат, 1986. – 176 с.

15. Толмачев В.В., Ройтер Ф. Инженерное карстоведение. – М.: Недра, 1990. – 152 с.

16. Аникиев А.В. Провалы и воронки оседания в карстовых районах: механизмы образования, прогноз и оценка риска. – М.: Рос. ун-т дружбы народов, 2017. – 328 с.

17. Протодьяконов М.М. Попытка опытного исследования законов давления пород на горные выработки // Горный журнал. – 1912. – № 4–5. – С. 12–19.

18. Хоменко В.П. Карстово-обвальные провалы «простого» типа: полевые исследования // Инженерная геология. – 2009. – № 4. – С. 40–48.

19. Хоменко В.П. Карстово-суффозионные процессы и их прогноз. – М.: Наука, 1986. – 97 с.

20. Aderhold G. Classification of sinkholes and subsidence troughs in karst-hazardous regions of Hesse. Recommendations for assessing geotechnical risks during construction activities. – Wiesbaden, 2005. – 113 p.

References

1. Gotman N.Z, Kajumov M.Z. Raschet fundamentov zdanij s zaglublennoj podzemnoj chast'ju na zakarstovannyh territorijah [Calculation of foundations of buildings with a buried underground part in the karst territories]. *Bulletin of Civil Engineers*, 2010, no. 4, pp. 68-72.

2. Gotman N.Z., Panteleev Y.I. The karst protection of highways using geosynthetic materials and alarm systems design. *Construction and Geotechnics,* 2022, vol. 13, iss. 3, pp. 5-14. DOI: 10.15593/2224-9826/2022.3.01.

3. Gotman N.Z., Evdokimov A.G. Determination of additional load on the bridge foundation pile when the karst deformation development. *Construction and Geotechnics,* 2021, vol. 12, iss. 4, pp. 5-18. DOI: 10.15593/2224-9826/2021.4.01

4. Kovalev V.A., Patrikeev A.B. O raschete parametrov karstovogo provala [Calculation of the parameters of the karst cavity]. *Industrial and Civil Engineering*, 2016, no. 10, pp. 36-41

5. Podol'skij V.A., Logacheva V.M., N.P. Panchukov Chislennyj metod modelirovanija razvitija deformacij pri verojatnom obrazovanii karstovyh polostej [Numerical method for modeling the development of deformations in the probable formation of karst cavities]. *Proceedings of Tula State University. Earth Sciences,* 2021, no. 1, pp. 283-289.

6. Richardson J.J. Fitting regulatory square pegs into round holes: local land use regulation in karst terrain. *Karst Groundwater Contamination and Public Health. Advances in Karst Science*. Springer, Cham, 2018. DOI: 10.1007/978-3-319-51070-5_29.

7. Richardson J. Local land use regulation of karst in the United States. 2003, pp. 492-501. DOI: 10.1061/40698(2003)45.

8. Zhang D., Gao L., Wu J. Mechanism of the rock stratum resisting inrush in filling-type karst tunnels and its application. *Arabian Journal of Geosciences*, 2022, no. 15. DOI:10.1007/s12517-022-10825-9.

9. Xu Z.H., Wu J., Li S.C., Zhang B., Huang X. Semianalytical solution to determine minimum safety thickness of rock resisting water inrush from filling-type karst caves. *International Journal of Geomechanics*, 2018, no. 18. DOI: 10.1061/(ASCE)GM.1943-5622.0001071.

10. Hui H., Wang Q., Yanyan Z., Chunmei Z., Yize W., Zeng G. The mechanism and numerical simulation analysis of water bursting in filling karst tunnel. *Geotechnical and Geological Engineering*, 2018, no. 36. DOI: 10.1007/s10706-017-0386-6.

11. Guo J.-Q., Qiao C.-S. Study on water-inrush mechanism and safe thickness of rock wall of karst tunnel face. Tiedao Xuebao. *Journal of the China Railway Society*, 2012, no. 34. DOI: 105-111. 10.3969/j.issn.1001-8360.2012.03.018.

12. Krashennikov V.S., Homenko V.P. Izuchenie pokryvajushhej tolshhi, kak odin iz vazhnejshih komponentov inzhenernyh izyskanij v rajonah pokrytogo karsta. [The study of the covering thickness as one of the most important components of engineering surveys in areas of covered karst]. *Bulletin MGSU*, 2011, no. 5, pp. 113-119.

13. Anikiev A.V. Ob ispol'zovanii modeli Birbaumera v inzhenernom karstovedenii [On the use of the Birbaumer model in engineering karst studies]. *Sergeevskie chtenija. Modelirovanie pri reshenii geojekologicheskih zadach. Issue. 11: Materialy godichnoj sessii Nauchnogo soveta RAN po problemam geojekologii, inzhenernoj geologii i gidrogeologii 23-24 marta 2009 [Sergeyev readings. Modeling in solving geoecological problems. Issue 11: Materials of the annual session of the Scientific Council of the Russian Academy of Sciences on problems of geoecology, engineering Geology and Hydrogeology March 23-24, 2009*]. Moscow, GEOS, 2009, pp. 257-262.

14. Tolmachev V.V, Troickij G.M., Homenko V.P. Inzhenerno-stroitel'noe osvoenie zakarstovannyh territorij [Engineering and construction development of karst territories]. Moscow, Strojizdat, 1986, 176 p.

15. Tolmachev V.V., Rojter F. Inzhenernoe karstovedenie. [Engineering karst research]. Moscow, Nedra, 1990, 152 p.

16. Anikiev A.V. Provaly i voronki osedanija v karstovyh rajonah: mehanizmy obrazovanija, prognoz i ocenka riska [Sinkholes and cavities in karst areas: formation mechanisms, prognosis and risk assessment]. Moscow, RUDN, 2017, 328 p.

17. Protod'jakonov M.M. Popytka opytnogo issledovanija zakonov davlenija porod na gornye vyrabotki [An attempt of experimental investigation of the laws of rock pressure on mine workings]. *Gornyj zhurnal* [*Mining Journal*], 1912, no. 4-5, pp.12-19.

18. Homenko V.P. Karstovo-obval'nye provaly «prostogo» tipa: polevye issledovanija [Karst-collapse cavities of the "simple" type: field research]. *Engineering Geology*, 2009, no. 4, pp. 40-48.

19. Homenko V.P. Karstovo-suffozionnye processy i ih prognoz [Karst-suffusion processes and their prognosis]. Moscow, Nauka, 1986, 97 p.

20. Aderhold G. Classification of sinkholes and subsidence troughs in karst-hazardous re-gions of Hesse. Recommendations for assessing geotechnical risks during construction activities. Wiesbaden, 2005, 113 p.