Determination of additional load on the bridge foundation pile under karst deformation

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Abstract. It is necessary to assess the additional loads transferred to the piles during the growth of a karst cavity in karst soils for designing bridge support pile foundations in karst areas. Additional loads arise due to the displacement of the soil mass above the cavity and the emergence of "negative friction" forces on the pile lateral surface. The paper proposes a method for determining the additional load on the pile depending on the distance from the pile bottom to the karst soil roof and the predicted diameter of the cavity in karst soils. A method for numerical variation calculations based on the analysis of the change of shear stresses on the pile lateral surface at different stages of loading with the growth of a cavity and the stable arch over the cavity is proposed. The correct design model and criteria for stability evaluation of the arch over the cavity are selected. A series of numerical calculations are made. An analytical solution to determine the additional load on the pile depending on the distance from the pile bottom to the karst soil roof and the predicted diameter of the cavity in karst soils is obtained.

1. Introduction

The increase in the volume of long highway and railway construction on the territory of the country, as well as numerous bridge crossings, including those on karst territories, leads to the need to improve methods of structural analysis for linear structures on such unfavorable sites.

According to the analysis and systematization of design solutions for bridge supports, their foundations represent, in most parts, a pile block of monolithic bored piles united by a monolithic grillage.

The design of the support pile foundation can be carried out in accordance with the requirements of CR 24.13330.2011. In this case, the load-bearing capacity of the piles and the load transferred to the pile are determined. Studies of the pile behavior during the formation of a karst hole in the base [1-5] carried out in Russia and abroad show that additional vertical and horizontal loads are transferred to the piles. In the norms of the Russian Federation (CR 24.13330.2011, clause 13. 10) additional vertical loads are considered as "negative friction" and it is indicated that they must be taken into account. However, so far there have been no proposals to define such additional loads either in the normative or scientific literature.

This paper contains the results of numerical studies aimed at defining additional loads on the bridge support foundation piles during the karst cavity formation in the soil under the pile bottoms, depending on the distance to the karst soil, where the cavity is formed, and its predicted size. As a result of the
studies performed, the regularities of changes in the additional load transferred to the pile, depending on the variable parameters, are established and formulas for calculating the support foundation piles above the karst cavity are proposed.

2. Numerical research technique and justification of the accepted computational model

To develop an engineering calculation method, complex numerical studies were performed by means of mathematical modeling of the bridge support pile foundation in various geological conditions. The calculation method was based on the analysis of the design documents for bridge crossings at Moscow-Kazan HSL section. As a result of the analysis, a variable finite element calculation model with the following parameters was compiled (figure 1):

- the soil mass under the rocky karst soil is represented by firm clay with the characteristics specified in table 1;
- a square-shaped grillage combining 36 piles with a diameter of 1.2 m and a length of 33 m. The design is shown in figure 2;
- the size of the calculated area L (along X and Y axes) was determined by the condition that it did not affect the results of the calculation, the nodes at the boundaries of the area were fixed;
- the size of the calculated area H (along Z-axis) was limited by the roof of the rocky karst soils, the nodes at the boundaries of the area were fixed, except for the predicted karst cavity;
- the predicted karst cavity was represented by the absence of anchoring of the nodes (along Z-axis) within it (figure 1);
- structure deformations – soil incompatibility was taken into account in accordance with clause 9.16 of CR 22.13330.2016 with the help of special interface elements on the pile-soil contact.

![Diagram](image-url)

**Figure 1.** Finite element model (section).

The calculations were performed by varying the following parameters (figure 2):

- the distance to the rock roof ($b$): 6 m, 10 m, 14 m, 18 m, 22 m;
- estimated cavity size during operation ($B$): 3 m, 5.5 m, 7.8 m, 10 m;
- distributed load over the grillage top: 400 kN/m$^2$, 550 kN/m$^2$ (corresponds to the load on the pile of 2800 kN and 3900 kN).

![Figure 2. The scheme of calculated foundation.](image)

### Table 1. Physical and mechanical properties of soils.

| Characteristic Name                  | Clay |
|-------------------------------------|------|
| Density, kN/m$^3$                   | 18.0 |
| Deformation modulus, MPa            | 25.0 |
| Angle of internal friction, degree  | 20   |
| Cohesion, kPa                       | 80.0 |

Numerical calculations were made in a three-dimensional representation. Soil, grillage, and piles were modeled by three-dimensional elements. A linear-elastic model was used to model concrete. The elastic-plastic Coulomb-Mohr model was used for soil modeling. Using the strength criterion implemented in the model, it was possible to estimate the "collapse arch" size in the cover layer of the soil above the karst cavity. By this way the "subsidence" deformation type and "failure" deformation type [6-9] can be realized. The possibility of using that strength criterion was confirmed by the convergence of the calculation results with the model experiment data of the “collapse arch” formation above the cavity [10].

The calculation was performed in the following sequence:
- the initial stress-strain condition of the soil mass was determined;
- the pile foundations of the supports were calculated for the design loads under normal operating conditions and the tangential stresses on the lateral surface of the piles were determined;
- the cavity size growth in karst soils located at a given distance from the bottom of the piles was determined step-by-step and the tangential stresses on the lateral surface of the piles were defined.

During calculations, the growth of the "collapse arch" above the karst cavity was monitored (figure 3). Assuming the possibility of the arch development up to the bottom of the piles, the additional load on the pile, realized at the time of the cavity formation, was determined.

The additional load was transferred to the pile at the time of the cavity formation due to the occurrence of "negative friction" on the lateral surface of the piles in their lower part. When modeling the formation of a cavity in karst soils, the occurrence of "negative friction" was determined by
changing of the tangential stresses on the lateral surface of the piles in comparison with the calculated ones in normal operating conditions.

Figure 3. Mohr-Coulomb points above cavity.

Under normal operating conditions, tangential stresses on the lateral surfaces of piles increased with depth, while on the extreme and corner piles the growth began from the top of the pile (the pile was included into work entirely). In the central piles tangential stresses developed in the lower part of the pile (due to the "compression" effect, the side surface friction of the central piles was not fully realized). Similar results of experimental and theoretical studies of piles behavior in the group were obtained in Russian and abroad [11-15].

When a cavity was formed, the soil of the cover layer subsided, which led to a change in the nature of the pile lateral surface work: the tangential stresses on the lateral surface in the lower part decreased, but along the rest of the pile length they increased (figure 4). That indicated the occurrence of the "negative friction" effect in the lower part of the piles and the inclusion of the most part of its lateral surface at the time of the cavity formation. The additional load on pile \( P_i \), kN, was determined by the formula:

\[
P_i = u \cdot \sum \Delta \tau_{zi} \cdot h_i,
\]

where: \( u \) is the perimeter of the pile, m; \( \Delta \tau_{zi} \) is the change in the shear stress value on the pile lateral surface in the considered \( i \)-th layer in comparison with the design phase under normal operating conditions, kN/m²; \( h_i \) is the thickness of the \( i \)-th soil layer in contact with the lateral surface of the pile, m. Thus, when calculating by the formula (1) only those layers were taken into account where \( \tau_z \) decreased or its direction changed.

The proportion of the increase in the load on the pile \( \Delta P = P/P_i \), where \( P \) was the load on the pile under normal operating conditions, was determined. With these data the graph for dependence of the value \( \Delta P \) on the ratio \( b/B \) was plotted. So, the additional load on the pile can be determined, having the values of the load on the pile in normal operation \( P \), the distance from the roof of the karst soils to the bottom of the piles \( b \) and the calculated diameter of the karst cavity \( B \).

3. Analysis of numerical study results

After performing the variable calculations, the following results were obtained and processed:

- the position of the Coulomb-Mohr points above the karst cavity to assess the size of the "collapse arch" and control the development of that arch to the bottom of the piles (figure 3);
change of the tangential stresses on the lateral surface of the pile (Δτ, kN/m²) during the growth of the karst cavity (figure 4).

Figure 4. Tangential stresses on the lateral surface of the pile (τ, kN/m²): (a) is before cavity formation, (b) is after cavity formation.

Based on the calculation of Coulomb-Mohr points location, the curves of the ratio h/b (“arch collapse” height / distance from the karts soil roof to the bottom of the pile, respectively) dependence on the ratio b/B (distance from the karts soil roof to the bottom of the pile / cavity diameter, respectively) were plotted. The defined parameters are shown in figure 2 and 3, and the graph is shown in figure 5. The possibility of developing the arch above the cavity to the bottom of the piles was determined by the condition h/b ≤ 1. This condition could be met at b/B > 1, which limited the scope of the results of this study and the proposed solution for determining the additional load on the pile.

Figure 5. Dependence of the relative distance from the predicted top of the collapse vault to the bottom of the piles (h/b) on the ratio of the distance from the top of karst soils to the bottom of the piles to the maximum cavity diameter (b/B): a, b – distributed load over the grillage top: 400 kN/m², 550 kN/m²
Figure 6 shows graphs of the dependence of the additional load on the pile \((P_1, \text{kN})\) on the diameter of the cavity \((B, \text{m})\) and the distance to the karst soil roof \((b, \text{m})\). These graphs are based on variable numerical 3D calculations of the bridge support pile foundation during the formation of karst deformations. However, such calculations are complicated and laborious and require specialized software to make them.

![Graphs of the dependence of additional load on pile on diameter of cavity and distance to karst soil roof](image)

**Figure 6.** Dependence of the additional load on the pile \((P_1, \text{kN})\) on the diameter of the cavity \((B, \text{m})\) and the distance to the karst soil roof \((b, \text{m})\): a, b – distributed load over the grillage top: 400 kN/m\(^2\), 550 kN/m\(^2\).

To determine the additional load on the pile \((P_1)\) to the load on the pile under normal operating conditions \((P)\) before the formation of the cavity, statistical processing of the calculation results was performed (figure 7) and analytical dependence \(P/P_1\) from \(b/B\) was obtained:

\[
P/P_1 = 2.1e^{-0.7 \frac{b}{B}}.
\]

**Figure 7.** Dependence of \(P/P_1\) on \(b/B\) ratio.

The value of a reliable approximation was \(R^2=0.9194\). Thus, the additional load on the pile \(P_1\) was determined in accordance with the design load transferred to the pile under normal operating
conditions ($P$) before the formation of the cavity, the size of the cavity ($B$) and the distance from the bottom of the piles to the karst soil roof ($b$):

$$P_1 = P/2.1e^{1.7b/\mu}.$$  \hspace{1cm} (3)

4. Conclusion

On the basis of numerical calculations, it was shown that there were additional loads on the piles under karst deformations at the base of the bridge support foundation. The value of those loads for clay cover layers over karst soils was determined.

It was established that additional loads largely depended on the distance from the bottom of the piles to the karst soils roof and the cavity diameter in the karst soils.

The relations of the distance from the bottom of the piles to the roof of the karst soils and the cavity diameter, at which the stable arch was formed above the cavity with a height of no more than the distance to the bottom of the piles, were determined.

The formula was deduced for calculating the additional loads on the bridge support piles depending on design load transferred to the pile under normal operating conditions before the formation of the cavity, the size of the cavity and the distance from the bottom of the piles to the karst soil roof.

References

[1] Gotman A L and Magzumov R N 2014 Method of pile analysis in strip foundation with karst hole *Vestnik MG SU* 2 74–83

[2] Gotman N Z and Davletyarov D A 2017 Investigation of pile strip foundation operation during the formation of a karst sinkhole *Soil Mechanics and Foundation Engineering* 2 2–7

[3] Gotman N Z 2008 Analysis of karst protective foundations of buildings and structures *Soil Mechanics and Foundation Engineering* 1 20–5

[4] Tolmachyov V V, Troitskiy G M and Khomenko V P 1990 *Engineering and Construction Development of Karst Territories* (Moscow: Nedra)

[5] Waltham T 2005 *Sinkholes and Subsidence: Karst and Cavernous Rocks in Engineering and Construction* (Chichester: Praxis Publishing Ltd)

[6] Aderhold G 2005 *Classification of sinkholes and subsidence troughs in karst-hazardous regions of Hesse. Recommendations for assessing geotechnical risks during construction activities.* (Wiesbaden)

[7] Anikeev A V 2017 *Collapses and Sinkholes of Subsidence in Karst Areas: Mechanisms of Formation, Forecast and Risk Assessment* (Moscow: RUDN)

[8] Tolmachyov V V 2012 Methods of karst hazard assessment for the construction purposes: state-of-art and prospects *Geoecology. Engineering geology. Hydrogeology. Geocryology* 4 354–63

[9] Khomenko V P 1986 *Karst-Suffusion Processes and Their Prediction* (Moscow: Nauka)

[10] Gotman N Z 2019 Evaluation of karst manifestation parameters by results of numerical calculations of foundations *Soil Mechanics and Foundation Engineering* 5 2–7

[11] Bartolomey A A, Omelchak I M and Yushkov B S 1994 *Forecast Pile Foundations Settlement* (Moscow: Strojizdat)

[12] Gotman N Z and Alekhin V S 2020 Calculation of the ultimate resistance of the pile bases in pile groups *Soil Mechanics and Foundation Engineering* 1 8–13

[13] Katzenbach R 2001 Recommendations for the design and construction of piled rafts *15th Int. Conf. on Soil Mechanics and Foundation Engineering (Istanbul)* pp 927–30

[14] Randolph M 1978 Analysis of deformation of vertically loaded piles *Journal of Geotechnical and Geoenvironmental Engineering* 1465–88

[15] Randolph M 1994 Design methods for pile groups and piled rafts *Soil Mechanics and Foundation Engineering* 13 61–82