Analysis of karst protective slab foundations taking into account the features of the base modeling

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Abstract. This paper presents a practical application of the improved method for calculating of slab foundations designed in karst rock areas. The method implementation is associated with the application of the updated analytical model taking into account behavior patterns of the ground base in the karst hole zone. The analytical solution obtained in the closed-form in the nonlinear formulation, allowed to obtain two key parameters of the foundation bed in the zone being studied - R and k_red. The dependence to determine the size of the weakening zone around the karst sinkhole area - R and the developed criterion for the quantitative change of the coefficient of subgrade reaction k_red in the zone of this weakening made it possible to propose a bilinear model of the interaction of the “foundation slab - base” system. The parameters of the base weakening obtained as a result of the problem solution have a wide range of changes depending on the physical and mechanical characteristics of the base soils and can be used for engineering calculations of slab foundations designed in karst areas. The comparative analysis of the calculations made according to the proposed and normative methods showed a substantial under-reinforcement of the foundation slab projected in the karst-hazardous zone.

1. Introduction

The principles of the calculations of karst protective slab foundations are closely related to the study of the nature of karst deformations development [1]. Foundations calculated according to existing methods [2, 3] must ensure reliability and provide efficient protection of buildings in-service. The origin of karst deformations development depends on the physical and mechanical characteristics of the soils of the construction site and, as a rule, the ratio of foundations depth to the distance to the karst-hazardous zone of a base [4, 5]. At a shallow footing depth, the use of the karst protective slab foundations is a reliable option, and their calculation is performed considering the karst sinkhole formation under the most loaded part of a foundation slab [6, 7]. Well-tried on multiple occasions and well-acclaimed computed software suites are applied for the analysis basing on the use of the coefficient of subgrade reaction.

2. Materials and methods

In the existing analytical models, the key parameter of the analysis is the diameter of the karst hole d (determined from the norms [8] based on probabilistic and statistical design methods), within which the coefficient of subgrade reaction C_z is considered equal to zero. Further changes in the coefficient...
of subgrade reaction in the area adjacent to the karst hole occur either spasmodically, up to its maximum value $C_{z,0}$ (Figure 1), or stepwise, in accordance with the decreasing coefficient $C_z^{red}$ (Figure 2), for which a criterion for its quantitative assessment should be developed.

To determine the size of the weakening area occurring around the karst sinkhole zone and to quantify the decreasing coefficient, the problem of the stress-strain state of the foundation weakened by a circumferential cutout (simulating a karst sinkhole zone) was solved. The analytical solution of the problem obtained in a closed form, taking into account the nonlinear operation of the ground base, allowed to propose for consideration the updated analytical model for calculating karst protective slab foundation of buildings [9]. In the updated analytical model, the variable coefficient of subgrade reaction is adopted, which varies according to the bilinear law (Figure 3). With the aid of the obtained solution, it became possible to determine the radius of the foundation weakening zone around the karst sinkhole zone and the decreasing coefficient of subgrade reaction taking account of this weakening. These characteristics are obtained for their use in engineering calculations of karst protective slab foundations.

The graphical representation of the described analytical models for calculation of karst protective slab foundations is shown in Figure 1-3.

![Figure 1. Linear model.](image1)

![Figure 2. Linear model (two-level).](image2)

![Figure 3. Bilinear model.](image3)

In the proposed analytical model (Figure 3) it is more convenient to use not two coefficients of subgrade reaction $C_{z,0}$ and $C_z^{red}(d/2)$, but their ratio – the decreasing coefficient $k_{red} = C_{z,0}/C_z^{red}(d/2)$, which is determined from the formula (1):

$$k_{red} = \left(\frac{N_1 \cdot \tan \varphi + \frac{c}{p} - N_2}{N_3 \cdot \tan \varphi + \frac{c}{p} - N_3}\right) \left(\frac{N_1 \cdot \tan \varphi + \frac{c}{p} - N_2}{N_3 \cdot \tan \varphi + \frac{c}{p} - N_3}\right)$$

(1)

where $\varphi$ - internal friction, $\nu$ - Poisson ratio, $c$ - cohesion coefficient, $N_1, N_2, N_3$ - coefficients values are listed in Table 1.
Table 1. The coefficients values $N_i$ for calculating the decreasing coefficient $k_{red}$.

| $N_i$ | $v$ | 0.28 | 0.30 | 0.32 | 0.34 | 0.36 | 0.38 | 0.40 |
|-------|-----|------|------|------|------|------|------|------|
| $N_1$ |     | 1.78 | 1.86 | 1.94 | 2.03 | 2.13 | 2.23 | 2.33 |
| $N_2$ |     | 0.53 | 0.54 | 0.56 | 0.59 | 0.62 | 0.65 | 0.69 |
| $N_3$ |     | 0.35 | 0.33 | 0.31 | 0.28 | 0.25 | 0.22 | 0.19 |

The weakness zone radius $R$ is determined from the formula (2):

$$R = \sqrt{\frac{d}{2} \left[ 0.05 \cdot \frac{1}{\sqrt{3}} \cdot \frac{\tan \varphi + 0.05 \cdot \frac{\sqrt{3}(1-v)}{p} + 0.95 \cdot (1-2v)}{3v^2} \right]^2 - (1-2v)^2}$$

The parameters of the foundation bed weakening obtained as a result of the problem solution – $R$ and $k_{red}$ are of a wide range of changing depending on the mechanical characteristics of the base soil and the design features of the underground part of a building. Thus, the weakening coefficient $k_{red}$ varies in the range from 0.3 to 0.7, and the radius of the foundation weakening zone $R$ increases to the value of the karst sinkhole diameter $d_k$. The use of the resulting parameters in engineering practice considerably simplifies the procedure of slab foundations calculation.

3. Results and discussion

The practical application of the obtained results is considered on the example of calculating the foundation slab of a multistory building with a single-level underground part for two versions
- modeling of the base with a karst pothole occurrence in a linear statement,
- modeling of the base with a karst pothole occurrence in a bilinear statement (according to the obtained solution).

General view of the design model in the SCAD Office program is shown in Figure 4. The calculation of the "building-foundation" system is performed in the Plaxis software package (Figure 5).

Figure 4. The calculation model of the building in SCAD Office.

Figure 5. The calculation model of the building in Plaxis.

The engineering and geological conditions of the construction site are represented by the following engineering geological elements:
- EGE-1 – fill soil;
EGE-2 – clay, medium-hard (cover layer);
EGE-3 – average coarse sand, dense, moist, with layers of coarse sand;
EGE-4 – fractured limestones (karst soils).

The diameter of the karst sinkhole, amounting to $d_k = 5$ m, is located under the base slab in the zone of its transition with the most loaded pier tower of the load-bearing frame. The chosen location of the sinkhole ensures the occurrence of the largest values of bending moments ($M_x$ and $M_y$) and transverse loads in the base slab ($Q_x$ and $Q_y$).

The isofields of distribution of the coefficients of foundation subgrade reaction $C_2 [t/m^3]$ in linear and bilinear formulations are shown in Figure 6, 7.

![Figure 6. Distribution of the coefficients of subgrade reaction without considering the weakness zone.](image)

![Figure 7. Distribution of the coefficients of subgrade reaction taking account of the weakness zone.](image)

The results of the further calculation are shown in Figures 8-11. For convenient visual comparison, the drawings for the linear and bilinear models of the foundation are shown in pair.

![Figure 8. The distribution of pressure under the base of foundation slab without considering the weakness zone.](image)

![Figure 9. The distribution of pressure under the base of foundation slab taking account of the weakness zone.](image)
According to the obtained values of internal stress, the reinforcement is selected automatically. The results of the reinforcement selection are shown below in the form of isofields of the required reinforcing (Figure 12, 13).

The demonstrable calculation results of the foundation slab reinforcement in linear and bilinear formulations in the form of comparative graphs are presented in Figure 14. For the convenience of evaluating these results, the difference in the obtained values of the reinforcement areas in the percentage ratio is shown in the lower part of the diagram.
Figure 14. The comparative diagram of the results of foundation slab reinforcement
$A_{s1}$, $A_{s3}$ – working reinforcement of the lower grid,
$A_{s2}$, $A_{s4}$– working reinforcement of the upper grid.

4. Summary

Analysis of the calculation results presented as the diagram in Figure 6 indicates that the area of the required reinforcement increases on average by ~30% in the foundation calculation in the bilinear formulation compared to the calculation in the linear formulation, which must be taken into account in designing and reinforcing foundation slabs that are used in the karst-suffusion hazard zones.

5. References

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