Interaction of drilled shafts in rock under the action of lateral load

M G Zertsalov, V V Znamenskiy, I N Khokhlov

Moscow State University of Civil Engineering, Yaroslavskoe shosse, 26, Moscow, 129337, Russia

E-mail: zertsalov@mgsu.ru, geosts@yandex.ru, inh.2017@yandex.ru

Abstract. The article presents the results of numerical simulation of the interaction of drilled shafts with rock mass under the action on its head of horizontal load or bending moment. The studies were carried out using finite element method with the use of factor analysis (method of experiment planning). Numerical calculations allowed to obtain the factor dependencies (regression equation) that connect the response functions (the bearing capacity of the shaft and the displacement of its head) with the selected independent factors that have the significant effect on the behavior of shafts. As factors were taken: the ratio of modulus of elasticity of shaft to modulus of deformation of intact rock, ratio of length of the pile to its diameter and RQD of the rock mass. The equations allow to construct graphs of dependence of displacements of the head of the shaft from applied loads: horizontal force or bending moment. Considering that the regression equations are very cumbersome, for convenience of their use nomograms were constructed. On the base of the study were also obtained two factor dependencies (regression equations) that take into account the character of the shaft interaction with the rock mass. One regression equation is used to define the line separating two regions of different interaction of shafts with rock mass. The one region is the region of "short" shafts that deform into rock with rotation and the bearing capacity of this kind of shafts depends on strength of the rock. The other region is the region of "long" shafts. The bearing capacity and horizontal displacements of this kind of shafts is determined only by the strength of the shaft material. The second regression equation allows to find the boundary into the rock mass below which the shaft doesn't work (no displacements of shaft). For the convenience of use of the obtained regression equations were constructed nomograms.

1. Introduction

During the last century socketed shafts in rock were used as foundations of different structures in the case when rock have soil overburden. In many cases, depending on geological conditions, socketed shafts entirely embedded in rock are used.

- Socketed shafts in rock have some advantages in comparison with other types of foundations:
  - Less vibrations during the construction process;
  - Bearing material can be visually inspected and tested to estimate rock quality;
  - Shaft length can be easily changed on the basis of actual data about rock properties after boring;
  - Large diameter shafts are well-suited to resist large lateral loads (e.g. earthquake, wind impact, vessel impact loads). Nowadays socketed shafts are often used as foundations of large-span structures, such as arch bridges.
The interaction of socketed shafts and rock was studied in laboratory and field conditions by many researchers. The behavior of socketed shaft in rock is similar to the behavior of large diameter piles in soil, but the structure of a rock mass and their highly variable mechanical characteristics considerably affect on bearing capacity and horizontal displacements of socketed shafts.

Another important factor, which requires careful analysis is the influence of the sidewall interface on the interaction of the shaft with surface of the rock. Variability of the properties of the interface introduces uncertainty in calculation of the bearing capacity and the horizontal displacement of the shafts.

To determine the mechanical properties of rock mass field tests and empirical solutions are often used by surveyors [1, 2]. Variety in a wide range of rock mass structural features complicates the study of their characteristics.

The problem of prediction of horizontal displacement of the head of the shaft has been usually studied through analytical and numerical analyses. With this purpose, in recent years, the finite element method (FEM) is successfully used. This method, with the advent of powerful software packages, has become a very powerful instrument to solve complex problems of interaction of engineering structures with rock mass.

Taking into consideration the capabilities of the solution of complex problems of the interaction of engineering structures with the rock mass using FEM, in recent years a number of papers performed of joint use of numerical simulation and the method of planning of experiments were published [3]. Based on factor analysis, the method of experiment planning [4] makes it possible to determine, using the matrix of experiment planning, required number of numerical experiments and conditions for their implementation. Processing of results of numerical modeling with the use of factor analysis allow to obtain dependencies in the form of regression equations describing the interaction of structure with rock mass, taking into account its mechanical properties and specific structural features.

2. Numerical simulation of laterally loaded socketed shafts

The load – displacement behaviour of laterally loaded shafts in rock is considered under three-dimensional conditions, taking into account the presence of the sidewall interface, which affects on the bearing capacity and top displacement of the shaft.

Fig.1 shows the FE-mesh of single socketed shaft – rock mass system generated using Z – Soil software package. The cylindrical shaft body and the surrounding rock mass are simulated by eight-node prismatic elements of the second order. The behavior of rock – concrete interface is simulated by special contact element for modelling of shear displacement of the shaft relatively to the borehole wall [5]. Based on recommendations of several researchers boundaries of the FE-model were assigned to avoid the effect of the fragment boundaries on the work of the socketed shaft. The following dimensions of the fragment are taken: from the shaft to the lateral boundaries of the fragment – 6 Dp; from the toe of the shaft to the lower boundary of the fragment – 1.7 Lp (Dp and Lp are respectively diameter and length of shaft). The displacements of the nodes at the fragment boundaries are equal to zero.
Figure 1. FE- model of socketed shaft body and surrounding rock mass.

The behavior of the socketed shaft under lateral loading is simulated by elastic isotropic model. To simulate the behavior of the rock mass and the sidewall interface Mohr-Coulomb model is used. Jointed rock mass with RQD=25…75 % can be considered as continuous isotropic medium so the elasto-plastic Mohr-Coulomb model can be applied for calculations.

The most significant impact on the interaction of socketed shafts and rock mass have the following factors, which was mentioned in some of the studies [6]:

- the degree of fracturing of the rock mass,
- the ratio of modulus of elasticity of the shaft to the modulus of elastic of intact rock,
- the ratio of the length of the shaft to its diameter,
- the mechanical characteristics of the sidewall interface.

Three following factors were used as the independent variables for the experiment planning within this article: RQD, Ec/Er, Lp/Dp, where RQD is the rock quality designation, Ec/Er is the ratio of the modulus of elasticity of the shaft material to the modulus of elasticity of the intact rock and Lp/Dp is the ratio of the length of the shaft to its diameter.

The influence of the characteristics and the state of sidewall interface were investigated separately, taking into account that, according to the observations of different researchers, it plays a special role in the interaction of the shaft body with the surrounding rock mass.

In this study, the parameters and the limits of their variation were chosen and the matrix of experiment planning was prepared to carry out the numerical experiment. That allowed to obtain a mathematical relationship (response function) of bearing capacity of the shaft from three selected effecting factors.
The modulus of elasticity of the shaft material was taken to be equal to $E_c = 25,000$ MPa. The range of variation of deformation and strength characteristics of intact rock were taken within the following limits: for modulus of elasticity $E_r (5000 \text{ MPa} - 50,000 \text{ MPa})$, for uniaxial compression strength $\sigma_c (20 \text{ MPa} - 100 \text{ MPa})$, which corresponds to the lower and upper limits of medium rock strength.

Further, using known values of moduli of elasticity of intact rock, the values of rock mass deformation moduli for numerical simulation were assigned, taking into consideration, the degree of fracturing of rock mass within the limits of variation of the factor $RQD$ (from 25% to 75%). These limits of variation of $RQD$ correspond to medium quality of rock mass.

Thus, for two values of $RQD$ (25% and 75%), and two values of the intact rock elastic moduli ($E_r = 5000$ MPa and $E_r = 50,000$ MPa), using the graph in Fig. 2, the four values of rock mass deformation moduli were obtained for numeric simulation. These values respectively amounted to: $E_m = 200$ MPa, 1500 MPa, 2000 MPa and 15,000 MPa.

![Figure 2. Graph of dependence of $(E_m/E_r) = f (RQD)$ [7].](image)

Since, to simulate the behavior of a rock mass the Mohr-Coulomb model was used, the strength of a rock mass in the studied cases was characterized by a cohesion $c_m$ and the friction angle $\varphi_m$ the empirical values of which were determined by the technique proposed in (Hoek, 1999). The values of these parameters were, respectively: $c_m = 0.4 \text{ MPa}, 0.7 \text{ MPa}, 2.8 \text{ MPa} \text{ and } 4.5 \text{ MPa}; \varphi_m = 26^\circ, 29^\circ, 30^\circ \text{ and } 36^\circ$.

The characteristics of the sidewall interface were simulated, as already noted, by special contact elements, using Mohr – Coulomb model. Tangential (along the pile) and normal stiffness – $K_t$ and $K_n$ were used as the elastic characteristics of the contact element. The values of $K_n$ were calculated according to the formula [8]:

$$K_n = \frac{E_m}{R(1 + \nu_m)} \quad (1)$$

where $R$ is the drilled shaft radius, $\nu_m$ is the Poisson ratio of the rock mass. The value of $K_t$ was taken $K_t = 100,000 \text{ kN/m}^3$. 


The strength properties of interface: the cohesion \( c_k \) and angle of internal friction \( \phi_k \), were taken according to recommendations (SP 23.1330. 2011). Respectively, they had the values: \( c_k = 0.15 \) MPa, 0.18 MPa, 0.25 MPa, 0.3 MPa, and \( \phi_k = 36^\circ, 37^\circ, 38^\circ, 39^\circ \).

3. Numerical simulation of laterally loaded socketed shafts

The results of the study allowed to determine the main peculiarities of the interaction of socketed shafts and the rock mass under the action of lateral loads. For practical purposes, the calculated curve of the displacements of pile under the action of horizontal loads can be approximated by two lines in the case where the second nonlinear portion of the graph is approximated as linear. In soft rocks the turning point of this graph will correspond to the beginning of rock mass failure, and the end point – to the loss of shaft bearing capacity due to the rock mass failure or to the failure of the shaft material (Fig. 3, a). In the strong rocks the load - displacement curve of socketed shafts can be described by a linear dependence «load – displacements», which is presented in Fig. 3 b.

![Graphs of horizontal displacements of socketed shafts](image)

**Figure 3.** Graphs of horizontal displacements of socketed shafts in soft rock (a) and strong rock (b).

Depending on the nature of deformation in the rock mass [9] laterally loaded socketed shafts can be divided into two groups:

- "short rigid shafts" (Fig. 4, a) – shafts, which rotate under the action of lateral loads into the rock mass practically without bending deformation around some fixed "zero point"; the bearing capacity of these shafts is determined either by the strength of the shaft body, or the strength of the rock mass surrounding the shaft in which during the loading in front of the shaft the volume of broken rock is formed;

- "short flexible shafts" - shafts, which under the action of lateral loads can rotate and at the same time have significant bending deformation (Fig. 4. b);

- "long flexible shafts" – shafts which under lateral load can only bend in the rock mass without rotation because of the fixity of the lower part of the shaft (Fig.4, c). In this case its bearing capacity is determined only by the strength of the shaft body.
After mathematical processing of the results of FEM calculation using method of experiment planning the results of numerical simulation the regression equations (2) and (3) were obtained which limited the borders of areas of deformation of described types of shafts:

\[
\frac{L_p}{D_p} = 2.2 + 0.75 \cdot X_1 - 0.35 \cdot X_2 + 0.1 \cdot X_1 \cdot X_2
\]

(2)

\[
\frac{L_p}{D_p} = 6.75 + 1.25 \cdot X_1 - 0.75 \cdot X_2 - 0.25 \cdot X_1 \cdot X_2
\]

(3)

where: \(X_1 - \frac{E_c}{E_r}, X_2 - RQD, X_3 - L/D\).

Equation (2) defines the border between areas of deformation of "rigid" and "flexible" shafts. Equation (3) defines the boundary line of the "fixity" of the socketed shaft. Taking into consideration the size of regression equations on their basis for express analysis the nomograms were constructed.

Based on the analysis of numerical simulation results and processing them using regression analysis (method of experiment planning) the equations, which make possible to determine the horizontal load and the corresponding horizontal displacement of the piles in the characteristic points of the deformation curve at any combination of factors within their variation were obtained. After processing of the results the following parametric dependencies and nomograms were obtained: bearing capacity related to rock mass, bearing capacity related to reinforced concrete, horizontal load at the start of failure of rock mass, displacement at the start of failure of rock mass, displacement at the end of failure of rock mass, displacement at the end of failure of reinforced concrete.

Figure 4. Three cases of deformation of drilled socketed shafts.

Figure 5. Nomograms for definition of the borders of areas of deformation.
The results of this study may be used for the preliminary assessment of the bearing capacity and deformation of laterally loaded drilled shafts in rocks.

4. Influence of the sidewall interface properties on the lateral displacements of socketed shafts

Fig. 6 shows the results of the research of the study of dependence of the shaft lateral displacements from changes of the sidewall interface tangential stiffness under different ratio $E_c/E_m$. Analysis of the curves shows that with increasing stiffness $K_s$ in the range from 50,000 kN/m$^3$ up to 400,000 kN/m$^3$ the value of the shaft lateral displacements, is reduced in the range of from 5 to 10 times, depending on the values of the modulus of deformation of rock mass, with the increase of which, the decrease of the settlement is more intensive.

At the same time, changing of the tangential stiffness of the interface from 400,000 kN/m$^3$ to 1,000,000 kN/m$^3$ affects the values of the shaft displacements change very little. This suggests that within the range of variation of the tangential stiffness of the interface, its impact on shafts displacements is insignificant, and the values of settlements are mainly determined by the deformation modulus of the rock mass.

![Figure 6](image)

Figure 6. Curves of the shaft settlements from the change in the tangential stiffness of the sidewall interface under different ratios $E_c/E_m$.

5. Conclusion

1. The combination of numerical simulation and the method of experiment planning significantly expands the research opportunities, allowing to solve problems of interaction of engineering structures with rock mass, which cannot be solved analytically or by physical simulation

2. Numerical studies of drilled socketed shafts in rock allowed to analyze their behavior in rock mass of medium strength. Studies have shown that the case of deformation of shaft body under the action of lateral loading depends from the values of the deformation characteristics of the shaft and the rock mass, and the ratio of the length of the shaft to its diameter.

3. Socketed shafts, depending on the depth of their embedment in the rock mass and their properties, have three types of deformation “rigid” and “flexible”. FE-modelling of shaft-rock interaction allowed to obtain dependence in the form of the regression equation, determining the boundary of the deformation type in the rock mass of the shafts. Also the regression equation was obtained that defines the depth of the fixity of “flexible” shafts, below which there is no displacements of the shaft body.
4. The research allows also to study the shaft sidewall interface with rock mass in the conditions of elasto–plastic problem and to assess the tangential stiffness influence on the behavior of the socketed shaft, in particular, on its displacements. Taking into account the lack of information to assign reasonable values of this mechanical properties in the analysis and design of socketed shaft foundations, it is necessary to conduct special studies to determine its values at different conditions and creating a corresponding database.

References
[1] Zhang L 2004 Drilled shafts in rock Analysis and design (A.A. Balkema publishers) p 383.
[2] Zertsalov M G and Konyuokhov D S 2007 O raschjote svaj v skal'nyh gruntah Osnovaniya fundamenty i mehanika gruntov I pp 8–12.
[3] Tolstikkov V V and Karlush A B M 2015 Chislennoe modelirovanie rabotosposobnosti gravitacionnyh plotin iz osobo toshhego ukatannogo betona Estestvennye i tehnicaskie nauki 1 pp 617–619.
[4] Adler Y P 1968 Vvedenie v planirovanie jeksperimenta (M.: Metallurgia) p 155.
[5] Orekhov V G and Zertsalov M G and Tolstikkov V V 1987 Issledovanija shemy razrushenija sistemy betonnaja plotina – skal'noe osnovanie Izvestija VNIIG im. B.E. Vedeneeva T 204 pp 71–76.
[6] Wyllie D 1999 Foundation on Rock Second edition (E and FN and FH London New York) pp 424.
[7] Zhang L and Einstein H H 2000 Estimating the deformation modulus of rock masses Pacific Rocks 2000 In Proc 4th North American Rock Mech Symp Seattle WA Eds: J Girard et al pp 703–708.
[8] Boresi A P 1965 Elasticity in engineering mechanics (Prentice-Hall Englewood Cliffs N J) pp 434.
[9] Znamenskij V V 2000 Inzhenernyj metod rascheta gorizontal'no nagruzhennyh grupp svaj (Moscow: ASV) pp 128.