Express-Method for Determination of Rock Heaving Parameters

Oleksandr SHASHENKO[1], Eugeniusz Jacek SOBCZYK[2], Volodymyr SHAPOVAL[3], Volodymyr KONOVAL[4], Sofiia BARSUKOVA[5]

[1] Doctor of Technical Sciences, Professor of the Department of Construction, Geotechnics and Geomechanics; Dnipro University of Technology, ave. D. Yavornytskoho 19, Dnipro, Ukraine; ORCID https://orcid.org/0000-0002-7012-6157; email: shashenko.o.m@nmu.one
[2] Professor of the Department of Mineral Resource Management Mineral and Energy Economy; Research Institute of the Polish Academy of Sciences, ul. Wybickiego 7A, Krakow, Poland, ORCID https://orcid.org/ 0000-0003-3968-2312; email: jsobczyk@meeri.eu
[3] Doctor of Technical Sciences, Professor of the Department of Construction, Geotechnics and Geomechanics; Dnipro University of Technology, ave. D. Yavornytskoho 19, Dnipro, Ukraine; ORCID https://orcid.org/0000-0003-2993-1311; email: shapvv27@gmail.com
[4] Candidate of Technical Sciences, Docent of the Department of industrial and civil construction; Cherkasy State Technological University, boulevard. Shevchenko, 460, Cherkasy, Ukraine; ORCID https://orcid.org/0000-0002-6740-6617; email: konovalvolodymyr2019@gmail.com
[5] PhD student of the Department of Construction, Geotechnics and Geomechanics; Dnipro University of Technology, ave. D. Yavornytskoho 19, Dnipro, Ukraine; ORCID https://orcid.org/0000-0003-0821-1091; email: barsukova.s.o@nmu.one

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Abstract

Purpose. The problem of determining the contours of the area in which rock heaving occurs is important in the design of underground excavations. The solution of such problems is usually performed either in an elastic-plastic formulation using numerical methods, or using semi-empirical methods, which, as a rule, form the basis of regulatory documents. When writing this article, an attempt was made to use the approach described in work Determining the parameters of a natural arch while forming support load of a horizontal roadways to find answers to such questions: is it possible under these conditions to heave rock at all; what are the outlines of the heaving area.

Theoretical studies of geomechanical processes occurring in the vicinity of horizontal excavations using analytical and numerical mathematical methods. Analysis and generalization of the results of theoretical studies. Simple analytical dependencies are obtained that allow calculating the boundary of the base area in which rock heaving occurs and the stability coefficient of this area. As a stability coefficient, it is proposed to use the ratio of the projection onto the vertical axis of the forces holding the heaving rock mass to the projection of the forces that shift this mass. It has been established for the first time that the maximum depth under the excavation, where the heaving of the rock occurs, is directly proportional to its strength, calculated using the strength criterion of O. Shashenko, multiplied by half the width of the excavation and inversely proportional to the specific adhesion of the rock. It was also established for the first time that the coefficient of rock stability in the area of its heaving is directly proportional to its strength, calculated using the strength criterion of O. Shashenko, and back - to rock pressure at the calculated depth. The results obtained in the course of this work make it possible, using mathematical methods, to perform: forecast of the stability of horizontal excavations in the area of rock heaving, taking into account the depth of the excavation, its geometric dimensions, specific gravity and strength properties of the rock; the boundaries of the rock heaving area, taking into account the depth of the excavation, its geometric dimensions, specific gravity and strength properties of the rock.

Keywords: *excavation, Mohr-Coulomb strength criterion, strength criterion O. Shashenko, rock heaving, arched effect, rock pressure*

1. ANALYSIS OF ACHIEVEMENTS IN THIS AREA

From the practice of operating underground mine excavations, it is known that in their lower part, rock heaving occurs.

A large amount of research in this direction was carried out by M. Protodyakonov, P. Tsimbarevich, M. Pokrovsky, M. Evdokimov-Rokotovsky, V. Orlov, D. Rostovtsev, A. Labas, O. Gurdus, I. Chernyak, O. Shashenko and representatives of his school (O. Solodiankin, S. Hapieiev, O. Sdvyzhkova), as well as other scientists [1, 2, 3, 4, 5, 6, 7].

These studies differ in approaches to assessing the causes of the heaving process, the acting forces, etc. and as a result – results that contradict each other.

In our opinion, when studying the process of rock heaving, the answers to such questions are very important:

1. Does the heaving process take place under given specific conditions (i.e. at the calculated depth, with given excava-tions sizes, given rock properties, etc.).
2. If so, what area of the base is subject to heaving.

In our opinion, answers to these questions can be obtained using the arch effect hypothesis (it was proposed by M. Pro-todyakonov) and the interpretation of this hypothesis set out in [10].

2. MATERIALS AND RESEARCH METHODS

The research task was formulated as follows.:

1. A horizontal excavation is arranged inside the base (fig. 1).
2. The rock pressure in the upper part of the excavation and the lateral pressure are taken by the support, which is able to move vertically. At the same time,

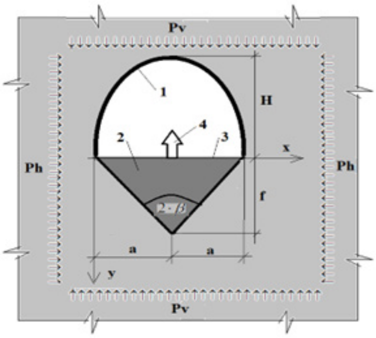


Fig. 1. To determine the area of destruction of rock under a horizontal excavation. Note. The following designations are adopted in the figure: 1 – holding structure; 2 – heaving area; 3 – load-free from loads adit surface; 4 – heaving deformation direction; – vertical pressure; – horizontal pressure; – arch lifting boom; – half the width of the excavation span; – coordinates

Rys. 1. Określenie obszaru zniszczenia skały pod wykopem poziomym. Na rysunku przyjęto następujące oznaczenia: 1 – struktura podtrzymująca; 2 – obszar wypiętrzania; 3 – wolna od obciążeń powierzchnia wyrobiska; 4 – kierunek wypiętrzania; – nacisk pionowy; – ciśnienie poziome; – wysięgnik do podnoszenia łuku; – połowa szerokości przęsła wykopu; – współrzędne

movements of the support and its elements in the horizontal direction are excluded. This is achieved by embedding foundations into the rock and (or) horizontal spacers (fig. 1).

3. There is no support at the bottom of the excavation (fig. 1).
4. The shape of the contour of the area of the rock fall above the excavation is known (more precisely, its equation Y(x). At the same time, the parameters of this are unknown and they should be determined in the course of solving the problem.
5. The rock destruction mechanism is shear. Therefore, its behavior during destruction obeys the Coulomb-Mohr strength condition.
6. The strength characteristics of the rock are known (specific cohesion c and the angle of internal friction φ or the strength of the rock for uniaxial compression R_c and uniaxial tension R_p)
7. The specific gravity of the soil (rock) is known γ.
8. The horizontal and vertical pressures at the estimated depth are known (fig. 1).
9. We need:
   9.1. Find out if rock heaving takes place in this particular case.
   9.2. Determine the boundary separating the destroyed and undestroyed rocks in the roof of the excavation (fig. 1).

In order to determine the zone in which rock heaving takes place, we will take the following assumptions:

1. Rock strength obeys the Coulomb-Mohr law [8]:

$$\tau = \sigma \cdot tg(\varphi) + c = \frac{\sigma}{2} \cdot \frac{R_c - R_p}{\sqrt{R_c \cdot R_p}} + \frac{1}{2} \cdot \sqrt{R_c \cdot R_p}, \tag{1}$$

Here: τ – breaking stress;
σ – normal stress;
$\varphi = \arcsin\left(\frac{R_c - R_p}{R_c + R_p}\right)$ – rock internal friction angle;
$c = \frac{1}{2} \cdot \sqrt{R_c \cdot R_p}$ – specific cohesion;
R_c – soil compressive strength;
R_p – the same, in tension.

2. Equation of the boundary for the heaving region using the Heaviside step function in the first approximation can be represented as a lancet arch:

$$Y(x) = \frac{f}{a} \cdot x \cdot \left[1 - U(a - x)\right] + f \cdot \left(2 - \frac{x}{a}\right) \cdot \left[U(a - x) - U(2 \cdot a - x)\right]. \tag{2}$$

Next, consider the holding and shearing forces acting at some point M (fig. 3).

Since the reason for the destruction of the rock is shear, the forces holding and shifting the rock are directed tangentially to the curve Y(x) at point M (fig. 2).

We also take into account that

$$\beta = \pi/2 - \alpha, \tag{3}$$

(this follows from the scheme in figure 2).

In view of symmetry, in the future we will consider the left side of the arch.

First, we find the differentials of the forces acting at the point M. To do this, consider infinitely small increments of the abscissa dx , ordinate dy и arcs ds (fig. 2 and fig. 3). We have:

$$\left.\begin{aligned} & tg(\alpha) = \frac{dY(x)}{dx} = \frac{f}{a}; \quad \alpha = arctg\left[\frac{dY(x)}{dx}\right] = arctg\left(\frac{f}{a}\right); \\ & dy = dx \cdot tg(\alpha) = dx \cdot \frac{f}{a}; \quad ds = \sqrt{d^2x + d^2y} = \frac{dx}{a} \cdot \sqrt{a^2 + f^2}. \end{aligned}\right\}. \tag{4}$$

Next, we find the differential of the shearing and holding forces. The shear force differential dT_{sd} is equal to:

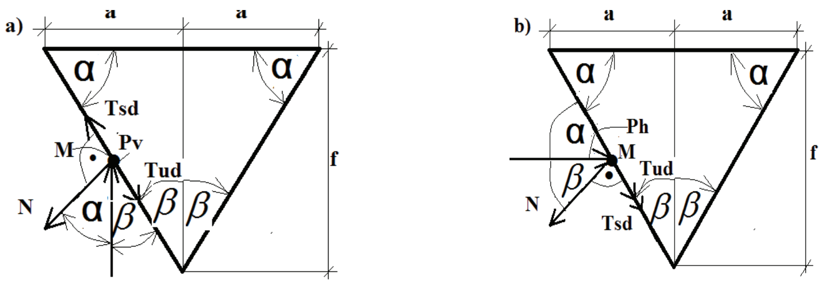
$$dT_{sd} = P_v \cdot \cos(\beta) \cdot dx = P_v \cdot \sin(\alpha) \cdot dx = P_v \cdot \frac{f}{\sqrt{f^2 + a^2}} \cdot dx. \tag{5}$$

The normal force differential dN is equal to:

$$dN = P_v \cdot dx \cdot \cos(\alpha) = P_v \cdot \frac{a}{\sqrt{f^2 + a^2}} \cdot dx. \tag{6}$$

Driving force differential dT_{ud} is equal to:

$$\begin{aligned} dT_{ud} &= dN \cdot tg(\varphi) + c \cdot ds = P_v \cdot tg(\varphi) \cdot \cos(\alpha) + \frac{c}{\cos(\alpha)} = \\ & P_v \cdot tg(\varphi) \cdot \frac{a}{\sqrt{f^2 + a^2}} \cdot dx + c \cdot \frac{\sqrt{f^2 + a^2}}{a} \cdot dx \end{aligned} \tag{7}$$



Note: The following designations are adopted in the figure: α – angle of inclination of the generatrix of the wedge to the abscissa axis; $\beta = \pi/2 - \alpha$; $\alpha = \frac{\pi}{2} - \beta$; P_v and P_h – vertical and horizontal components of rock pressure, respectively, acting within one meter of the excavation length (they are measured in $\frac{kN}{m^2} \cdot m$); T_{sd} and T_{ud} – shearing and holding wedge loads, respectively, at a certain point on the wedge surface.

Fig. 2. To the definition of shearing and holding forces (scheme). a) scheme for determining the holding and shear forces from a vertical load P_v; b) the same, from the horizontal

Rys. 2. Do definicji sił ścinających i trzymających (schemat). a) schemat wyznaczania sił trzymania i ścinania od obciążenia pionowego P_v; b) jak w a), od obciążenia poziomego.

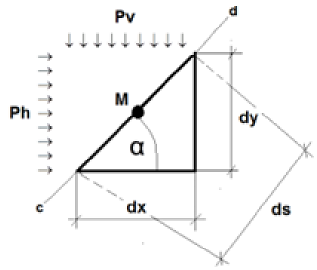


Fig. 3. To the definition of differentials of shearing and holding forces (scheme). Note: this figure should be read together with figure 2

Rys. 3. Do definicji różniczek sił ścinających i trzymających (schemat). Uwaga: ten rysunek należy czytać razem z rysunkiem 2

After that, we find the projections of the holding and shear forces on the vertical axis.

Projection of shear forces on the vertical axis $T_{sd,y}$ is equal to:

$$T_{sd,y} = 2 \cdot \int_0^a dT_{sd} \cdot \cos(\beta) = 2 \cdot \int_0^a P_v \cdot \frac{f}{\sqrt{f^2 + a^2}} \cdot dx \cdot \cos(\beta) = 2 \cdot P_v \cdot \frac{a \cdot f^2}{f^2 + a^2} \tag{8}$$

Projection of holding forces on the vertical axis $T_{ud,y}$ is equal to:

$$T_{ud,y} = 2 \cdot \int_0^a dT_{ud} \cdot \cos(\beta) + Q_{op} = 2 \cdot f \cdot c + 2 \cdot f \cdot P_v \cdot tg(\varphi) \cdot \frac{a^2}{a^2 + f^2} + \gamma \cdot a \cdot f \tag{9}$$

Here $Q_{op} = \gamma \cdot a \cdot f$ – the weight of the rock enclosed within the heaving zone, and γ – specific gravity. In order to simplify (9) and provide some margin of safety, we set $Q_{op} = 0$.

Equalities (8) and (9) make it possible to estimate the strength of the rock subjected to heaving by introducing the stability coefficient in the form of the ratio of the projection onto the vertical axis of the holding forces to the projection onto this axis of the shearing forces:

$$k_u = \frac{T_{ud,y}}{T_{sd,y}} = \frac{c \cdot \left(a^2 + f^2\right) + P_v \cdot a^2 \cdot tg(\varphi)}{f \cdot P_v \cdot a}. \tag{10}$$

This approach allows you to quite simply establish in what state (stable, indifferent or unstable) the base area under the excavation is located.

So, if the rock in the heaving zone is in a stable state, $k_u = (T_{ud,y})/(T_{sd,y}) > 1$. If the rock in the heaving zone is in an indif-ferent state, then $k_u = (T_{ud,y})/(T_{sd,y}) = 1$. Finally, if the rock in the heaving zone is in an unstable state, then $k_u = (T_{ud,y})/(T_{sd,y}) < 1$.

From equalities (8)–(10) it follows that, given different values of the height of the arch lifting boom f we obtain dif-ferent values of the stability coefficient k_u.

However, of interest are such values of the arch lifting boom f at which the value of the stability coefficient will be minimal.

From a mathematical point of view, the above statements are the formulation of the problem of finding the minimum of a certain functional [9].

To find the function $k_u = (T_{ud,y})/(T_{sd,y}) < 1$ take from the functional (10) the first partial derivative with respect to the variable and equate the function thus obtained to zero. We have:

$$\frac{\partial k_u}{\partial f} = -\frac{c \cdot a^2 + P_v \cdot a^2 \cdot tg(\varphi) - c \cdot f^2}{f^2 \cdot P_v \cdot a} = 0, \tag{11}$$

where:

$$f_{1,2} = \pm(a/c) \cdot \sqrt{P_v \cdot c \cdot tg(\varphi) + c^2}. \tag{12}$$

Next, we find out which of the values (12) corresponds to the minimum or maximum of the functional (10).

To do this, we find from (10) the second partial derivative with respect to the variable f and substitute the values of the arch lifting arrow (18) into the expression obtained in this way. We have:

$$\frac{\partial^2 k_u}{\partial^2 f} = 2 \cdot a \cdot \frac{c + P_v \cdot tg(\varphi)}{P_v \cdot f^3}. \tag{13}$$

Tab. 1. The results of determining the stability coefficient of the rock and the depth of the heaving area (see the scheme in fig. 1)
Tab. 1. Wyniki wyznaczenia współczynnika stateczności skały i głębokości strefy wypiętrzania (patrz schemat na rys. 1)

№	Depth of the roof of the excavation, m	Excavation width $2 \cdot a$, m	Depth of heaving deformation area f, .m	Minimum stability factor k_u, fractions of a unit
1	10	6	3,26	11,53
2	100	6	5,04	1,78
3	200	6	6,47	1,14
4	250	6	7,07	1,00
5	300	6	7,63	0,90

Next we find:

$$\lim_{f \to f_{1,2}} \left(\frac{\partial^2 k_u}{\partial^2 f} \right) = \pm \frac{2 \cdot c^2}{P_V \cdot a^2 \cdot \sqrt{P_V \cdot tg(\varphi) \cdot c + c^2}} \tag{14}$$

According to [9], functional (10) has a minimum at the value of the lifting arrow equal to:

$$f = (a/c) \cdot \sqrt{P_V \cdot c \cdot tg(\varphi) + c^2}\ . \tag{15}$$

Next, we find the minimum value of the stability coefficient of the excavation during heaving of the rock. To do this, we substitute into formula (10) the value of the depth of the heaving region (15). We have:

$$k_{u,\min} = \lim_{f \to f_1} \left(\frac{T_{ud,y}}{T_{sd,y}} \right) = \lim_{f \to f_1} \left\{ \frac{c \cdot \left(a^2 + f^2\right) + P_V \cdot a^2 \cdot tg(\varphi)}{f \cdot P_V \cdot a} \right\} = = 2/P_V \cdot \sqrt{P_V \cdot c \cdot tg(\varphi) + c^2} \tag{16}$$

It is also appropriate to note that despite the fact that the above results were based on the Coulomb-Mohr criterion, the stability coefficient is numerically equal to its double strength, calculated in accordance with the strength criterion of O. Shashenko [1, 2, 3, 4, 5, 6, 7], divided by the vertical component of rock pressure at the estimated depth.

In rock mechanics, it is customary to operate with such strength characteristics as the strength of the rock in uniaxial compression R_c and its strength in uniaxial tension R_p. Therefore, it is advisable to consider the results obtained above using strength characteristics c and φ the results with strength characteristics R_c and R_p.

To pass to new characteristics, we use relations (1). We have:

- for the maximum depth of the base in which heaving takes place:

$$f = a \cdot \sqrt{1 + P_V \cdot \left(1/R_r - 1/R_c\right)}\ ; \tag{17}$$

- for the minimum value of the stability coefficient:

$$k_{u,\min} = \sqrt{R_c \cdot R_r + P_V \cdot \left(R_c - R_r\right)} \Big/ P_V\ . \tag{18}$$

To illustrate our results, consider the problem of determining the size of the heaving area at the base of horizontal exca-vation with a span of 6 meters located at various depths equal to 10, 100, 200, 250 and 500 meters using the following initial data: specific gravity of the rock $\gamma = 20$ kN/m^3; rock compressive strength – Rc = 5000 kPa; compressive strength – Rr = 900 kPa. These strength values are typical for sedimentary rocks such as siltstone, mudstone, marl, chalk, and weak limestone in a fully water-saturated state [11].

The results of calculations by formulas (17) and (18) are summarized in Tab. 1. Analysis of the data presented in Table 1 allowed us to draw the following conclusions:

1. When the bottom of the excavation is located at depths of up to 250 meters, the rock is in a stable state (because Ku>1).

2. When the bottom of the excavation is located at a depth of 250 meters, the rock is in an indifferent state (because Ku=1).

3. When the bottom of the excavation is located at a depth of more than 250 meters, the rock is in an unstable state (because Ku<1). In this case, for example, when the bottom of the excavation is at a depth of 300 meters, the lower boundary of the heaving area is at a depth equal to 300+7,63=307,63 meters.

In our opinion, this information is very important in the design of underground excavations. In particular, from the data presented in the table 1, it follows that there will be no rock heaving up to a depth of 250 meters.

At the same time, if the bottom of the excavation is at a depth of 300 meters, in order to avoid heaving, the rock should be fixed at a depth interval of 300...307,63 meters.

3. CONCLUSIONS

In general, the research materials presented in this paper made it possible to draw the following conclusions.:

1. It is shown that the modification of the theory of the arch effect by M. Protodyakonov proposed by the authors of [10] can be used to determine the geometric dimensions of the heaving zone of rocks in underground excavations.

2. To solve this problem, it is proposed to introduce the so-called stability coefficient k_u , numerically equal to the ratio of the forces holding the rock in the zone of its heaving to the shearing forces. In this case, if the k_u >1 rock in the heaving zone is in a stable state, k_u =1 – in an indifferent state, and if k_u <1 – in an unstable.

3. It has been established that the maximum depth of the soil heaving area is numerically equal to the strength criterion of O. Shashenko [1, 2, 3, 4, 5, 6, 7], divided by the specific cohesion of the soil and multiplied by the excavation span width. This result is obtained for the first time.

4. It is shown that the rock stability coefficient in the area of its heaving is numerically equal to the strength calculated in accordance with the strength criterion of O. Shashenko [1, 2, 3, 4, 5, 6, 7], divided on the vertical component of the rock depth and multiplied by two.

5. Application area of the obtained results: Forecast of the state in which the rock is located in the lower part of the excavation (i.e. is heaving or not). Approximate determination of the boundaries of the base area in the vicinity of an excavation, in which rock heaving takes place. Initial data for the first approximation when solving problems of determining the parameters of the heaving area of the soil by numerical methods using the iteration process.

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Ekspresowa metoda wyznaczania parametrów wypiętrzania skał

Problem określenia konturów obszaru, w którym występuje wypiętrzanie skał, jest istotny w projektowaniu wyrobisk podziemnych. Rozwiązanie takich problemów jest zwykle wykonywane albo w preparacie sprężysto-plastycznym metodami numerycznymi, albo metodami półempirycznymi, które z reguły stanowią podstawę dokumentów regulacyjnych. Pisząc niniejszy artykuł, podjęto próbę wykorzystania podejścia opisanego w pracy: Determining the parameters of a natural arch while forming support load of a horizontal roadways do znalezienia odpowiedzi na następujące pytania: czy w tych warunkach w ogóle możliwe jest wypiętrzanie skał; jakie są kontury wypiętrzania obszaru.

Zastosowano następujące metody: teoretyczne badania procesów geomechanicznych zachodzących w sąsiedztwie wyrobisk poziomych z wykorzystaniem analitycznych i numerycznych metod matematycznych; analiza i uogólnienie wyników badań teoretycznych. Otrzymano proste zależności analityczne pozwalające na obliczenie granicy obszaru bazowego, w którym występuje wypiętrzanie skały, oraz współczynnika stateczności tego obszaru.

Jako współczynnik stateczności proponuje się przyjąć stosunek rzutu na oś pionową sił utrzymujących falujący górotwór do rzutu sił przesuwających ten masyw. Po raz pierwszy ustalono, że maksymalna głębokość pod wyrobiskiem, na której występuje wypiętrzanie skał, jest wprost proporcjonalna do jej wytrzymałości, obliczonej według kryterium wytrzymałościowego O. Szaszenki, pomnożonej przez połowę szerokości wyrobiska, i odwrotnie proporcjonalna do przyczepności właściwej skały.

Po raz pierwszy ustalono również, że współczynnik stateczności skały w obszarze jej wypiętrzania jest wprost proporcjonalny do jej wytrzymałości, obliczonej za pomocą kryterium wytrzymałościowego O. Szaszenki, i odwrotnie – do ciśnienia na obliczonej głębokości. Uzyskane w toku pracy wyniki pozwalają, metodami matematycznymi, na wykonanie: prognozy stateczności wyrobisk poziomych w rejonie wypiętrzenia skał z uwzględnieniem głębokości wyrobiska, jego wymiarów geometrycznych, ciężaru właściwego i właściwości wytrzymałościowych skały; granic obszaru falowania skał z uwzględnieniem głębokości wyrobiska, jego wymiarów geometrycznych, ciężaru właściwego i właściwości wytrzymałościowych skały.

Słowa kluczowe: *wyrobisko, kryterium wytrzymałościowe Mohra-Coulomba, kryterium wytrzymałościowe O. Shashenki, wypiętrzanie skał, efekt łukowy, ciśnienie skał*