Formation of soil sinkholes in the form of a collapse pipe

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Abstract. The mechanism of formation of sinkholes of the ground surface in the form of a collapse pipe, which characteristic feature is the existence of almost vertical walls with a sinkhole depth exceeding its lateral dimension, is considered in the article. The authors solve the geo-mechanical problem of stress distribution in the rock mass near the underground cavity that initiates the formation of the sinkhole. The extreme parameters (geometrical and strength) which make it possible to initiate the progressive destruction in the form of a vertical pipe of destruction, are defined according to the integrated criterion of durability. The ratio, that relates the depth of the cavity location, the horizontal size of the sinkhole, the strength properties of the rocks (adhesion, internal friction angle), and the lateral pressure coefficient in the massif is obtained.

1. Introduction

Sinkholes arise when the roof collapses over underground voids (caves, etc.), formed during the karst formation or man-made intervention in the rock massif. The recent sinkholes have the mine-like form (fig. 1) which can pass over time into the tapered form as a result of collapses and slipping of rock. The sinkhole in the settlement of Neledino in Shatkovsky district of Nizhny Novgorod Region is presented in the Figure 1 as an example. The sinkhole depth was ~35 meters at the time of measurement in August, 2018. The diameter in the upper was ~ 20 m, and in the zone of the exit of the Perm limestones it was 10-12 meters.

Figure 2 presents the example of a technogenic sinkhole in case of working off of the potash field (Berezniki town), appeared in February, 2015 [1]. Let us note that such sinkholes are usually related to flooding of mines and dissolution of the salt rocks on practically entire thickness of the ore body. That leads to the complete loss of operability of a mining company. The steep sinkholes walls of failures gradually smooth out over time, and bulks are filled with the falling soil and water.
Figure 1. Sinkhole in the settlement of Neledino in Shatkovsky district of Nizhny Novgorod Region (Photo by A. A. Lavrusevich)

Figure 2. Sinkhole over the potash field in Berezniki town

This type of sinkholes is even more shown for underground nuclear explosions [2, 3]. Figure 3 presents the development of the collapse process in time schematically. When a 100 Kt nuclear charge explodes at a depth of 800 m from the surface, the radius of the cavity reaches 50 m. Then there is a collapse of the overlapping rocks for which the formed and newly formed cavity is a compensation space. At the same time there is a collapse of rocks up to filling of the entire compensation space over time. The coefficient of loosening of the brought-down rocks makes 1.3 … 1.35; that finally determines the vertical size of the zone of collapse. The formation of a pipe-like zone of collapse can sometimes last up to several months depending on the properties of rocks. This zone can reach the surface, forming on it a sinkhole in the friable rocks with insignificant coefficient of loosening, i.e. when their density is close to the density of the material which is brought down in the cavity.
2. Conceptual model

Common features of all the considered cases of formation of sinkholes structures is the existence of almost vertical walls of the sinkholes, at least during the initial stage.

Further we will consider the mechanism of the formation of collapse in the form of a vertical pipe in the rock massif. The necessary condition of the formation of such violation of continuity of the massif is the existence of rather big free underground space. It has to contain all the falling material (taking into account loosening) and, besides, to create the open bulk of a sinkhole itself.

Numerous works which are mostly concern the identification of regularities of the formation of a trough of displacement over the underground developments are devoted to the theoretical description of subsidence of a day surface.

In case of the collapse of rocks in a roof of excavations on the ground surface the subsidence trough without formation of sinkholes is usually formed. At the same time the sizes of this trough, usually multiply surpass the sizes of the fallen roof site. They are defined by the depth of the development arrangement and the characteristic angles of the displacement, depending on straining and strength properties of the rocks, which compose the roof. In this case there is a gradual stratification of the roof rocks to lowering of high layers on the lower ones from below-up.

Because of the insignificant thickness of the extracted ore body (~ the 1-3 m) the deflection and loosening of the settling (collapsing) rocks completely compensates the developed space for the depths of several hundred meters. Because of low gradients of tension in the horizontal direction in the massif there are no conditions for the formation of the considerable vertical cutting-off tension, i.e. for the formation of sinkholes with vertical walls.

As a rule, the roof of the development consists of several sandstone layers which are poorly connected among themselves. It is possible to distinguish a some enough thick layers among them, defining the roof deformation. Thinner layers, located in the massif usually have no significant effect on its state and they collapse in the developed space during the clearing works. Thick layers of the roof hang over the developed space, partially filled with the fallen rocks of the immediate roof gradually settling in process of the increase in flight of the hanging roof. Once it settles down on the brought-down rocks, gradually squeezing and loading them. The smooth landing of the roof does not exclude the possible collapses of the immediate roof of the development, which usually has a local character and acts as the insignificant part of the entire overlapping thickness of rocks, which eventually determines the regularities of the formation of the intense strained state of the rock massif up to the ground surface.

Such mechanism of deformation and destruction of the massif of the overlapping rocks leads to the formation of the smooth trough of subsidence. At its formation a defining role is played by picking of an upper of the falling massif by the brought-down rocks, leaning on those, already brought down.
When filling the compensation space this interaction stops the process of further gradual collapse. Being within such a concept it is impossible to describe the emergence of sinkholes in the form of a well.

At the moment there are various theoretical approaches to the description of the considered manifestation of the deformation and destruction processes in a near-surface part of the rock massif. It is possible refer to the works be such authors as Rusin E. P., Stazhevskii S. B., and Khan G. N. [4], Stuart Hardy [5], Bakeev R. A., Stefanov Yu. P., Duchkov A. A., and Myasnikov A. V. [6].

Let us analyze the option of redistribution of the initial tension in the massif when a cavity with a horizontal roof is formed due to some reasons at a certain depth from the day surface. The considered task is presented schematically in figure 4. The zones of possible destructions in the massif and the nature of behavior of the entire overlapping massif can be defined with the use of acceptable criterion of durability.

As for the case under consideration, the main roof representing a layer with thickness \( R \) hangs over the entire free space \( 2L \) long at the depth \( H \). At the same time the boundary conditions of the task be the following (Figure 4):

\[
\sigma_y = 0, \quad \tau_{xy} = 0, \quad |x| < L, \quad y = 0, \quad (1)
\]

\[
\nu = 0, \quad \tau_{xy} = 0, \quad |x| > L, \quad y = 0.
\]

**Figure 4.** Diagrammatic representation of the early state of the sinkhole formation

Because of the symmetry of conditions on the \( x \) axis (1) for the task the tension and shift within the theory of complex potentials are found with the help of the unique holomorphic function \( F(z) \), which can be presented as [7]:

\[
F(z) = \frac{\nu H}{2} \left( 1 - \frac{z}{\sqrt{z^2 - L^2}} \right), \quad z = x + iy, \quad L < L_0, \quad (2)
\]

\[
L_0 = \frac{E h_{eff}}{2(1-\nu^2)\gamma H} = \frac{\beta}{H'}, \quad \beta = \frac{E h_{eff}}{2(1-\nu^2)\gamma'}, \quad (3)
\]

where \( E, \nu \) – the elastic constants characterizing the roof material, \( h_{eff} \) – effective thickness of layer, \( \gamma \) – average specific weight of rocks of the overlying massif.

In this case, the stresses in the entire massif, including the main roof, are expressed through additional stresses, which are caused by the development sinking. Additional stresses in the overlying rock massif according to the function \( F(z) \) are expressed as follows [7]

\[
X_x = 2 \text{Re} \ F(z) - 2y \text{Im} \ F'(z),
\]

\[
Y_y = 2 \text{Re} \ F(z) + 2y \text{Im} \ F'(z),
\]

\[
X_y = -2y \text{Re} \ F'(z).
\]

At the same time the complete tension in the rock massif can be written as follows:

\[
\sigma_x = \sigma_x^0 + X_x, \quad \sigma_y = \sigma_y^0 + Y_y, \quad \tau_{xy} = X_y, \quad (5)
\]

where \( \sigma_x^0 \) and \( \sigma_y^0 \) - initial tension in the rock massif. They are usually considered to be linearly increasing according to the depth
\[ \sigma_y^0 = k\gamma(y - H), \quad \sigma_x^0 = \gamma(y - H), \]

where \( k \) is the coefficient of side pressure.

Let us notice that the ratios (6) for the initial tension can be considered to be precisely reflecting the condition of the rock massif before layer working off. Besides, the ratios (4) also describe the secondary stresses within the problem definition for the infinite upper half plane precisely. The complete tension (5) is approximate as it is applied unlike (4) for the case of existence of a day surface. At the same time the accuracy of such representation is higher, if the \( H/L \) ratio is more. The maximum mistake for each component of tension is determined by the size of the corresponding secondary stress on a day surface, i.e. if \( y=H \). In this regard, the solution (5) describes the condition of the massif well enough only if \( H/L>3\div4 \) [8].

3. Results

We will estimate the possibility of shift destruction of the main roof on AB vertical with the formation of the corresponding shift destruction. According to the symmetry of problem definition that will mean the collapse of the site of the main roof in limits on \( x \) from - \( L \) to \( L \) with the formation of vertical walls on the site \( 0<y<R \).

The task is solved with the use of the integrated criterion of durability, associated with an arbitrary rather extended surface in the rock massif [9].

As for the studied case, the surface represents a vertical piece \( 0<y<R, \ x=L \), and the criterion will be written as

\[ F_R = \frac{\int_0^R [C(y) + t\rho(y)\sigma_n(y)]dy}{\int_0^R \tau_n(y)dy} \quad \text{or} \quad F_R = \frac{C + t\rho\overline{\sigma}_n}{\overline{\tau}_n}, \]

where \( \sigma_n(y), \tau_n(y) \) are the normal and tangent components of tension on the platforms of the surface along the line AB, \( y\in\text{AB} \); \( \overline{\sigma}_n, \overline{\tau}_n \) are average normal and tangent stresses in the range from 0 to \( R \); \( C(y), \rho(y) \) are couplings and corners of internal friction on the same platforms, \( R \) is the thickness of the main roof. It is obvious that the numerator is integrated limiting value of confining forces, and the denominator is the integrated value of shifting forces on this line. Comparison of these integrated forces also makes the physical substance of the functional (7) as the integrated criterion of durability on the chosen line.

Unlike [9], in the considered task the line on which the durability functional minimum is implemented, is predetermined in advance. Let us notice that incase of the made assumptions concerning the form and location of the line of a possible cut, size \( R \) should not be big in comparison with the development extent. Otherwise the line of the cut, most likely will not be a straight line any more. The task consists in determining such an extent of the developed space \( L^{np} < L_o \), when \( F_{\text{R}=1} \).

At the same time average tension on line AB can be easily calculated in a final form so, that the ratio (7) will be transformed as

\[ \frac{1}{2}(1 + \frac{1}{r'}) \left[ \frac{r'-1}{2} \right] = \frac{C + t\rho\left[ I - \frac{1}{r'} \left( I + \frac{1}{2} \right) \right]}{\gamma H} + t\rho \left[ I - \frac{1}{r'} \left( I + \frac{1}{2} \right) \right] - k\left( I - \frac{R}{2H} \right), \]

or

\[ r' = \frac{1}{1 + \left( \frac{2L^{np}}{R} \right)^2}. \]
The task is to resolve the ratio (8) regarding \( L^{sp} \). Taking into account that in actual practice it makes sense to consider mining situations when \( L/R > 2 \pm 3 \), it is possible to consider definitely that \( R/H << 1 \).

Considering \( k \) in the equation (8) as a parameter and resolving it numerically regarding \( L^{sp} \), we can receive a family of curves for parameter \( k \), shown in the Figure 2 by points. It is enough to take \( k \) from the range \( 0.5 \pm 2 \), and the dimensionless coupling \( 0.5 < \frac{C}{\gamma H} < 3 \) for practical purposes. At the same time the size of \( \frac{L^{sp}}{R} \) for fixed \( \alpha \) will change in the range \( \sim 1 < \frac{L^{sp}}{R} < \sim 100 \).

In the same figure straight lines represent functions of the following type: \( \frac{L^{sp}}{R} = A(k) \left( \frac{C}{\gamma H} \right)^{B(k)} \), approximating calculated data best of all.

At the same time, it turns out that dependences \( A(k) \) and \( B(k) \) in turn come nearer the linear functions, namely

\[
A(k) = 13.2 - 4.7 k, \quad B(k) = 1.5 + 0.5 k.
\]  

(9)

Thus, we have the following ratio for the limit flight of \( L^{sp} \) depending on the rocks coupling \( C \) and the coefficient of side pressure \( k \):

\[
\frac{L^{sp}}{R} = (13.2 - 4.7 k) \left( \frac{C}{\gamma H} \right)^{1.5 + 0.5 k}.
\]  

(10)

Finally, this ratio demonstrates how geometrical parameters of the exposure are bound to the strength parameters of rock massif at the time of the collapse of the roof.

Let us note that after the collapse of the rock layer of the main roof with the thickness \( R \), the mining situation completely repeats already for a new cavity in which roof the layer with thickness \( R \)
is located again. If \( R / \leq R \), then the ratio (10) is carried out and the conditions of collapse of a new layer etc., are created.

4. Conclusion
This is the general scheme of the formation of a sinkhole with vertical walls. Let us note a rather simplified approach to the creation of geo-mechanical model of the process [10]. Firstly, if there is a flat roof of a cavity the zone of the stretching vertical tension is practically always formed in it, and if \( k < 1 \) and a zone of horizontal pulling stresses appears. In case of small durability of rocks on stretching the stratification of rocks, i.e. the cross joint of stretching which promotes the collapse of a layer, can be created in the roof. Secondly, the more detailed consideration of the formation of a shift crack through the AB line roves that the stretching crack interacting with the shift crack can be created on the upper of this piece depending on k size.

These details complicate the problem definition and result in the need to use some numerical analysis algorithms of the intense strained state unlike the one explained above. However, they do not in essentially change the received results; they only specify the numerical values of the calculated parameters to some extent.

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