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Geotechnical Calculations for Prediction of Clandestine Undermining

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Abstract:

When coalition forces realize enemy's intention to make use of the underground space for his belligerence, they must predict all options how to make military facilities less vulnerable from below. The article is focused on the simple geotechnical situation: Tunnel of 1m diameter, excavated by handy tools in loose materials, like sands or gravel. Further, the stability of the unsupported tunnel and effect of mining support is considered. Finally, which depth is presumable, when improvised tunnel should be done and profile reinforcement should be omitted. The best way how to explain it is to recognize the basic rules of the underground excavations stability. We cannot suppose drifting in the solid rocks. On the contrary, the clandestine excavations could to be achieved in loose materials, where silent technique, like shovels or pickaxe can be applied. The article would like to put the reader's mind to geotechnical features that can facilitate or hamper the enemy's effort to undermine coalition forces facility.

Keywords:

Underground Drifts, Excavations, Undermine, Stress-Strain Status

1. Introduction:

This article follows the [1] having been published in the previous Volume. The author decided to continue due to the extraordinary affair in Kandahar – the insurgents excavated a tunnel to prison and liberated almost 500 prisoners in April 2011. The length of tunnel reached allegedly 500metres. From the technical point of view it is a significant achievement, when the diggers had to keep a precise azimuth and inclination. They were capable to ensure a proper illumination, ventilation, support and camouflage. And they worked under permanent risk of roof collapse. Nobody should neglect this capability of enemy although Afghanistan is a traditional region for tunnel drifting – see Karez, water distribution system described in the article [1]. The

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undermining of any coalition facility should not be considered a theoretical option since the April 2011. That is why the author contributes to this effort by the geotechnical calculations explaining the questions of the stability of the improvised tunnels.

2. The Positive Conditions for Underground Digging

The efficient measures cannot be assumed without assessment of conditions preferable for our enemy. The first question to be answered is the potential depth of underground opening. Our experience from childhood and from sand on the playground tells that each excavation has to be covered by certain thickness of the tamped sand otherwise it collapses. From this "naive" experience is to be concluded, the deeper the better. But it is preferable for our enemy. Not for us. The deeper cavity represents a problem how to detect and eliminate adversary's excavation.

2.1. Elastic Status on Walls of the Underground Opening

The first approach to our problems could be the elasticity status of the material at excavated profile. Its validity of the solid competent material is correct. But we have to take into account permanently that our area of interest is focused on the loose material, excavated by hand tools. However, regardless of the final status at the profile, the initial one starts elastically and keeps it for a certain time. Although the elasticity model has the transitional validity only, its description is simple and results instructive facts for the mentioned first approach.

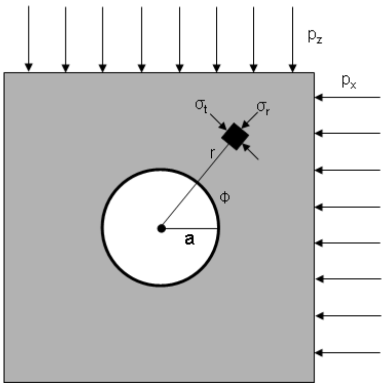

Fig. 1 Stress acting on the massif element near underground opening, by [2]

The area of our interest is the profile of the underground opening. Simplification of the task is done by circular profile and equality of the horizontal and vertical stresses. This describes so called Airy's function [2] presented here without deriving:

$$\sigma_r = \frac{p_z}{2}\left[1-\frac{a^2}{r^2}-\left(1-4\frac{a^2}{r^2}+3\frac{a^4}{r^4}\right)\cos 2\Phi\right]+\frac{p_x}{2}\left[1-\frac{a^2}{r^2}+\left(1-4\frac{a^2}{r^2}+3\frac{a^4}{r^4}\right)\cos 2\Phi\right]$$

$$\sigma_t = \frac{p_z}{2}\left[1+\frac{a^2}{r^2}+\left(1+3\frac{a^4}{r^4}\right)\cos 2\Phi\right]+\frac{p_x}{2}\left[1+\frac{a^2}{r^2}-\left(1+3\frac{a^4}{r^4}\right)\cos 2\Phi\right]$$

Assuming two positions at the profile, sidewall (where Φ = 0) and *a* ceiling (Φ = 90°), we can conclude that $\sigma_r = 0$, $\sigma_t = 2\ p_z$ in the both cases.

2.2. Clastogene Status on Walls of the Underground Opening

As told in the previous sub article, the elastic status of the profile does exist for a while and transfers itself subsequently into another status. Loose (arenaceous) materials are characterized by clastogene deformation, while argillaceous materials are characterized by plastic deformation on the opened profile. The interest of this article is focused on the loose materials. Assuming the circular profile again, the new model originates itself as a combination of elastic zone inside massif (marked by **E** in Fig. 2) and clastogene zone (marked **C** in Fig. 2) just adjacent the profile of the underground opening. The Mohr's graphs describe the stress distribution in the both, elastic and clastogene zones respectively.

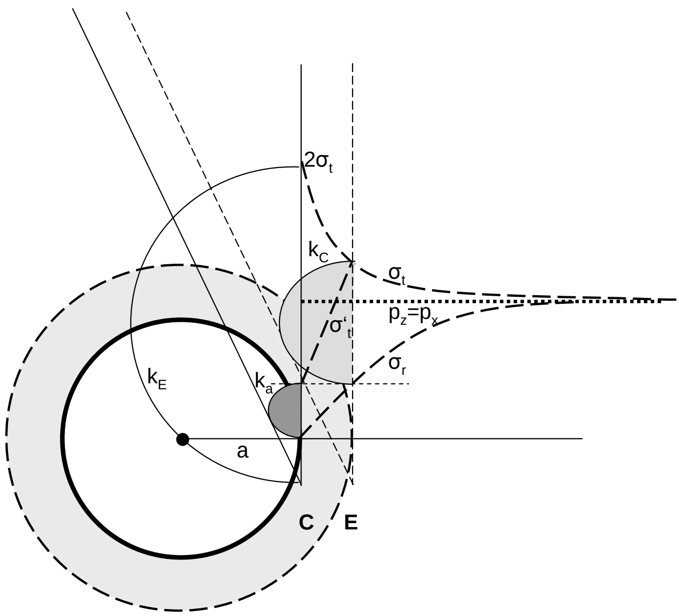

Fig. 2 Stress/strain statuses around circular underground opening by [3], (modified by Author)

The deviator k_E indicates the original elastic stress/strain status just after the opening has been done. The elastic status is redistributed into clastogene one adjacent to the profile and elastic zone is moved from the profile towards massif. The deviator k_C indicates the stress/strain status of the clastogene zone towards massif. The deviator k_a indicates stress/strain status just on the profile. The important thing here is that $\sigma_r > 0$. Without this fact the profile would be apt to collapse immediately. The stabilizing factor is to find out in the circular profile and dilatancy. This component of the strength acts like reinforcement and induces certain force oriented towards massif. That is why the k_a occurs under stress envelope.

Another problem is the long term strength. The loose material requires reinforcement to remain stable for the longer time. From the technology point of view, excavating a supporting by simple, primitive means, the rectangular profile is preferable and we have to analyze it

2.3. The Stress-Strain Status on the Rectangular Profile of Underground Cavity

The distribution of the stress-strain status on the profile of underground cavity provides the Fig. 3. The graphs below and on the right side indicate the original status before the excavating has been done. Vertical stress prevails.

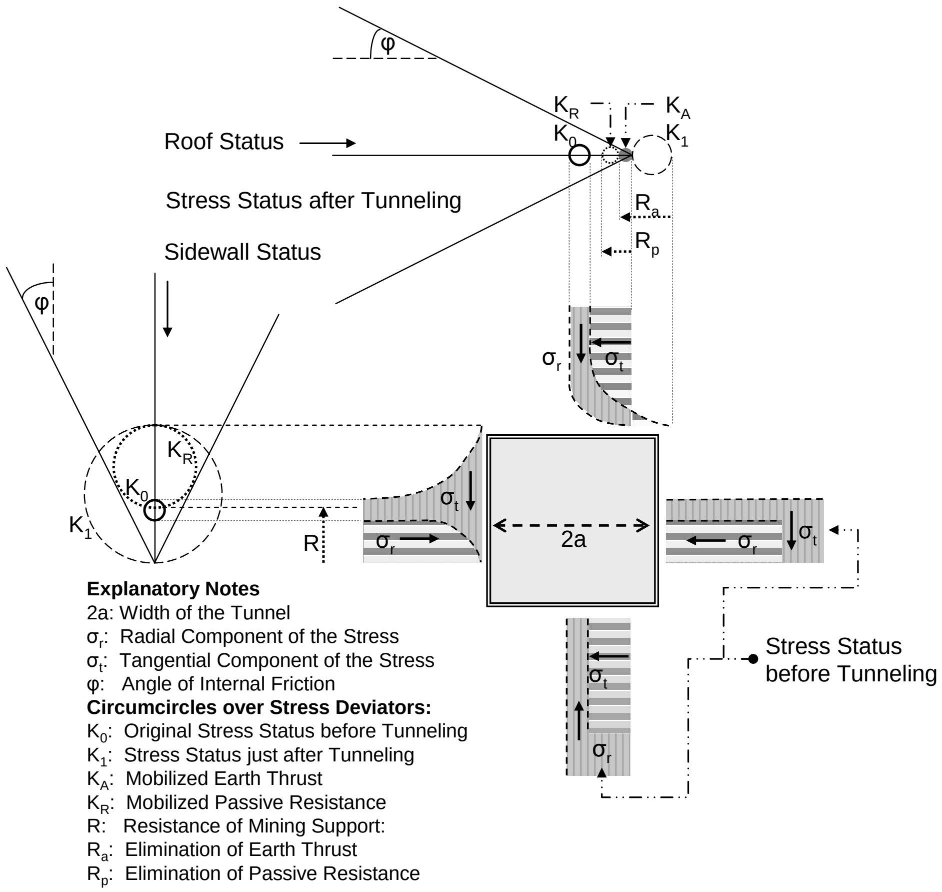

Fig. 3 Stress-Strain Status around Underground Opening by [3], (modified by Author)

The stress circles K_0, indicate this original status of massif, before opening. While the opening is excavated, the stress field changes as depicted on the top and left side of the orthogonal cavity. The stress circles K_1 indicate the shear stress at sidewalls and tensile stress on the roof. K_R represents the desired stress-strain status which indicates the stability of the profile and R the resistance of the mining support necessary to ensure this stability.

For the roof, the effect of the support resistance must induce the both force components R_a and R_p. The first one has to eliminate tensile stress while the second one has to insert force into massif, big enough to keep the deviator under strength envelope.

The calculation of the support resistance will be based on the equilibrium of the hanging wall weight and the support resistance. Those both forces keep massif stable. When inserted in time, the mining support does need the minimal resistance. The hanging wall (see Fig. 4, the thickness of it is *h*) is exposed to internal friction induced by earth thrust, further to the passive resistance inserted inside massif by the force R originated by the reaction of the mining support. The size of *R* shall add the missing thrust which changes $\sigma_t \le 0$ into certain $\sigma_t > 0$, as seen on Fig. 3.

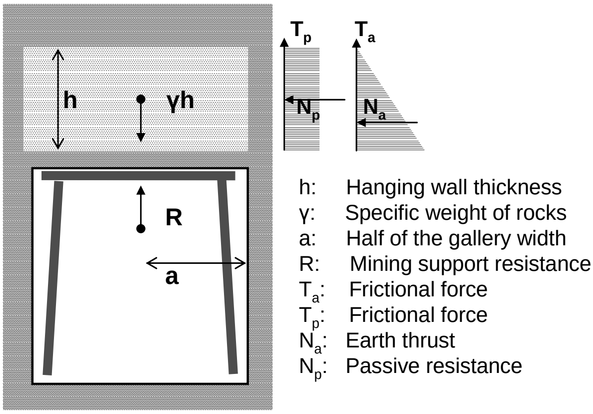

Fig. 4 Forces Acting on the Roof Stability Underground by [4]

The following calculation of the necessary resistance *R* was presented in [4] and rectified by Author:

$$T_a = N_a \tan\varphi = \frac{1}{2}\gamma h^2 K_a \tan\varphi = \frac{1}{2}\gamma h^2 K_p^{-1} \tan\varphi, \quad T_p = N_p \tan\varphi = RhK_p \tan\varphi \quad (1)$$

The equilibrium will occur when forces equal to the weight of the hanging wall. Then the profile stability is preserved:

$$a\gamma h - T_a - T_p = 0$$

Substituting here T_a and T_p from Eq. (1), relation for thickness *h* is obtained

$$a\gamma h - \frac{\gamma h^2 \tan\varphi}{2K_p} - RhK_p \tan\varphi = 0$$

with solution

$$h = \frac{2aK_p}{\tan\varphi} - \frac{2RK_p^2}{\gamma} \quad (2)$$

Coefficients K_a and K_p belong to earth thrust and passive resistance respectively. They are mobilized by initial movement of the hanging wall in the moment of opening. The necessary mining support resistance could be derived from the assessment, that earth thrust, passive resistance and mining support resistance together cause zero hanging wall thickness. For $h = 0$ we obtain

$$R = \frac{\gamma a}{\tan\varphi} K_p^{-1} = \frac{\gamma a}{\tan\varphi} \tan^{-2}\left(45 + \frac{\varphi}{2}\right) \quad (3)$$

Eq. (3) defines the minimal support resistance to reach stability of the rectangular opening. Let us emphasize that this model is valid for materials possessing an internal friction as the only strength component, like arenaceous materials, namely sand or gravel.

3. The Critical Depth

The sub articles 2.2 and 2.3 defined stability of self supporting openings and openings supported by artificial reinforcement. While the first case depends on the profile shape, the second case depends on the equilibrium of mining support resistance and hanging wall thickness. From this point of view we can define “critical depth” in accordance with cooperation opening profile-mining support.

3.1. The effect of the hanging wall

The effect of the hanging wall supposes the existence of the elastic status inside the massif except the profile of the opening, where a hanging wall represents a mass between a rectangular profile and elastic status inside a massif. The pressure envelope on the Fig. 5 (dotted) represents the interface between clastogene and elastic status inside a massif surrounding underground excavation.

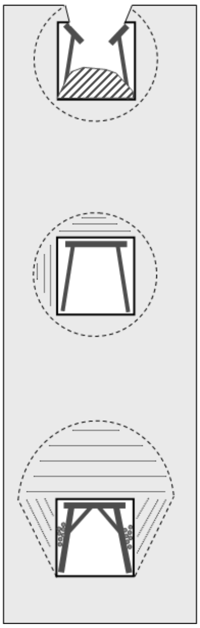

Fig. 5 Critical Depth of Profile Stability (by Author)

This situation is characterized on the Fig. 5 in the middle. The elastic status is marked by the pressure envelope (σ_t, see Figs 1 and 2). In the case of circular opening, the clastogene status could occur as depicted on Fig. 2. If somebody wants to open the massif in lower depth, the elastic status cannot establish itself and the support is exerted by the full thickness of the overburden, as seen on the Fig. 5 above. In the certain depth the dilatancy inside the clastogene zone is suppressed and thus the self supporting status cannot be achieved. The strong support only can ensure the stability of the excavation, regardless of the cross section shape. The overlaying rocks act as a natural backfill. Any attempt to remove those leads to increased vault span and may cause a collapse of the excavation finally. The calculation of this model presented Protodiakonov in the early of the 20th century. This is depicted on the Fig. 5 on the bottom.

3.2. The effect of the pressure envelope

For us as well as for enemy the depth where the self supporting profile remains stable is crucial. Assuming that calculation of the support resistance *R*, see Eq. (3), is correct. And now we have to calculate, which tangential stress is sufficient enough to induce the radial stress equivalent to the support resistance *R*. The Author in this article will make use the math process presented by [4]. Eq. (2) will be the starting point again. Analogically to find out the *R=0*, now, the necessary *h* has to be finding out. From Eq. (2) is to derive:

$$R = \left(\frac{2aK_p}{\tan\varphi} - h \right) \frac{\gamma}{2K_p^2} = \frac{\gamma a}{K_p \tan\varphi} - \frac{\gamma h}{2K_p^2}$$

For $R = 0$ we obtain after algebraic operations:

$$h = a\tan^2\left(45 + \frac{\varphi}{2}\right)\tan^{-1}\varphi \tag{4}$$

where $\tan^{-1}\varphi$ means $1/\tan\varphi$, not $\arctan\varphi$.

Note: To be more accurate the symbol *H* should be used as the calculation takes the full thickness of the overburden into account. For preventing a confusion of the algebraic procedure the h remained in this calculation.

To explain the sense of the equation 4 we could suppose arenaceous material of the angle of internal friction $\varphi = 30°$ [5]. Which depth *h* under surface is necessary to comply so that the circular profile of diameter $2a$=1 m remains self supporting? Inserting into Eq. (4):

$$h = 0.5\tan^2(45° + 15°)\cdot(\tan 30°)^{-1}\ \mathrm{m} = 0.5\times 3\times 1.73\ \mathrm{m} = 2.6\ \mathrm{m}$$

From the calculation (4) we should expect that the depth of our interest is more than 2 meters.

4. Conclusion

If we assume the intention to undermine military facility in the clandestine manner, we have to predict the depth of such sap 2 and more meters. The profile of that sap should be circular with diameter 1 m. This depth ensures stability of the profile without a requirement to support it. In this case the guard cannot realize any signs of the excavation on the surface. This risk could be neglected if the water table or the bedrock lay lower than 2 meters under surface. In this case the presumption of hanging wall collapse is high and guards can realize the undermining long enough ahead of approach of the sap to military facility perimeter.

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