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Critical sizes of cone-shaped opening in open mining

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Critical sizes of cone-shaped opening in open mining

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Abstract. In case of unstable cone-shaped pitwalls and dumps, the overlying rock weight is of importance. Different weight of overlying rocks generates different vertical pressures per horizontal sections of pits and dumps. In case that the type of a failure surface is known for the present slop of pitwall or dump, it is possible to detect a critical section of the maximum pressure. The location of the critical section is governed by the height and the bottom radius of a pit or a dump. This study relates the destruction zone location with the height and bottom radius of open pits (dumps). The results of the theoretical and experimental studies are reported.

1. Introduction
This study focuses on failure of rocks mass around a cone-shaped excavation. The aim is to interrelate such parameters as: pitwall slope, bottom radius, pitwall height and slope of possible failure zone. The research is based on the provision that rock mass failure takes place under overlying rock weight, thus, there is some pitwall height at which pressure generated by the overlying rock weight is maximum (derivative of the pressure-to-depth function goes to zero!). This pressure value is assumed as a critical pressure initiating failure in lower-lying rocks. The connection of possible failure and cone-shaped excavation is found thereof. Similar approaches are described in [1–16].

2. Cone-shaped excavation and critical section
Figure 1 shows a cone-shaped excavation *LMKB* with the bottom radius a, height $QA = H$ and slope α of the pitwall *KB*. The angle β stands for the slope of the sliding surface in failure. This angle can be free from the pitwall slope α (which conforms with the initial anisotropy of the medium), or can be related with α and parameters of the medium such as internal friction angle [17, 18]. However, in any case, the angle β at the preset values of α and the medium parameters is constant: $\beta = \beta(\alpha)$. We use this circumstance in determination of critical parameters of the cone-shaped excavation in Figure 1.

Let us calculate the volume of the ring with the trapezoidal section *EBCD* in Figure 1. To this end, we first find the volume of the cylinder with the bottom radius *FD* and height *DC* (Figure 1). Notice that $FD = FN + ND$, where $FN = a$, $ND = h\,\text{ctg}\,\beta$, $DC = H - h$; then:

$$V_{\text{cylinder}} = \pi[a + h\,\text{ctg}\beta](H - h)\,.$$

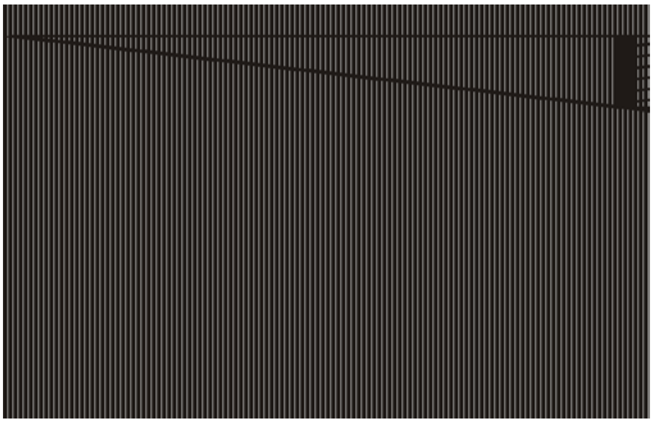

Figure 1. Schematic representation of the cone-shaped excavation.

Now, we find the volume of a conical collar with the bottom and top radii *FE* and *AB*, and the height *DC*. This volume is equal to the difference of volumes of two cones with the triangular sections *OAB* and *OFE*. The volume of the cone with the radius *AB* and height *OA* is given by:

$$V_1 = \frac{1}{3}\pi(AB)^2[H + a\,\mathrm{tg}\alpha] = \frac{1}{3}\pi(a + H\,\mathrm{ctg}\alpha)^2[H + a\,\mathrm{tg}\alpha].$$

The volume of the cone with the radius *FE* and height *OE* is:

$$V_2 = \frac{1}{3}\pi(FE)^2[h + a\,\mathrm{tg}\alpha] = \frac{1}{3}\pi(a + h\,\mathrm{ctg}\alpha)^2[h + a\,\mathrm{tg}\alpha].$$

There from, we find the volume of the unknown ring:

$$V_{\text{ring}} = \pi(a + h\,\mathrm{ctg}\beta)^2[H - h] - \frac{1}{3}\pi(a + H\,\mathrm{ctg}\alpha)^2[H + a\,\mathrm{tg}\alpha] + \frac{1}{3}\pi(a + h\,\mathrm{ctg}\alpha)^2[h + a\,\mathrm{tg}\alpha]\,. \quad (1)$$

Determine the area *S* of the ring with the external radius *FD* and internal radius *EF* as the difference of two areas:

$$S = \pi(FD)^2 - \pi(EF)^2 = \pi[(a + h\,\mathrm{ctg}\beta)^2 + (a + h\,\mathrm{ctg}\alpha)] = \pi h(\mathrm{ctg}\beta - \mathrm{ctg}\alpha)[2a + h(\mathrm{ctg}\beta + \mathrm{ctg}\alpha)]. \quad (2)$$

Multiply (1) by ρg and obtain the weight of the ring with the section *EBCD*. Divide the weight by the area *S* and have the pressure generated by the ring on the lower lying rocks. Introduce the denotations:

$$\frac{a}{H} = \tilde{a}\,, \quad \frac{h}{H} = x\,. \quad (3)$$

Then the pressure *p* generated by the ring weight on the surface *ED* in Figure 1 is:

$$\frac{p}{\rho g H} = \frac{V_{\text{cylinder}}}{H^3}\cdot\frac{H^2}{S} =$$

$$= \frac{3(\tilde{a} + x\,\mathrm{ctg}\beta)(1 - x) - (\tilde{a} + \mathrm{ctg}\alpha)(1 + \tilde{a}\,\mathrm{tg}\alpha) - (\tilde{a} + \mathrm{ctg}\alpha)^2(1 + \tilde{a}\,\mathrm{tg}\alpha) + (\tilde{a} + x\,\mathrm{ctg}\alpha)^2(x + \tilde{a}\,\mathrm{tg}\alpha)}{3x(\mathrm{ctg}\beta - \mathrm{ctg}\alpha)[2\tilde{a} + x(\mathrm{ctg}\beta + \mathrm{ctg}\alpha)]}\,. \quad (4)$$

At the fixed values of a, H, α, β, the relation (4) represents the function of the relative pressure $p/\rho g H$ on x. This means that at some height h in a cone-shaped excavation (Figure 1), the pressure can be maximum. For calculating this pressure, we find the first derivate with respect to $x = h/H$ in (4) and put it to zero. As a result, we arrive at the fourth-order equation for x:

$$(\mathrm{ctg}\beta + \mathrm{ctg}\alpha)(\mathrm{ctg}^2\alpha - 3\mathrm{ctg}^2\beta)x^4 + 4\tilde{a}(\mathrm{ctg}^2\alpha - 3\mathrm{ctg}^2\beta)x^3 +$$
$$+6\tilde{a}(\tilde{a}\mathrm{ctg}\alpha - 2\tilde{a}\mathrm{ctg}\beta - \mathrm{ctg}\beta\mathrm{ctg}\alpha)x^2 + 2\mathrm{ctg}\alpha(\mathrm{ctg}\beta + \mathrm{ctg}\alpha)(\mathrm{ctg}\alpha + 3\tilde{a})x + 2\tilde{a}\mathrm{ctg}\alpha(\mathrm{ctg}\alpha + 3\tilde{a}) = 0. \quad (5)$$

Solution of (5) yields x at the input $\alpha, \beta, \tilde{a}$. Let us analyze its roots.

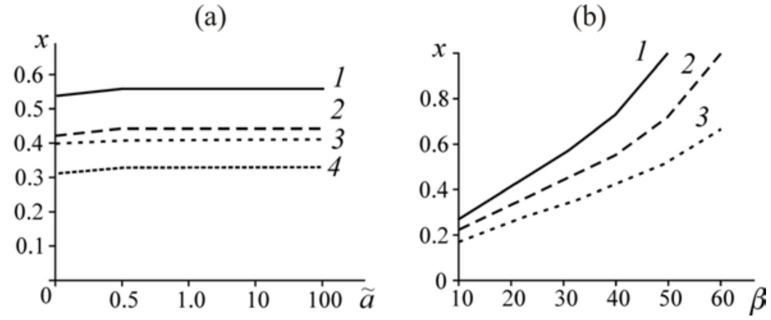

Figure 2. Curves of x versus (a) $\tilde{a}$ at different α, β: *1*—α = 60°, β = 30°; *2*—α = 50°, β = 30°; *3*—α = 50°, β = 20°; *4*—α = 60°, β = 20°; and (b) β at different α: *1*—60°, *2*—50°; *3*—70°; $\tilde{a} = 1$.

Figure 2 shows the variation in x (from 0 to 1) as function of $\tilde{a}$ at different values of α and β (Fig. 2a) and as function of β at different α and $\tilde{a} = 1$ (Fig. 2a). The relationship between (in the range of 0–1) and the angle α at different values of β and $\tilde{a} = 1$ is illustrated in Fig. 3a. With the known x, it is possible to calculate the relative $p/\rho gH$ from (4); the results are demonstrated in Fig. 3b.

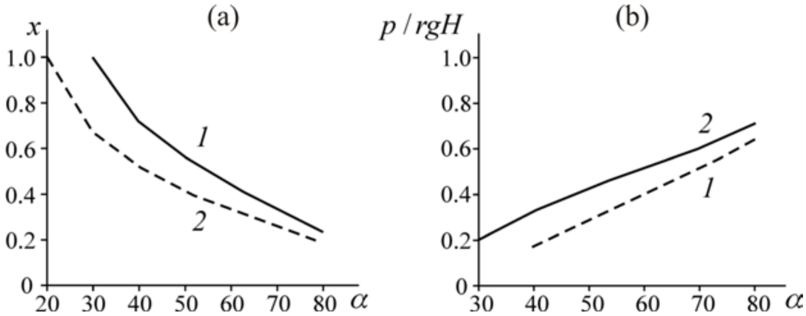

Figure 3. Relationships of (a) x and α at $\tilde{a} = 1$; (b) p / ρgH and α at: *1*—β = 30°; *2*—β = 20°.

3. Critical pressure

As regards the critical pressure on the surface *ED* in Figure 1, let us examine the face *KD* at the slope β relative to the horizontal axis r (*Orz* is a cylindrical coordinate system). it is assumed that in failure, the shearing stress on *ED* is insignificant, and the principal pressure is exerted by the vertical stress σ_z which creates shearing at the face *KD*. In order to find the shearing stress, we set a normal $\vec{n}$ and a tangent $\vec{t}$ to *KD*:

$$\vec{n} = (-\sin\beta, \cos\beta), \quad \vec{t} = (\cos\beta, \sin\beta).$$

Considering that the stress tensor T_σ in the axial symmetry is given by:

$$T_\sigma = \begin{pmatrix} \sigma_r & \tau_{rz} & 0 \\ \tau_z & \sigma_z & 0 \\ 0 & 0 & \sigma_\varphi \end{pmatrix},$$

we have that the stress vector at the face with the normal $\vec{n}$ is:

$$\vec{p}_n = (-\sigma_r \sin\beta + \tau_{rz}\cos\beta)\vec{e}_r + (-\tau_{rz}\sin\beta + \sigma_z\cos\beta)\vec{e}_z \,,$$

and the shearing stress is:

$$\tau_n = \tau_{zr}\cos 2\beta + \frac{\sigma_z - \sigma_r}{2}\sin 2\beta \,, \tag{6}$$

where $\vec{e}_z$, $\vec{e}_r$ are the orts of the coordinate system *Orz*.

Destruction of rocks under the surface *ED* affected by a press-tool requires that the modulus of the shearing stress τ_n equals or exceeds the shearing strength of rocks:

$$|\tau_n| \geq \tau_s \,.$$

Assuming that $\tau_{rz} = 0$ and σ_r is smaller than σ_z on the surface *ED*, we have in a zero approximation that $(|\sigma_z|\sin 2\beta)/2 \geq \tau_s$ or:

$$|\sigma_z| \geq \frac{2\tau_s}{\sin 2\beta}\,. \tag{7}$$

The angle β and shearing strength are fond experimentally. Equating of the pressures (4) and (7) produces the critical height of an open pit and the wanted relation between the open pit параметрами *α*, *β*, *a* and *H* at the moment of instability.

In the framework of this study, test series on failure of a cone-shaped excavation in a granular medium have been performed.

4. Conclusions

1. The authors have located the critical horizontal section in the cone-shaped excavation, at which pressure du to overlying rock weight is maximum.
2. The relation between the parameters of the cone-shaped excavation at the moment of instability is obtained.

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