COMPUTATIONAL POTHOLE MINE SUBSIDENCE ANALYSIS FOR MULTILAYER SITES

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ABSTRACT. The use of sites in old or active mining regions or with natural openings in the ground includes an elevated technical risk, as constructions can be constrained due to unplanned deformations of the subsoil. Typical failure modes include pothole subsidence or earth falls, when failing soil masses are displaced and loosened stepwise toward a collapsing opening in the ground. The displacement process continues until a stable static equilibrium is reached and a further propagation of displacements is prevented. In order to determine the failure probability on a given site due to pothole subsidence, an efficient generalised computational prognosis method for the practical estimation of the expected subsidence volume is required and proposed based on simple geotechnical assumptions for multilayer sites and general primary failure volume configurations.

Keywords: mine, subsidence, pot-hole, deformation, prognosis

ИЗЧИСЛИТЕЛЕН АНАЛИЗ НА МУЛДАТА НА СЛЯГАНЕ В МНОГОСЛОЙНИ ОБЕКТИ

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РЕЗЮМЕ. Експлоатирането на обекти и конструкции в стари или активни минни райони в земята включва повишен технически риск, тъй като конструкциите могат да бъдат ограничени поради непланирани деформации на подпочвените слоеве. Типичните разрушавания включват мулда на слягане или срутища, когато обрушаващите почвени маси се изместват и отслабват стъпаловидно към образувалото се срутище. Процесът на изместване продължава, докато се постигне стабилно статично равновесие и се предотврати по-нататъшното разпространение на пропаданията. За да се определи вероятността за разрушение на даден обект поради мулдата на слягане, е необходим ефективен обобщен изчислителен прогнозен метод за практическото изчисляване на очаквания обем на слягане. Такъв метод е предложен, основан на прости геотехнически предположения за многослойни обекти и общи конфигурации на обема на първични разрушавания.

Ключови думи: рудник, слягане, мулда на слягане, деформация, прогноза

Introduction

The use of sites in old or active mining regions or with natural openings in the ground includes an elevated technical risk, as constructions can be constrained due to unplanned deformations of the subsoil. Typical failure modes include pothole subsidence or earth falls, when failing soil masses are displaced and loosened stepwise toward a collapsing opening in the ground. The displacement process continues until a stable static equilibrium is reached and a further propagation of displacements is prevented.

In order to determine the failure probability on a given site due to pothole subsidence, an efficient generalised computational prognosis method for the practical estimation of the expected subsidence volume is required and proposed based on simple geotechnical assumptions for multilayer sites and general primary failure volume configurations.

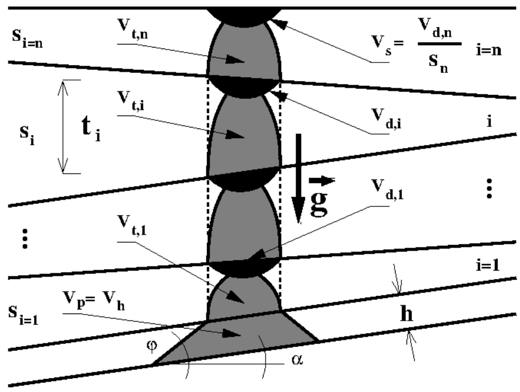

Fig. 1. The concept of the Generalised Failure Volume Balance Method (GFVBM) in the first layer above the initial volume

Generalised Failure Volume Balance Method

The simple and robust concept of the Generalised Failure Volume Balance Method (GFVBM) for computational pothole subsidence analysis on a site with multiple layers can be seen in Figure 1. The method is a straightforward extension of the Failure Volume Balance Method (FVBM) (Meier etal., 2005; Tamaskovics etal., 2017).

In an artificial or natural void space with the height of h and inclination α, a local failure with an assumed elliptical cross section takes place in the roof over a length of $2a_0$ and width of $2b_0$. The void space inclined with the angle α is filled with failing masses, where a primary (initial) volume V_p=V_h develops with a typical bulk friction angle φ. In the subsoil, a failure zone extends vertically in all layers consecutively towards the ground surface.

During the failure process, the material volume is increased with a material specific loosening factor s_i in each layer ''i'' that is well known from extensive long term field observations on different types of geogene materials (see Table 1).

If the failure process reaches the ground surface, a secondary (surface) subsidence volume V_s will result and can be computationally estimated with the simple theoretical framework of the Generalised Failure Volume Balance Method (GFVBM).

Table 1. *Typical loosening factor values derived from extensive long term field observations (Sroka et al.,* 2018*)*

Author	Value of the loosening factor s [1]
Kuzniecow (1950)	1.15 - 1.35 (for Russian conditions)
Lisnowski (1959)	1.40 - 1.80
Sałustowicz and Galanka (1960)	1.01 - 1.25
Chudek (Borecki, Chudek, 1972)	1.30 - 1.60
Czechowicz, Kuzniecow, Dawidianic, Kilaczkow (Borecki, Chudek, 1972)	1.40
Znański (1974)	1.08 (shales) - 1.35 (sandstones)
Niemiec (Jarosz 1977)	1.23 ± 0.064
Staroń (1979)	1.35 - 1.40
Peng (1986)	1.10 - 1.50
Whittaker and Reddish (1993)	1.33 - 1.50
Mazurkiewicz, Piotrowski, Tajduś (1997)	1.15 - 1.50 (for Polish conditions)
Das (2000)	1.05
Piechota (2003)	1.35 - 1.45 (shales and other rocks with low strength parameters) 1.40 - 1.60 (hard rocks with medium strength parameters) 1.45 - 1.80 (hard rocks with high strength parameters)
Heasley (2004)	1.05 - 1.35

Theoretical concept

The theoretical concept of the generalised failure volume balance method (GFVBM) is based on the governing volume conservation equation

$$V_{d,i} = V_p - \sum_{i=1}^{n} V_{t,i}\left(s_i - 1\right),\ [m^3], \tag{1}$$

where a deficit volume $V_{d,i}$ is systematically computed at each layer boundary ''i'' from the failure mass volume $V_{t,i}$, the material specific loosening factor s_i and the layer thickness t_i .

At each layer boundary, the propagation of the failure process is assumed to continue, if the resulting deficit volume $V_{d,i}$ in a layer ''i'' is positive

$$V_{d,i} > 0,\ [m^3]. \tag{2}$$

In layers with full propagation of the failure process, the form of the failure zone is assumed as a **cylinder** with an elliptical horizontal cross section. The propagation of the failure process is assumed to cease, if the resulting deficit volume $V_{d,i}$ in a layer ''i'' is negative or vanishes

$$V_{d,i} \le 0,\ [m^3]. \tag{3}$$

In all layers with ceasing propagation of the failure process, the form of the failure zone is assumed as a **half ellipsoid** with elliptic horizontal cross section.

If the pothole failure process propagates up to the ground surface through all ''n'' layers in the subsoil, a secondary (surface) failure volume V_s is expected to develop

$$V_s s_n = V_{d,n} > 0,\ [m^3] \tag{4}$$

that can be estimated with equations (1) and (4) from the primary failure volume V_p, the consecutive failure volumes $V_{t,i}$ and loosening factors s_i in the individual layers

$$V_s = \frac{1}{s_n}\left(V_p - \sum_{i=1}^{n} V_{t,i}\left(s_i - 1\right)\right),\ [m^3]. \tag{5}$$

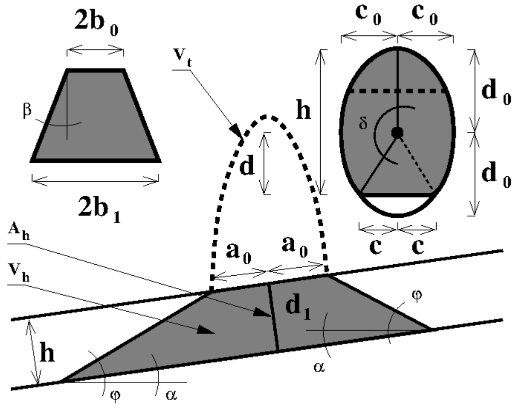

Fig. 2. Initial (primary) failure volume prognosis

Primary failure volume prognosis

The primary (initial) failure volume in a linear void space, like a mine road or tunnel with a height h, inclination α, bulk friction angle of the failing mass φ, elliptic failure aperture with surface area A_0 and void space cross section area A_h can be easily estimated from the general equation (see Figure 2).

$$V_p = V_h = A_0 h + A_h h \frac{\tan(\varphi-\alpha)+\tan(\varphi+\alpha)}{2\tan(\varphi-\alpha)\tan(\varphi+\alpha)},\ [m^3]. \quad (6)$$

Similar equations can be derived for different volumetric failures in caverns and mine roads or tunnel crossings (Meier et.al., 2005). The accuracy of the primary (initial) failure volume is essential for the quality and reliability of a computational pothole subsidence prognosis.

Failure aperture surface area

Under assumption of an elliptic form, the surface area A_0 of the failure aperture with a length of $2a_0$ and width of $2b_0$ in the roof of the void spacecan be estimated (see Figure 2).

$$A_0 = a_0 b_0 \pi,\ [m^2] \quad (7)$$

Timber securing

In case of a classical timber door securing of failing mine roads with a roof width of $2b_0$ and a side inclination angle β to the vertical, the cross section area A_h of the primary (initial) failure volume $V_p = V_h$ can be derived from (see Fig.2)

$$A_h = b_0 b_1 h,\ [m^2] \quad (8)$$

where b_1 is the width of the road base

$$b_1 = b_0 + h\tan\beta,\ [m^3]. \quad (9)$$

Roads and tunnels with elliptic or circular cross section

The cross section area of a tunnel with elliptic form with a height of $2d_0$ and a width of $2c_0$ can be calculated from the equations

$$h \le d_0 : A_h = 2c_0 d_0 \delta - cd,\ [m^2] \quad (10)$$

and

$$h > d_0 : A_h = 2c_0 d_0 \delta + cd,\ [m^2] \quad (11)$$

depending on the height of the void space h. The height d and the width c are obtained from the geometry of the elliptical road cross section of d_0 half height and c_0 half width. In the preceding equations, the angle δ is assumed to be symmetric to the vertical direction and must be inserted in radians.

In case, that the half height d_0 and half width c_0 coincide, the equations (10) and (11) transform to the case of a tunnel with circular cross section and radius $r=c_0=d_0$.

Table 2. *Computational pothole mine subsidence analysis with the practical application of the Generalised Failure Volume Balance Method for the case of a timbre door secured mine road failure in a multi-layer site*

Half length of failure aperture		a_0=	1.1 [m]
Half width failure aperture		b_0=	0.9 [m]
Height of failing mine road		h=	2.0 [m]
Inclination of failing mine road		α=	5.0 [°]
Inclination of timber door		β=	10.0 [°]
Bulk friction angle		φ=	30.0 [°]
Primary (initial) failure volume V_p= V_h = 21.602 [m^3]			
Layer:	Height:	Loosening factor:	Deficit volume:
I	t_i	s_i	$V_{d,i}$
[1]	[m]	[1]	[m^3]
1	7.0	1.10	+19.433
2	8.0	1.15	+15.663
3	9.0	1.20	+10.008
4	10.0	1.25	+4.772
Secondary (surface) failure volume V_s = 3.818 [m^3]			

Practical application

The practical application of the Generalised Failure Volume Balance Method (GFVBM) is demonstrated in an example calculation for a failing timbre door secured mine road in a multi-layer site. The input values and calculation results can be seen in Table 2.

The mine road with a height of h=2.0[m], a side inclination of β=10[°] and a base inclination of α=5[°] is assumed to fail in its roof over an elliptic failure aperture with a half width of b_0=0.9[m] and a half length of a_0=1.1[m], being filled with failing masses depositing with a bulk friction angle of φ=30[°]. In the individual layers in the subsoil with heights t_i and loosening factors s_i, consecutively positive deficit volumes $V_{d,i}$ indicate the propagation of the pothole subsidence failure process up to the ground surface, leading to an expected secondary (surface) failure volume of V_s=3.818[m^3].

Summary and Conclusions

The use of sites in old or active mining regions or with natural openings in the ground includes an elevated technical risk, as constructions can be constrained due to unplanned deformations of the subsoil. Typical failure modes include pothole subsidence or earthfalls, when failing soil masses are displaced and loosened stepwise toward a collapsing opening in the ground. The displacement process continues until a stable static equilibrium is reached and a further propagation of displacements is prevented. In order to determine the failure probability on a given site due to pothole subsidence, an efficient generalised computational prognosis method for the practical estimation of the expected subsidence volume is required and proposed based on simple geotechnical assumptions for multilayer sites and general primary failure volume configurations.

The simplistic theoretical framework and low number of required input parameters make the practical application of the Generalised Failure Volume Balance Method (GFVBM) very easy and advantageous for inverse analyses, probabilistic studies or risk evaluations with mathematical methods (Tamaskovics, 2019). Based on available long term observations and field studies, the proposed prognosis method can be applied independently from the geogene material in the subsoil (see Table 1).

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