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DEVELOPMENT OF LOAD EXERTED ON THE LINING OF THE SHAFT AFTER ITS LIQUIDATION

KSZTAŁTOWANIE SIĘ OBCIĄŻEŃ OBUDOWY SZYBU PO JEGO LIKWIDACJI

This article applies to forecasting of the shaft stability after its liquidation on the basis of the probable, current load of its lining. The stability of the shaft after its liquidation is affected by many factors: *that have occurred in the past, during its operation*, e.g.: the degree of technical wear and liquidation method, *that presently exist such as*: changes in the parameters of backfill and the level of shaft backfilling, *or may occur in the future*: changes of hydrogeological conditions, the influences of present mining extraction, the effect of vibrations, etc. The variability of these conditions over time may consequently lead to arising of discontinuous deformations in the area surrounding the shaft and, as an consequence, to construction disaster.

Keywords: rock mass, mine shafts, shaft liquidation

Likwidacja szybu górniczego w sposób trwały poprzez wypełnienie go za pomocą materiałów sypkich winna zapewniać jego stateczność w okresie czasu mierzonym setkami lat, szczególnie w obszarach nie w pełni wykorzystanego złoża. Bowiem te szyby mogą być w przyszłości wykorzystane przy przywracaniu do dalszej eksploatacji przedmiotowego złoża. W sytuacji koniunktury na węgiel czy inne surowce mineralne stateczność szybów zlokalizowanych w terenie zurbanizowanym ma także zapobiec katastrofom budowlanym. Autorowi niniejszego artykułu znane są przypadki świadczące o braku kontroli zachowania się podsadzki w zlikwidowanym szybie oraz projektowaniu i realizacji nowych obiektów w strefie ochronnej wyznaczonej wokół zlikwidowanego szybu. W pracy w oparciu o założenia metody Janssena dla schematu obliczeniowego (Rys. 1) przedstawiono wyprowadzenie wzorów na wielkość pionowego i poziomego obciążenia działającego wewnątrz zlikwidowanego szybu. Z analizy wzorów (10) i (11) jednoznacznie wynika, że wielkości te wraz ze zmianą głębokości dążą do maksimum określonego asymptotami $p_x = \frac{\gamma a}{2k\mu}$ i $p_y = K\frac{\gamma a}{2k\mu}$, przy czym osiągają je już około 20÷40 m pod ustabilizowanym poziomem podsadzki w szybie. W prawidłowo zlikwidowanym szybie podsadzka winna szczelnie wypełniać rurę szybową do poziomu zrębu, a w przypadku wystąpienia procesu jej osiadania – okresowo uzupełniana. W takim przypadku obciążenie wypadkowe obudowy zlikwidowanego szybu można wy-

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razić wzorami (12), (13). Jednak w zależności od rodzaju zastosowanego materiału podsadzkowego do likwidacji szybu, jak to wynika z prowadzonych badań ich parametry fizyko-mechaniczne mogą ulegać zmianie w czasie w mniejszym lub większym stopniu. W artykule powołano się na badania górniczych materiałów odpadowych pochodzących z robót dołowych i przeróbczych. Zmianę istotnych parametrów, z punktu widzenia obliczanych wartości obciążenia pionowego i poziomego wywieranego przez podsadzkę na obudowę zlikwidowanego szybu przedstawiono na wykresach 3 i 4. Uwzględnienie tych zmian dla przedstawionego przykładu obliczeniowego wykazało wzrost wielkości parcia podsadzki o około 19%. Ponadto w zlikwidowanych szybach, w których występuje dopływ wody zza obudowy koniecznym jest, aby materiał użyty do likwidacji posiadał wymagany współczynnik filtracji, co obrazuje graficzna interpretacja przykładowych wyników obliczeń przedstawiona na Rys. 6. Nawet prawidłowo dobrany materiał zasypowy (z punktu widzenia wymaganej wartości współczynnika filtracji) może ulegać zmianom uziarnienia w wyniku takich czynników jak: swobodny spadek do szybu w czasie likwidacji, długotrwałe narażenie na oddziaływanie wody, wynoszenie drobnych cząstek gruntu wraz z wodą dopływającą zza obudowy (sufozja) itp. Przykład zmiany współczynnika filtracji związany ze zmianą uziarnienia badanego materiału przedstawia Rys. 7. W wyniku zmiany wartości współczynnika filtracji w czasie może dojść do gromadzenia się wody w podsadzce, co powoduje dalszy wzrost obciążenia poziomego działającego na obudowę szybu i zastosowane w wyrobiskach łączących się z szybem konstrukcje stabilizujące zasyp. W niekorzystnej sytuacji może dojść do zniszczenia tych konstrukcji zasypu, wypłynięcia uwodnionej podsadzki z szybu, lokalnego uszkodzenia obudowy w wyniku wyrywania pozostawionego w szybie zbrojenia, a w konsekwencji powstania na powierzchni deformacji nieciągłej o charakterze powierzchniowym. Stąd dla oceny prognozowanej stateczności zlikwidowanego szybu proponuje się stosowanie wzoru (16), uwzględniającego omawiane powyżej zmiany w czasie, oraz wpływ zmienności obciążenia powierzchni w strefie ochronnej wyznaczonej dla zlikwidowanego szybu. Wyznaczone w ten sposób wypadkowe obciążenie obudowy pozwala na określenie wielkości naprężeń w poszczególnych jej odcinkach i porównanie z wielkościami dopuszczalnymi lub krytycznymi. Do tego celu można wykorzystać wzory stosowane przy ocenie stanu technicznego szybów czynnych lub wzór (17) zaproponowany w niniejszym artykule.

Słowa kluczowe: górotwór, szyby górnicze, likwidacja szybu

1. Introduction

During the restructuring process of the mining sector in Poland which has been in progress over the last 20 years, the number of coal mines has been reduced from 70 to 33. In effect of the carried out works, over 340 shafts have been liquidated in the Upper Silesia and Wałbrzych Basins, including 320 coal mines liquidated permanently i.e. with the application of filling materials. Main rising opening-out headings such as shafts should be liquidated by filling them tightly with the filling material appropriately selected for specific geological conditions, and the applied liquidation method should allow for the hydrological and gas conditions in the vicinity of the shaft, methane hazards, fire hazards or other hazards that can occur after the liquidation and can adversely affect the surface area and the adjacent coal mining plants.

The shafts in operation are subjected to periodic technical surveys and the results of the carried out tests and inspections are used for the assessment of their stability.

In the case of liquidated shafts such surveys can not be carried out. The ongoing corrosive processes of the shaft lining, the restoration of aquifers which change the load exerted on shaft lining, subsidence of the filling material and no possibility to supplement the lost material, the impact of ground vibration effected by the tremors of rockmass or the traffic of heavy vehicles or finally the construction of new building structures in the protection zone where the potential hazard has been overlooked are the main reasons which may result in stability loss of the shaft lining, which can, in effect, bring about discontinuous deformations of surface character in the vicinity of the shaft.

2. Load exerted on shaft lining

The lining of the shaft is designed in accordance with the Standards PN-G-05015:1997, PN-G-05016:1997. It is assumed that the lining of the shaft is affected by the load of the surrounding rocks deposited below the critical depth and by the hydrostatic or piezometric pressure of water in waterlogged rock layers.

Standard load exerted on shaft lining for the layers deposited below the critical depth, depending on the satisfied conditions, is calculated from the following equations:

$$p_N = \gamma_{sr}^{(n)} \cdot (H - H_{kr}) \cdot \mathrm{tg}^2\left(45^{\mathrm{o}} - \frac{\phi'^{(n)}}{2}\right) \tag{1}$$

$$p_N = \sigma_{z\gamma\cdot} \cdot \mathrm{tg}^2\left(45^{\mathrm{o}} - \frac{\phi}{2}\right) \tag{2}$$

$$\phi = \mathrm{arctg}\left(\frac{R_{cs}^{(n)}}{10}\right) \tag{3}$$

$$p_N = 55 \cdot \gamma_{sr}^{(n)} \cdot \mathrm{tg}^2\left(45^{\mathrm{o}} - \frac{\phi'^{(n)}}{2}\right) \tag{4}$$

where:

$\sigma_{z\gamma}$ — vertical stress in the non-waterlogged layer of rockmass:

$$\sigma_{z\gamma} = \gamma_{n,1}^{(n)} \cdot h_1 + \gamma_{n,2}^{(n)} \cdot h_2 + \cdots + \gamma_{n,j-1}^{(n)} \cdot h_{j-1} \tag{5}$$

$\sigma_{z\gamma}$ — vertical stress in the waterlogged layer of rockmass:

$$\sigma_{z\gamma} = \gamma_1^{*(n)} \cdot h_1 + \gamma_2^{*(n)} \cdot h_2 + \cdots + \gamma_{j-1}^{*(n)} \cdot h_{j-1} - \gamma_w \cdot H_w \tag{6}$$

$\gamma_{n,1}^{(n)}, \gamma_{n,2}^{(n)} \cdots + \gamma_{n,j-1}^{(n)}$ — characteristic value of the natural bulk density of the rock in the *i*-th layer, [MN/m^3],

$\gamma_{sr}^{(n)}$ — characteristic value of the average natural bulk density of the overlying rocks, [MN/m^3],

$\gamma_1^{*(n)} \cdot, \gamma_2^{*(n)} \cdots + \gamma_{j-1}^{*(n)}$ — characteristic value of bulk density of the waterlogged rock in the *i*-th layer with water buoyancy taken into consideration, [MN/m^3],

$h_1, h_2 \ldots h_{j-1}$ — thickness of particular layers forming the rockmass [m],

γ_w — specific gravity of water [MN/m^3],

$R_{cs}^{(n)}$ — characteristic value of compressive strength of rock [MPa],

H — depth of the investigated section of the shaft [m],

H_w — height of water column in the test well [m].

H_{kr} — critical depth of the rock [m],

$\phi'^{(n)}$ — characteristic value of the effective interior friction angle of the rock [°].

The total load exerted by the i-th layer of ground is the sum of the load exerted by the ground layers and by the pressure of water. The calculation value of the load impact on the shaft lining is obtained by multiplying the standardized value by the load factor “n”.

3. Pressure of filling material in the liquidated shaft

The permanent liquidation is effected by filling the shaft with loose or binding materials. When binding mixtures are applied, the load exerted on the shaft by the filling material until its solidification is equal to the hydrostatic pressure, and its value depends on the height of the unbound filling layer. The situation is different when using rock filling.

In this case the problem involving the behaviour of filling material in the liquidated shaft is defined as analogous to the pressure of grain material of quasi-static flow in vertical parallel channels, which are understood as tanks with the walls parallel to the vertical axis, which can be compared to a shaft tube.

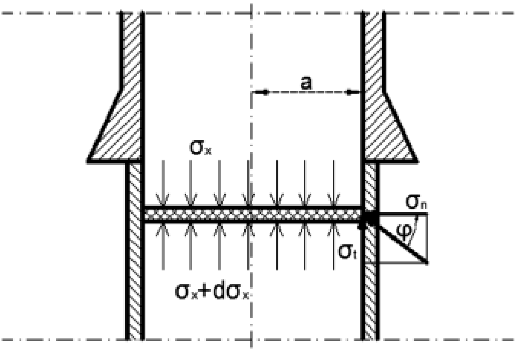

Fig. 1. Distribution of stresses in the flat layer of filling material of the height *dx* and width 2a

The equilibrium equation of forces along the direction of vertical axis for the shaft of the circular section has the following form:

$$\sigma_x \pi a^2 - \left(\sigma_x + d\sigma_x\right)\pi a^2 - \sigma_t 2\pi a dx + \gamma 2\pi a^2 = 0$$

$$\frac{d\sigma_x}{dx} + \frac{2\sigma_t}{a} - \gamma = 0 \tag{7}$$

Due to two unknowns, the above differential equation is statically indeterminate. The equation can be solved when we accept the Janssen assumptions:

- the ratio of normal stress σ_n to the vertical one σ_x is constant along the whole length of the channel

$$\frac{\sigma_n}{\sigma_x} = k = \text{const.} \tag{8}$$

- the weight of the filling material is constant,
- the inclination angle of the stress vector on the walls of channel ϕ corresponding to the transgression of friction defined by the factor $m = \mathrm{tg}\phi$ is constant.

The solution of the above equation (7) can be presented in the following form:

$$p_x = e^{-\frac{2k\mu}{a}} \left(\frac{\gamma a}{2k\mu} e^{\frac{2k\mu x}{a}} + C \right) \tag{9}$$

On the unloaded surface of the filling $x = 0$ ($p_{xo} = 0$), the equation (9) has the following form:

$$p_x = \frac{\gamma a}{2k\mu} \left(1 - e^{-\frac{2k\mu x}{a}} \right) \tag{10}$$

The horizontal load can be calculated by substituting the vertical stress defined by the equation (10) to the Janssen condition as in (8), and then we obtain:

$$p_y = \mathrm{tg}^2 \left(45^{\mathrm{o}} - \frac{\phi}{2} \right) * p_x \tag{11}$$

When there is no inflow of water to the shaft, the filling remains dry and its calculation parameters do not change. In such a case the value of vertical load is increasing from zero at the level of the shaft cheek to the value defined by the asymptote $p_x = \frac{\gamma a}{2k\mu}$, and the value of the vertical load (side pressure) is increasing to the value of $p_y = \mathrm{tg}^2 \left(45^{\mathrm{o}} - \frac{\phi}{2} \right) \frac{\gamma a}{2k\mu}$.

4. Load exerted on shaft lining after the liquidation of the shaft

Immediately after the liquidation of the shaft its lining is burdened by the external load exerted by the surrounding rocks and water and by the vertical pressure of the filing inside the shaft. The value of the resultant load exerted on the lining in the *i*-th layer can be determined from the following equations:

$$\begin{gathered} p_o = \left(\gamma_{sr}^{(n)}(t) \cdot (H - H_{kr}(t) \right) \cdot \mathrm{tg}^2 \left(45^{\mathrm{o}} - \frac{\phi'^{(n)}(t)}{2} \right) - \\ K(t) \left(\frac{\gamma(t)a}{2k\mu(t)} + \left(p_{xo}(t) - \frac{\gamma(t)a}{2k\mu(t)} \right) e^{-\frac{2k\mu(t)x(t)}{a}} \right) \end{gathered} \tag{12}$$

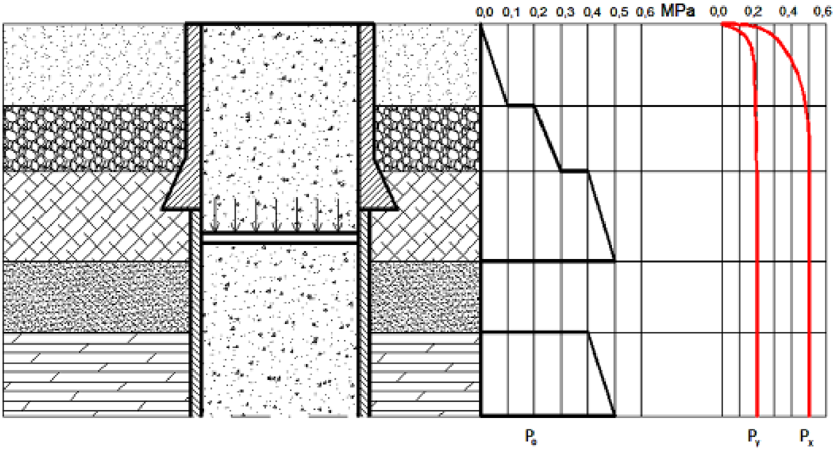

Fig. 2. Load exerted on the lining of the liquidated shaft

$$p_o = \left(\sigma_{zy\cdot}(t)\right) \cdot \mathrm{tg}^2\left(45^\circ - \frac{\phi'^{(n)}(t)}{2}\right) - K(t)\left(\frac{\gamma(t)a}{2k\mu(t)} + \left(p_{xo}(t) - \frac{\gamma(t)a}{2k\mu(t)}\right)e^{-\frac{2k\mu(t)x(t)}{a}}\right) \tag{13}$$

The value of the load exerted by the filling is therefore dependent on the material used in the liquidation process, hydrogeological conditions in the vicinity of the shaft and on the applied structure of the filling.

The material applied for the liquidation of shaft must not become soggy. It involves both dry shafts and waterlogged ones, since the liquidation of a shaft by filling is a rather irreversible process and the stability of the filling must be ensured even after the change of hydrogeological conditions, e.g. when the dewatering process of rockmass is relinquished. Waste materials, e.g. from post-mining dumping sites, which were being applied for the liquidation of shafts in the early 1990s, are characterized by changeable physicomechanical properties in time when subjected to the long-term influence of water. The results of the investigation studies carried out on the wastes demonstrate that as early as after 3 months the content of dusty fraction and clayey fraction increases twice. The change of grain size of the filling material (rocks from the post-mining dumping site) brings about the rise of bulk density of the filling and the reduction of the interior friction angle. The discussed changes are presented in Figs. 3 and 4.

The rise of the share of the summary percentage content of the dusty and clayey fraction in the mass of the filling material from 5% to 30% results in the rise of horizontal load, which is presented in Fig. 5.

When the content of fine fractions in the filling of the waterlogged shaft is rising, there is a great possibility that the filling may lose its stability, i.e. a liquefaction process of the filling can take place.

The material used for the liquidation should have the filtration index ensuring the flow of

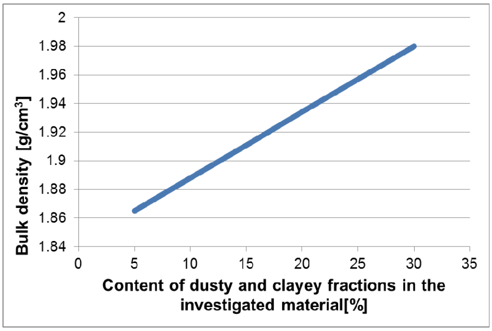

Fig. 3. Influence of the content of dusty and clayey fraction on the value of bulk density

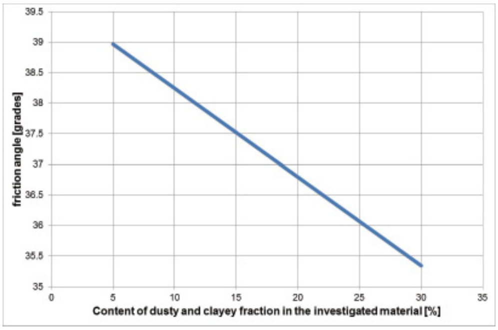

Fig. 4. Influence of the content of dusty and clayey fraction on the value of interior friction angle

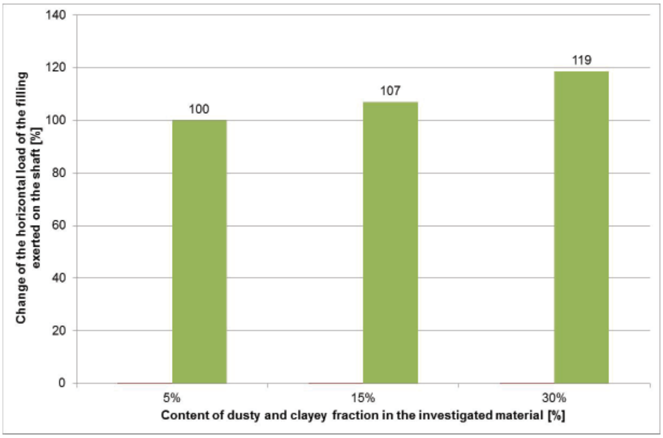

Fig. 5. Horizontal load of the shaft as dependent on the percentage content of the dusty and clayey fraction

water in the volume corresponding at least to the volume of water leaks in the shaft. The filtration index of the filling material should be higher than the value resulting from the equation below:

$$k \geq \frac{Q}{F * i} \tag{14}$$

where:

Q — summary inflow of water to the shaft,
F — cross-section area of the shaft,
i — hydraulic gradient; for the vertical filtration without water column over the filling $i = 1$.

An example is presented in Fig. 6 which presents the calculation results of the required filtration index of the filling material in the liquidated shaft, depending on the cross-section of the shaft and water inflow from outside the lining, and in Fig. 7 which presents the dependence

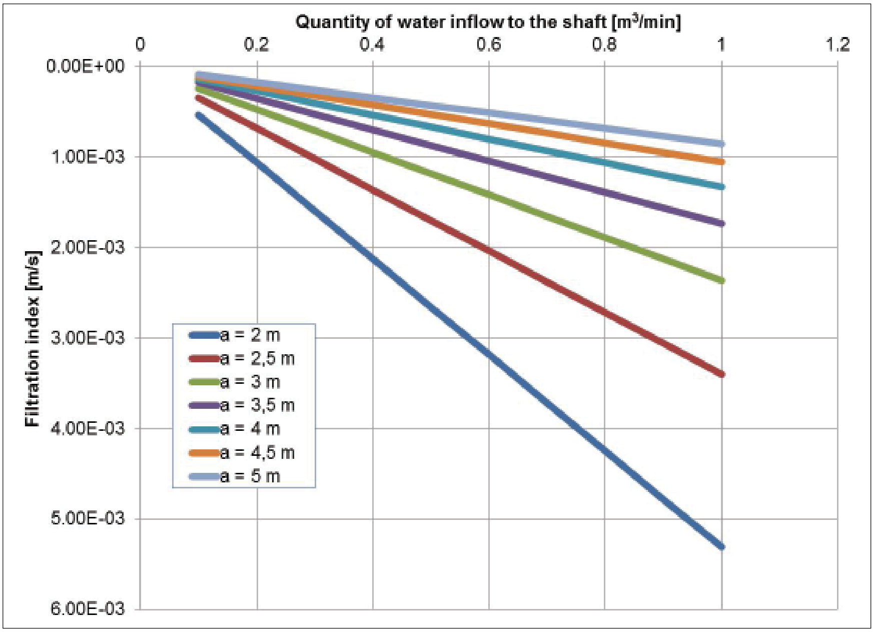

Fig. 6. Dependence of the required filtration index of the filling on the inflow of water to the shaft for the condition of no water damming over the filling

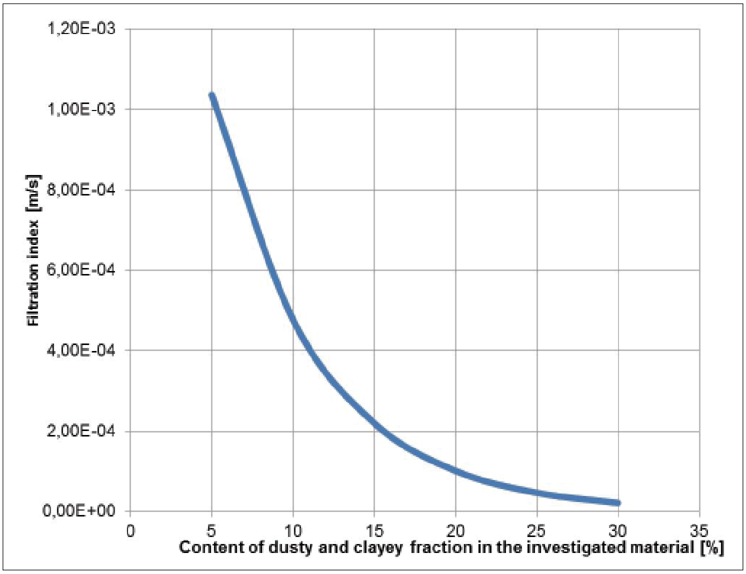

Fig. 7. Dependence of the filtration index of the filling on the content of dusty and clayey fraction in the investigated material

of the filtration factor of mining wastes on the summary content of dusty and clayey fraction in he investigated material.

When the filtration index of the investigated material is lower than that required in the shaft, the summary pressure of water and filling material is rising.

As it was mentioned above, the value of horizontal load exerted by the filling in the liquidated shaft depends also on the structure of filling column. In practice, very frequently different materials are used for the liquidation of shafts, applied in an appropriate order from the shaft sump to the shaft cheek. Owing to this, so called filtration resistance plugs can be made in the vicinity of shaft inlets and around other workings. Using such plugs, we can reduce the value of horizontal load exerted by the filling on the planned dams in the workings which are joined with a shaft. The purpose of the plugs is to stabilize the filling material. By the application of appropriate materials for the fabrication of filtration resistance plugs which would have suitable grain size and required filtration index, supplemented with an appropriate design of dams safeguarding the inlets, furnished among others with water spillways, we can considerably improve the stability of the filling column, and in the same way ensure the safety of the shaft and around the shaft after the liquidation process.

In the case of shafts liquidated long time ago, there is sometimes no information about their location, function of the shaft or liquidation method. In effect, new objects can be constructed in the immediate vicinity of the liquidated shaft. A new object located within short distance from the shaft brings about the change of the load exerted on its lining, in particular its upper section. In such a case the load exerted on the lining can be calculated using the Boussinesq's equation for normal vertical stress under the center of the loaded circular area, which has the following form:

$$\sigma_z = \frac{3 \cdot Q \cdot H}{2\pi \cdot R^5} \tag{15}$$

Allowing for the quantity of additional normal stresses (15), the value of the resultant load exerted on the lining of the liquidated shaft at the depth of i-th layer can be determined from the equation presented in the paper:

$$\begin{aligned} p_o = &\left(\gamma_{sr}^{(n)}(t) \cdot (H - H_{kr}(t)) + q \left(1 - \frac{H^3}{\left[H^2 + r^2 \right]^{\frac{3}{2}}} \right) \right) \cdot \mathrm{tg}^2 \left(45^\mathrm{o} - \frac{\phi'^{(n)}}{2} \right) - \\ &K(t) \left(\frac{\gamma(t)a}{2k\mu(t)} + \left(p_{xo} - \frac{\gamma(t)a}{2k\mu(t)} \right) e^{-\frac{2k\mu x(t)}{a}} \right) \end{aligned} \tag{16}$$

Very frequently the liquidation process of the shaft is followed by the extraction of deposits trapped in the shaft pillar. During the exploitation and due to the ensuing impact on the surface area and rockmass, the shearing off process of the rockmass layers with respect to the shaft lining can occur. In such a situation, when assessing the stress in the shaft lining, we must allow for the deadweight of the lining, vertical dislocation of the filling inside the shaft tube and a possible rockmass slide with respect to the lining material of the shaft. In such a case the quantity of vertical stress in the shaft lining can be calculated with the following equation:

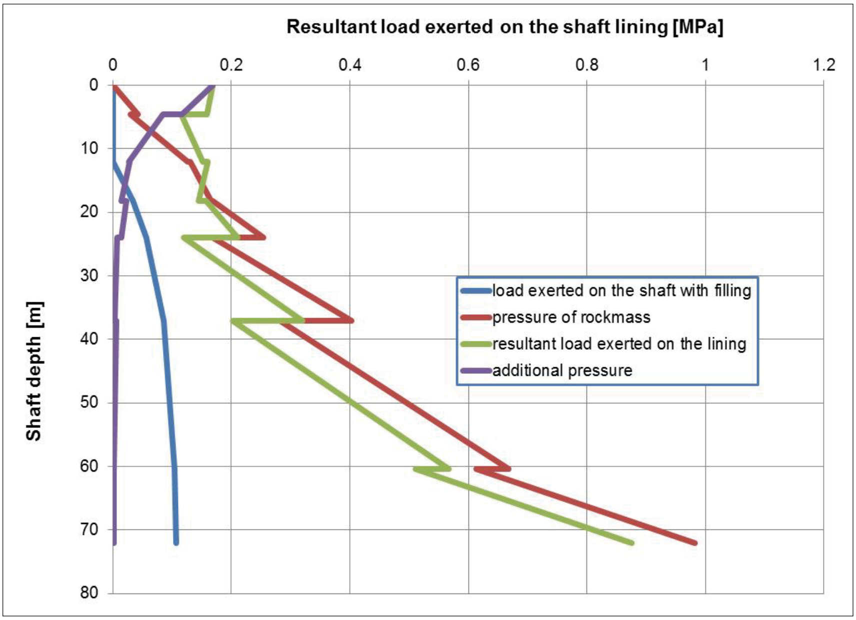

Fig. 8. Development of the resultant load exerted on the lining of a selected shaft

$$\sigma_p = \frac{\rho \cdot g \cdot h}{\pi \cdot d\left(2a + d\right)} + \frac{2 \cdot a * \mathrm{tg}\mu(t) \cdot p_y + 2 \cdot a \cdot \sum_{i=1}^{n} h_i \cdot \left(p_o \cdot \mathrm{tg}\phi_i + c_i\right)}{a^2 - \left(a - d\right)^2} \tag{17}$$

In the equation (17) the quantity of the resultant load exerted on the lining p_o should be calculated from the equations (12), (13) or (16). In other cases, for the determination of the stability of the analyzed shaft section, we can apply the equations used for the determination of stresses in shaft linings being in operation.

5. Summary and conclusions

The liquidation of a shaft is a complex process which must be proceeded by thorough analyses of geological, hydrogeological and mining conditions as well as natural hazards or other hazards which can occur both during the liquidation process and after its completion to ensure the selection of possibly the best liquidation method for given conditions.

In terms of the stability of the filling column in the liquidated shaft, it is important to select suitable filling materials and an appropriate deposition method into the shaft. The applied materials should be characterized by appropriate strength parameters, grain size, resistance to the impact of water and they should be environment friendly.

The lining of the liquidated shaft is not subjected to periodic technical surveys or maintenance works unlike the shafts being in operation. Yet, it is still subjected to the impact of negative factors which can lower its strength parameters or reduce its bearing capacity. In many cases there is no available information involving the actual location of liquidated shafts or the liquidation method which was applied, whereby the potential hazards resulting from the building development at such sites can be overlooked. To avoid such hazards, safety areas were to be mapped out, fenced and appropriately marked as on surveyor maps.

The construction of a new object in the vicinity of the shaft can change the condition and load distribution of the shaft lining, in particular around the shaft cheek, which, together with other factors contributing to its weakening, can in longer perspective lead to the formation of subsidence basin together with all ensuing consequences.

In the situation described above, the safety in the area around the liquidated shaft depends on the filling level of the shaft tube with filling material, which is in turn dependent on the type of the applied material, design of the filling column, how the workings connected with the shaft have been safeguarded etc. The filling material placed in the shaft tube of the liquidated shaft is expanding the lining up to the shaft cheek, whereby it can maintain its stability even with unfavorable load conditions or with weakened strength parameters of the material from which it was made.

Yet, when there is no information available about the location or liquidation method of the shaft the amount of filling in the shaft tube is unknown, which can bring about hazards to people and natural environment.

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