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Some Remarks on Slope Stability Analysis of Tailings Dams

1. Introduction

The most common technique of disposing of industrial post flotation waste is hydraulic deposition, because it ensures minimal costs for the whole construction. In such a way numerous huge tailings dams arise, which are nowadays among the largest man-made structures in the world. Although the largest, these hydraulic constructions are not the safest. There are at least three major reasons for this. The first is that the soil sediments used in construction is usually placed at low relative density – specially for embankments constructed by the upstream method. According to Brawner (1972) the average *in situ* relative density of tailings deposited by the upstream method ranges between 10 and 55% with an average of about 30%. The second reason is that the location of the tailings reservoir is in the vicinity of operating mines, which causes many shocks of different magnitude, sometimes dangerous for the embankments. The third and probably the most direct reason is that so far there is no clear and simple method of stability assessment for tailings dams. This paper is to elucidate some difficulties in slope stability analysis for tailings embankments and it suggests an approach which is under construction on the largest tailings reservoir in Poland.

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2. Selection of Shear Strength for Stability Analysis of Tailings

It is generally accepted that for tailings embankments, which are predominantly non-cohesive material, the undrained shear strength is the one which controls the stability of a dam. If this material is fully saturated, the value of shear strength depends on the undrained response of sand to monotonic or cyclic loading. The types of behaviour of saturated sand are best shown on deformation characteristics for undrained monotonic loading in triaxial test (Fig. 1). These types of response have been reported by

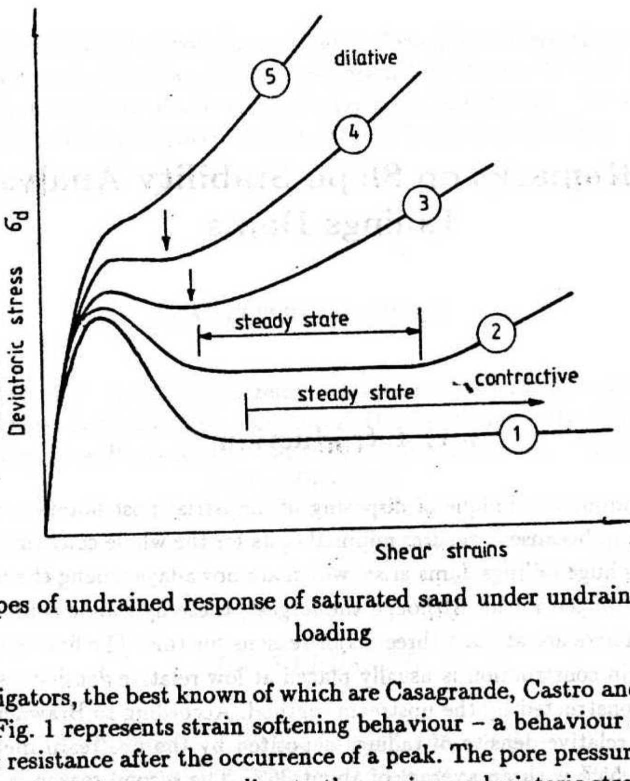


Fig. 1. Types of undrained response of saturated sand under undrained monotonic loading

many investigators, the best known of which are Casagrande, Castro and his associates. Curve 1 in Fig. 1 represents strain softening behaviour – a behaviour associated with loss of shear resistance after the occurrence of a peak. The pore pressure generated during a test, at the point corresponding to the maximum deviatoric stress, causes rapid decrease in effective normal stress which in terms of existence of shear stress leads to rearrangement of the soil skeleton. Afterwards, the mass is continuously deforming at constant volume, constant normal effective stress constant shear stress, and constant rate of shear strain. This state is referred to as the steady state of deformation and soils demonstrating such a behaviour are called contractive. According to Castro (1969, 1975), Castro and Poulos (1977) and their associates, the above described phenomenon is termed liquefaction.

Unlike curve 1 in Fig. 1, curve 5 shows strain hardening behaviour which is associated with negative increase in pore pressure during shearing. This type of response is referred to here as dilative. The other curves in Fig. 1 represent intermediate types of response to undrained monotonic loading. In the light of the above remarks, it is obvious that stability analysis of tailings dams leads to assessment of factor of safety against liquefaction. According to Poulos, Castro and France (1985) the factor of safety against liquefaction can be expressed in the following form:

$$F_s = \frac{\text{undrained steady state shear strength}}{\text{driving shear stress}}$$

The undrained steady state shear strength is the minimum (residual) strength that soil skeleton can have during a steady state deformation at the void ratio *in situ*.

The driving shear stress is the shear stress required to maintain static equilibrium, so it is a stress which exists due to weight of the mass and any other permanent loading. Such a definition implies that although liquefaction is often associated with earthquake, cyclic load tests are not required to evaluate the susceptibility to liquefaction – in other words – cyclic loading due to earthquake is not a driving shear stress. This can be easily explained by observing shear stresses in the soil skeleton versus shear strain for static and cyclic loading (Poulos 1988). Fig. 2 shows a situation when the soil is not susceptible to liquefaction because both factors of safety:

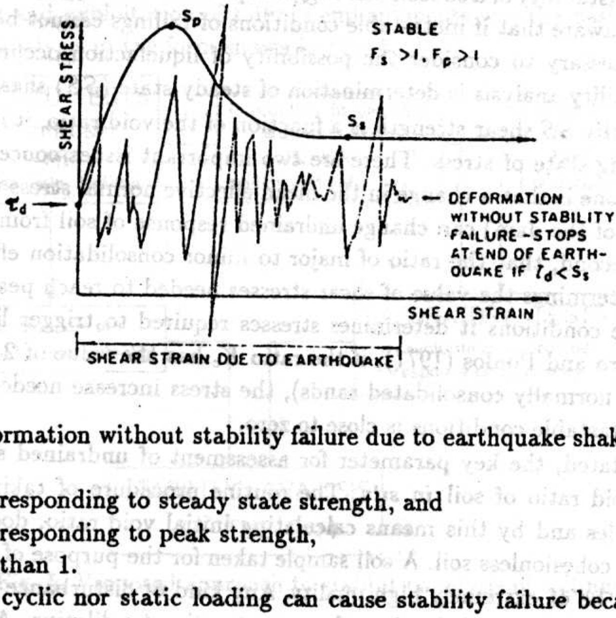


Fig. 2. Deformation without stability failure due to earthquake shaking (Poulos 1988)

F_s – corresponding to steady state strength, and
F_p – corresponding to peak strength,
are greater than 1.

Neither cyclic nor static loading can cause stability failure because even if shear strains due to earthquake reach a value corresponding to the steady state on the chart, they will immediately stop with the disappearance of seismic stress and there will be no unbalanced force to keep the soil mass moving. On the other hand, Figure 3 shows metastable conditions which are defined $F_s < 1$ and $F_p > 1$.

In this case the same (as in Fig. 2) seismic conditions can trigger liquefaction because when strains due to earthquake exceed strain at peak, driving shear stress becomes

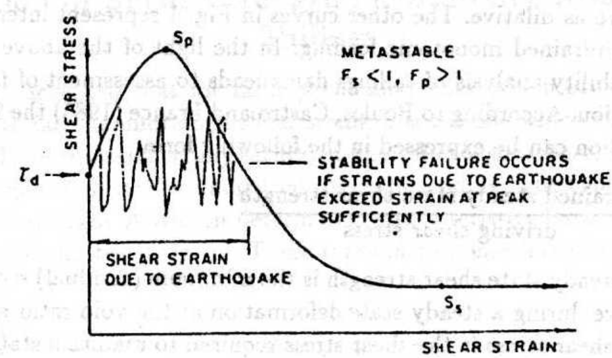


Fig. 3. Stability failure triggered by earthquake shaking (Poulos 1988)

greater than current (steady state) strength and soil flows in a manner resembling a liquid until the shear stress acting on the mass is as low as its reduced shear resistance. For tailings embankments, the value of strains required to reach peak strains does not have to exceed 1% (Marcuson, Hynes 1989) so even a slight shock caused by mining activity or limited instability of a subsoil can trigger liquefaction. Keeping this in mind a designer should be aware that if metastable conditions of tailings cannot be excluded, it is absolutely necessary to consider the possibility of liquefaction occurrence. The crucial item of stability analysis is determination of steady state (SS) shear strength.

Although basically SS shear strength is a function of the void ratio, it is necessary to know the existing state of stress. There are two important issues concerning state of stress. The first one is that a change in the mean effective normal stress (corresponding to the height of the dam) can change undrained response of soil from dilative to contractive. The second, that the ratio of major to minor consolidation effective normal stress (K_c) determines the value of shear stresses needed to reach peak strength, thus in metastable conditions it determines stresses required to trigger liquefaction. According to Castro and Poulos (1977), if the ratio K_c has the value of 2 (which is a common value for normally consolidated sands), the stress increase needed to trigger liquefaction in metastable conditions is close to zero.

As has been stated, the key parameter for assessment of undrained steady state strength is the void ratio of soil *in situ*. The routine procedure of taking so-called undisturbed samples and by this means calculating initial void ratio, does not work well in the case of cohesionless soil. A soil sample taken for the purpose of liquefaction assessment should be of extremely high quality. Any kind of disturbance done to soil before testing can change its behaviour from contractive to dilative. According to results obtained by Castro (1969) from consolidated – undrained triaxial tests on clean tailings sand (Fig. 4), an increase in density of only 48 kg/m^3, often within the range of test error, changes the undrained steady state strength from 20 kPa to 130 kPa.

This is evidence that stability analysis of tailings dams cannot be considered routine work and requires of geotechnical engineers great attention and special treatment.

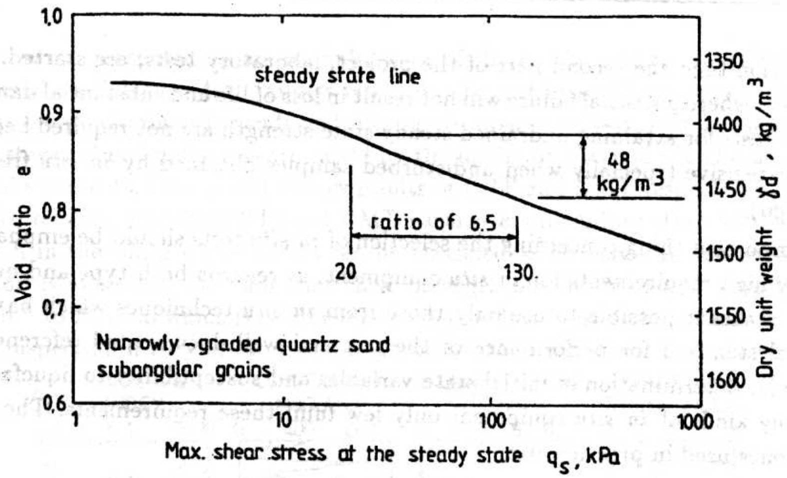


Fig. 4. Influence of density change on strength in steady state (Poulos at el. 1985)

3. Proposed Approach to Stability Analysis of Tailings

The authors experience associated with the work which has been performed for safe construction and exploitation of tailings embankments was the basis for an approach to stability analysis in the form shown in Fig. 5.

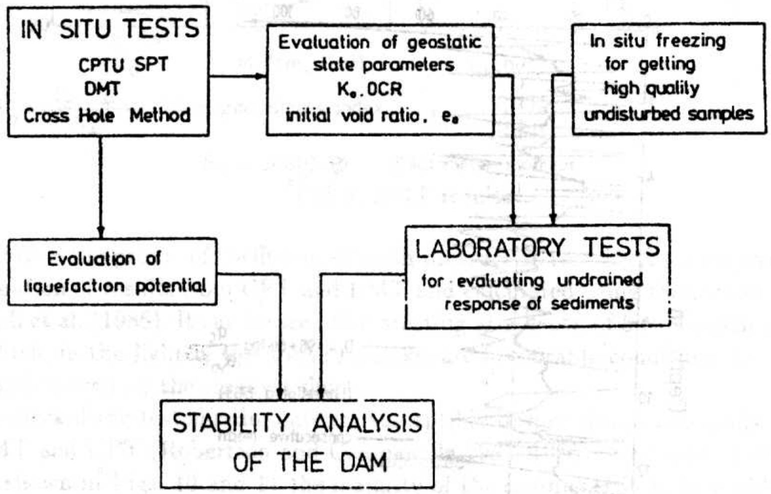


Fig. 5. Proposed approach to stability analysis of tailings dam

The essence of this approach is that both laboratory and *in situ* tests are needed for valuable quantitative evaluation of embankments stability. *In situ* tests are done ahead of laboratory tests because they provide for the latter, data concerning void ratio and geostatic stress anisotropy. Simultaneously, susceptibility to liquefaction is estimated on the basis of the sounding data. If *in situ* tests detect soil layers susceptible to liquefaction then the second part of the project, laboratory tests, are started. In a small project where potential failure will not result in loss of life and substantial damage, laboratory tests for attaining undrained steady state strength are not required because they are expensive (specially when undisturbed samples obtained by *in situ* freezing are required).

One important thing concerning the selection of *in situ* tests should be emphasized here. Very high requirements for *in situ* equipment, as regards both type and quality of results makes it possible to use only those from *in situ* techniques which have international standard for performance of the test and well documented references in literature for determination of initial state variables and susceptibility to liquefaction. From many kinds of *in situ* equipment only few fulfil these requirements. The most common ones used in practice are:

Standard Penetration Tests	– relative density, liquefaction potential
Cone Penetration Test	– relative density, liquefaction potential
Flat Dilatometer	– relative density, coefficient of earth pressure at rest K_0, liquefaction potential
Cross Hole Method	– void ratio (through shear waves velocity), liquefaction potential (rarely used).

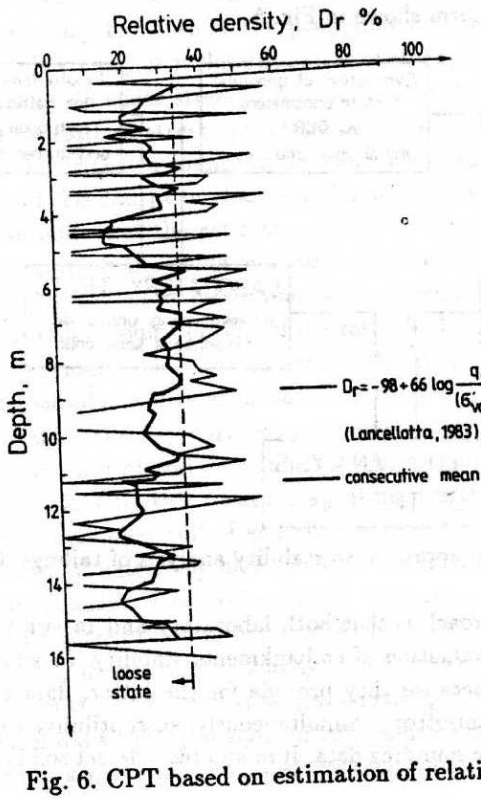
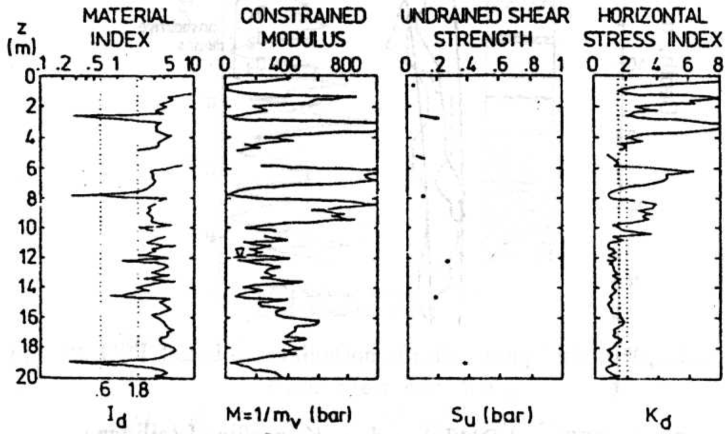


Fig. 6. CPT based on estimation of relative density

Below are presented, as an example, some of the *in situ* test results (CPT; DMT) performed on Żelazny Most tailings reservoir situated in south-western Poland. The tailings are predominantly sands and silty sands, quartz, sub-angular in shape. Subsequent stages of embankments are raised by the upstream method. To characterize the state of sediments, Figs. 6 and 7 show results of CPT and DMT respectively, interpreted into relative density (CPT) and DMT parameters including also undrained shear strength in the place where slimes can be classified as cohesive. In the whole profile the sand is loose and the undrained shear strength of cohesive lenses is in the range of from 5 to 25 kPa, which is satisfactory evidence that these sediments should receive closer inspection if they are to become subsoil for the next stages of embankments.



$K_d = \frac{P_0 - u_0}{\sigma_{v_0}}$ Horizontal stress index $\quad I_d = \frac{P_1 - P_0}{P_0 - u_0}$ Material index

$E_d = 34.6(P_1 - P_0)$ Dilatometer modulus

Fig. 7. DMT results

In Fig. 8 the profile of coefficient of earth pressure at rest K_0 is shown based on the combination of results from CPT and DMT and calculated using the formula reported by Baldi et al. (1986). It can be seen that starting at a depth of 5 m K_0 oscillates about 0.5, which, in the light of the above remarks, are favourable conditions for triggering liquefaction even by the smallest shock.

To check if the tested sediments are susceptible to flow slides, two kinds of criteria for DMT and CPT (Robertson and Campanella 1985, 1986) were applied (Fig. 9). As it was shown in Figs. 10 and 11 the majority of the sediments in both profiles exhibit the properties of contractive soils.

4. Conclusions

Castro's approach to undrained response of sands, presented in the paper, might be very useful in stability analysis of tailings embankments. Some of the shown test results explicitly indicate the importance of comprehensive analysis of the parameters needed for stability calculation. Different types of test *in situ* as well as laboratory

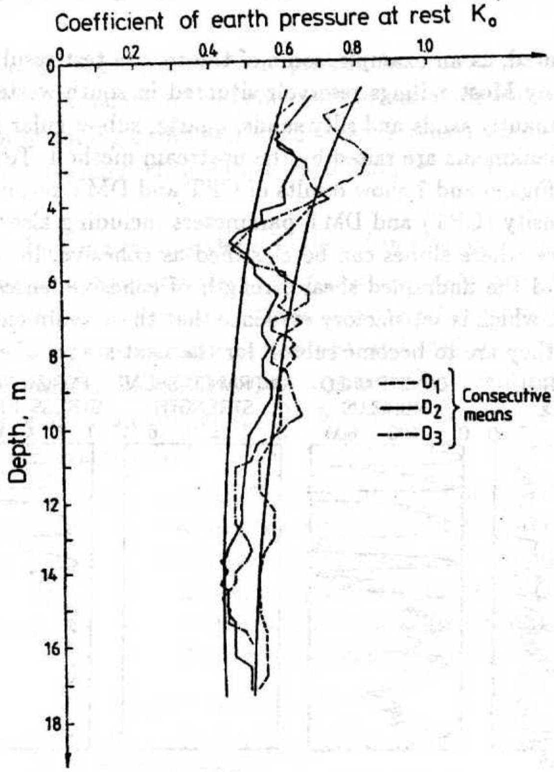


Fig. 8. CPT and DMT based on K_0 profile of tailings

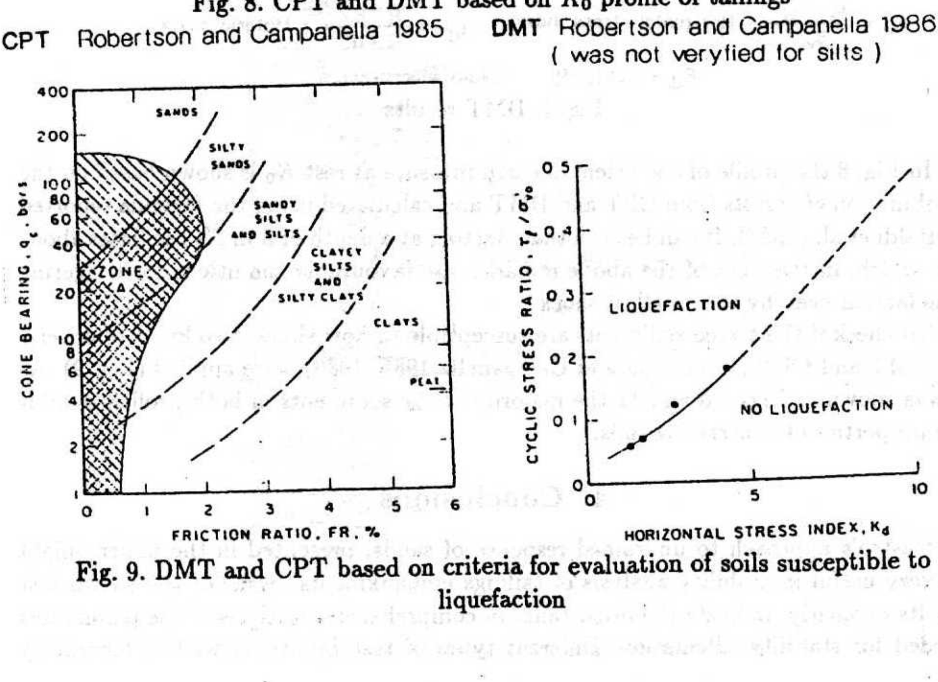


Fig. 9. DMT and CPT based on criteria for evaluation of soils susceptible to liquefaction

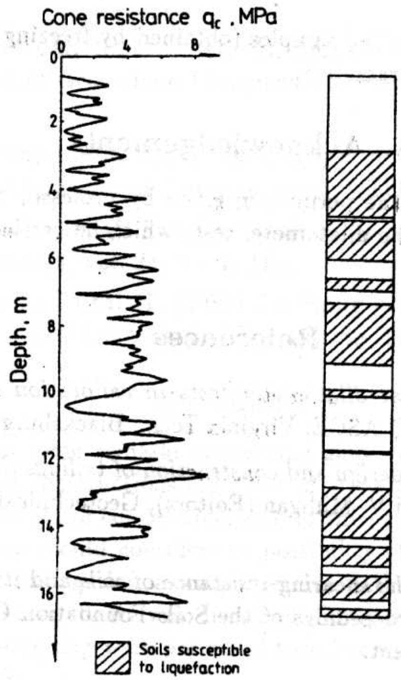


Fig. 10. CPT based on evaluation of soils susceptible to liquefaction

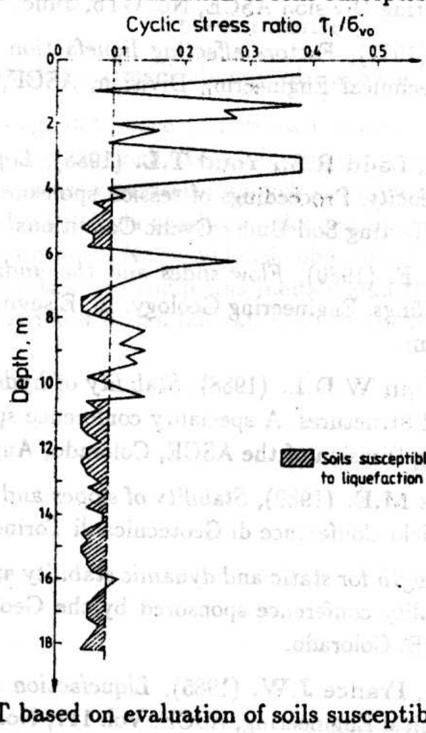


Fig. 11. DMT based on evaluation of soils susceptible to liquefaction

tests on high quality undisturbed samples (obtained by freezing) have to be used for designing and selection of parameters.

5. Acknowledgements

The authors appreciate the permission given by professor Silvano Marchetti, to present here the results of the dilatometer tests which he carried out during his visit to the site in October, 1989.

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Summary

The paper presents some remarks concerning slope stability analysis of tailings dams. Such engineering constructions are often in areas where small earthquakes induced by mining activities are conceivable. Due to this, any method of determination of stability safety factor should consider the possibility of liquefaction. Taking as an example a copper mine tailings dam ą comprehensive method of shear strength analysis using *in situ* and laboratory tests was discussed. Some results of *in situ* tests including CPT and DMT sounding were presented together with qualitative estimation of liquefaction appearance.

Streszczenie

Uwagi na temat stateczności zboczy obwałowań składowisk odpadów

Przedstawiono uwagi dotyczące stateczności zboczy obwałowań przemysłowych składowisk odpadów poflotacyjnch. Tego rodzaju konstrukcje inżynierskie występują często na obszarach wstrząsów parasejsmicznych wywoływanych działalnością górniczą. Z tego powodu metoda określenia współczynnika bezpieczeństwa powinna uwzględniać możliwość upłynnienia gruntu. Na przykładzie obwałowań składowisk odpadów poflotacyjnych miedzi przedstawiono kompletną metodę analizy wytrzymałości na ścinanie przy wykorzystaniu wyników badań laboratoryjnych i polowych.