Stability problems of tailings dams

Problèmes de stabilité des barrages de stériles

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SYNOPSIS Tailings dams are hydraulic fills susceptible to liquefy, not only when subjected to earthquakes but due to shear deformation under high confining stresses also. The liquefaction likelihood in retaining deposit is generally favorized by the grain size distribution without fine particles of the cycloned sand and by the loose state obtained as a result of hydraulic placement without compaction. The paper presents proposed procedures for taking into account in stability analysis of the liquefaction hypothesis, suitable for the specific deposition method. Stability charts may be useful for safety control of existing tailings dams, when piezometric measurements are available.

INTRODUCTION

Hydraulic transport and placement of tailings is usually the most efficient system for tailings disposal, as the mining operations for recovering valuable materials (copper, zinc, iron, and others) generally use water in large quantities. The resulted hydraulic fill is particularly susceptible to liquefy, so that liquefaction is a phenomenon having to be taken into account in stability analyses.

Liquefaction may be an effect not only of dynamic loadings (earthquake, blasting) but of shear deformations due to static (monotonically increasing) loads. As well, the possibility of liquefaction occurence must be considered even in zones with low seismic activity; this very type of situation is discussed in the following.

The stability analysis procedures must correspond to the chosen construction technique. According to the deposition technique used for resistant wall building, tailings dams can be classified in three main categories: tailings dams built by the upstream method, by the centerline method, and by the downstream method.

A decisive feature of tailings dams is that construction usually takes a long time to be completed, years or even tens of years. On another hand, the engineering properties of tailinngs can not be well known a priori, and may also modify with time. So, the initial design must periodically be re-examined, as the construction is accomplished; the corresponding stability analyses can accordingly rely on in situ measurements and tests, this fact being especially important for an accurate consideration of seepage action and for a good estimation of in situ density state.

As a result, stability charts for preliminary design, concerning simplified typical cross sections and assumptions, are useful for the stability control during the tailings dam construction. Some graphs, similar to those presented in the following, can be drawn up for important tailings dams, taking into account the actual conditions in the site, the real cross section, and the engineering properties of the tailings.

ENGINEERING PROPERTIES OF TAILINGS

Grain size distribution

Material produced by mill and flotation processing generally falls in the category of fine sand or silty sand; their unit weight of solid particles is usually about 27 - 29 kN/m^3, greater than that of soils in natural deposits.

For carrying out the resistant wall of tailings disposal, the coarse fraction of tailings separated by spigotting or cycloning is used. The coarse fraction leads to more permeable deposits that may easier be drained, and has more favourable strength caracteristics than deposits built up by fine or total tailings. Cyclones can be used for building by any deposition method, but are essential to the downstream and centerline methods of construction. A review of the requirements for tailings dam construction indicates that the fines content (less than o.o74 mm fraction) has usually been restricted to less than about 12%. As by cycloning the water content is substantially decreased, sand with up to 2o - 25 % fines can be used in the embankment construction when on - the dam cycloning technique for sand placement is followed (Mittal and Morgenstern, 1977).

Figure 1 shows the grain size distribution curves for some typical tailings dams that will be discussed in the following from point of view of their stability. It can be noticed that, in the case of the typical material T, the total tailings is initially liquefiable. After separation, the coarse fraction may be classified as easy liquefiable, that is more vulnerable than

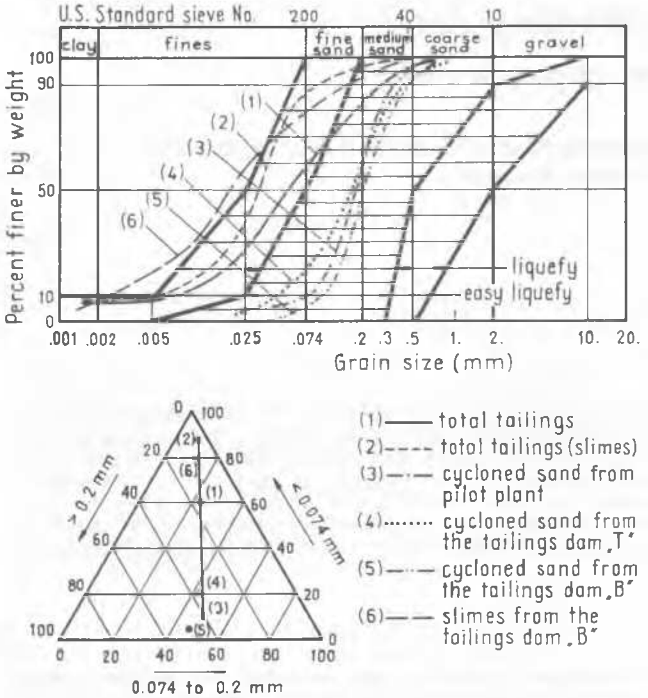

Fig.1 Grain Size Characteristics of Tailings from: Tarnitza Dam (T); Baia Borsha Dam (B); Pilot Plant for Tarnitza Dam

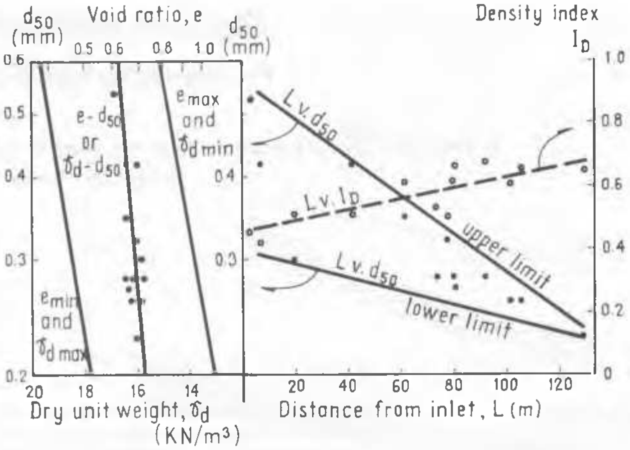

Fig.2 Relationships between Distance from Tailings Discharge Point and Grain Size of Deposited Material and its Density Index (for a given material, relationships in semi-logarithmic plot between 5o-percent diameter and maximum and minimum densities can also be established, as illustrated in the left side graph)

the total original tailings, according to the criterium presented in Figure 1 (Perlea V. and Perlea M., 1984).

Density properties

The material classified as liquefiable from the grain size distribution point of view may be stabilized against liquefaction by decreasing moisture content under the saturation value or by densifying. So, the degree of compaction is a determining feature for the liquefaction prevention.

Some densifying of the small containment dykes is usually accomplished in the upstream method of construction, but as a rule by means of low efficiency. The greatest part of the resisting wall is placed by sedimentation in water, in a rather loose state, and become denser due to overburden pressure only, as the dam is rising up. In the case of centerline and downstream methods of construction, equipments for spreading are usually used, but compaction achieved in this way is at random and not uniform.

Density state obtained by straight hydraulic placement without any mechanical compaction generally correspond to a relative density of about 2o - 6o%, and a mean value of 45 - 5o%. Density mainly depends on the grain size of tailings (distribution of fractions, uniformity coefficient, shape of grains), but also on the flow characteristics of the slurry (discharge quantity, concentration in solid particles, discharge velocity, deepness of water flow, drainage conditions). For a given material and in stable deposition conditions, relationships similar to those given in Figure 2 can be derived.

Shear strength

Tailings resulted from the mining industry on low grade ore bodies are generally cohesionless materials with the angle of internal friction $\phi = 25° - 4o°$. The angle of internal friction value primarily depends on the grain size distribution and to a lesser extent on the deposit density. The influence of confining stress level is negligible in the range of 5o to 5oo kPa but becomes sensible when confining stress increases to about 2ooo kPa, representative pressure for the lowest zones of high deposits.

Figure 3,a shows the variation of the angle of internal friction with density for some characteristic materials presented in Figure 1. Curves A and B have been obtained on the same material (4) by direct shear of samples consolidated under normal vertical stresses in the range of 5o to 3oo kPa; the distinction was that specimens corresponding to B-line have previously been subjected to a vertical pressure of 2ooo kPa.

Permeability

The increase in density is favourable as regards the shear strength; on the contrary, it has an unfavourable influence from the permeability point of view. Figure 3,b illustrates the variation with density of the coefficient of permeability determined in laboratory on remoulded specimens, for some tailings materials defined in Figure 1.

By deposition in horizontal strata, the resulting deposit has a marked anisotropy from the permeability point of view; this is much more important for the seepage network than the value of the coefficient of permeability.

As the anisotropy degree directly depends on the chosen deposition method, the variation of ore processing, possible interruption of disposal

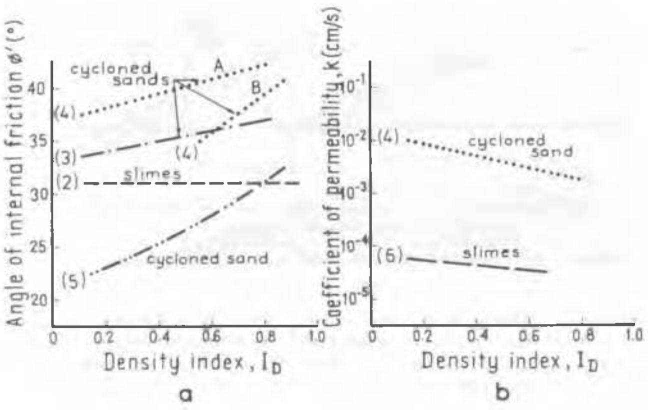

Fig.3 Curves that Illustrate the Influence of Density on Some Properties of Tailings

site operation, climatic conditions, and so on, it is impossible to estimate it a priori. As a result, it is convenient to have in view some more possible locations of the phreatic line, having to determine the actual location of this line by piezometric measurements during operation. Therefore, it becomes possible to establish by the initial design some alarm levels and some corresponding adequate measures to be taken for stability ensuring on measurement in situ basis.

Liquefiability

Loose sands show a tendency to densify when subjected to shear strain (are contractive); in drained conditions the densifying just occur, but when deformation takes place in undrained conditions, the densifying tendency finds expression in a build-up of pore pressure that can lead to liquefaction. Critical state, in which a soil can flow at constant void ratio, is a function of applied normal stress. The steady - state line represents the locus of these states in a normal stress - void ratio diagram (Castro and Poulos, 1977).

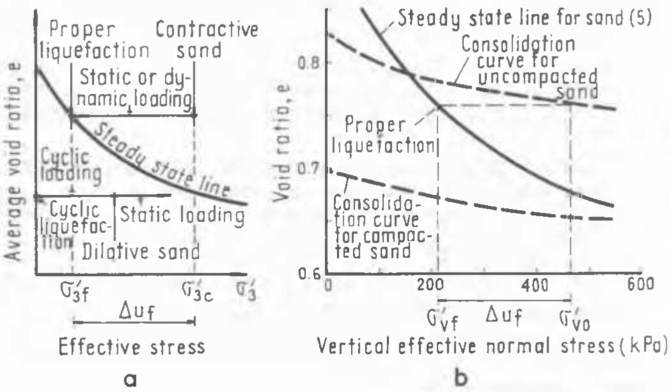

Fig.4 Liquefaction Potential of Saturated Sands, Undrained Loaded, Made Evident on the State Diagram

Figure 4,a illustrates the liquefiability of a loose sand subjected to static load, when its state corresponds to a point located above the steady-state line (it is contractive). The pore pressure build-up by liquefaction is so much the greater as the point is more distant from the steady-state line. A dense sand (dilatative) can not be liquefied but by a cyclic loading.

Clasical shear tests (direct shear, triaxial compression) with volume control are not accurate enough for steady state determination, as shear deformations take place in a rather thin zone as against the total height of the specimen; moreover, it is very likely that volume changes in the shear deformations zone to be partially compensated by opposite changes in adjoining zones. Nevertheless, a simple device with many shearing surfaces (e.g. 15 on 3o cm, as illustrated in Figure 5, where volume changes are of about 0.5 - 1.0 mm for shear strains of 40% at the most) can successfully be used.

In Figure 4,b the steady - state line for a cycloned sand is compared with oedometric curves for two initial density states: disposal by bulldozer spreading, with or without subsequent compaction. Liquefaction is possible in the case of uncompacted sand, the danger of liquefaction having to be taken into account when normal stresses are high, i.e. in the case of high deposits only.

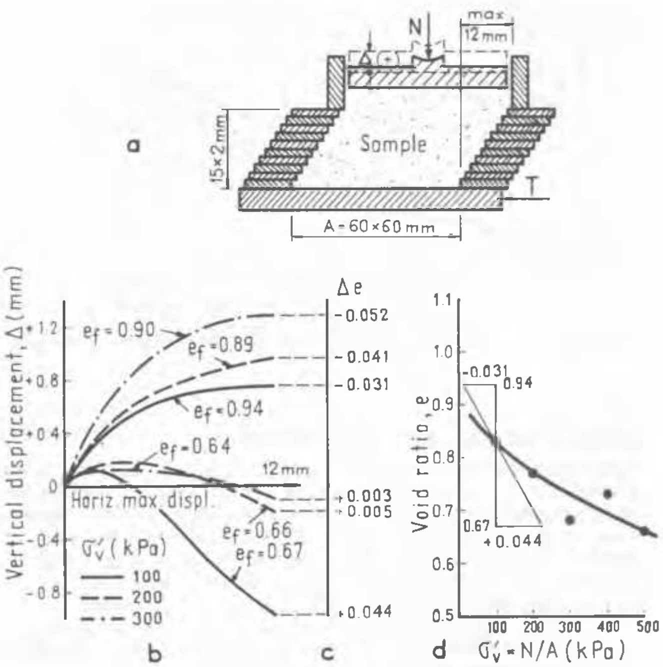

Fig.5 Steady State Line Determination:
a - the multiple shearing surfaces device; b - vertical displacement versus relative displacement of the two horizontal faces of the sample; c - void ratio change at the 12 mm maximum horizontal displacement; d - points defining the steady-state line for sand (5), determined by linear interpolation

STABILITY OF TAILINGS DAMS

Expression of material strength

Figure 6 presents two typical effective stress paths for loading of a cohesionless material, both in drained and undrained conditions (Bishop, 1971): the pore pressure build-up during shear strain development lead to a more reduced undrained strength as compared to the shear strength mobilizable in drained conditions (τ_r). When peak undrained shear strength (c_u) is attained, the angle of internal friction (ϕ') is only partially mobilized; at its complete mobilizing, undrained strength ($c_{u\ rez}$) is much more decreased, corresponding to the pore pressure build-up Δu_f. In stability analyses with liquefaction taking into account, it is more convenient to consider the residual strength, $c_{u\ rez}$, as a lower bond of undrained strength, directly or through a fictitious effective angle of internal friction (ϕ'_m) defined by:

$$c_{u\ rez} = (\sigma'_{vo} - \Delta u_f)\ \tan\phi' = \sigma'_{vo}\ \tan\phi'_m \qquad (1)$$

$$\tan\phi'_m = (1 - \Delta u_f/\sigma'_{vo})\ \tan\phi' \qquad (2)$$

where ϕ'_m has been named mobilizable angle of internal friction and has not a physical meaning.

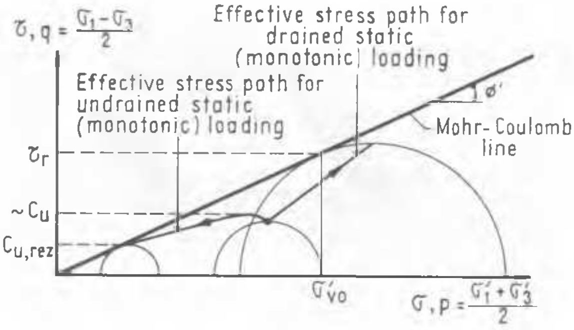

Fig.6 Effective Stress Paths for Sand

Impoundment by upstream method

Upstream method of tailings disposal is the most economical, since it implies the lowest investments both initially and during operation. Raising possibilities are limited however by the need of safety; in zones with relatively high seismicity risk, such impoundments are, as a rule, allowed only to low heights of about 5 - 10 m. Any of chosen deposition techniques (Figure 7) leads to a shell-type retaining wall, its thickness being a function of the disposal methodology.

The coarse material deposited in shell is, from the grain size point of view, more susceptible to liquefy as against the slime in pond, that can be a little cohesive, too. For the shallow stability of the resisting wall a good drainage is essential; this can be provided both by an adequate structure of the starter dam and a drainage system at the soil surface, and, if the

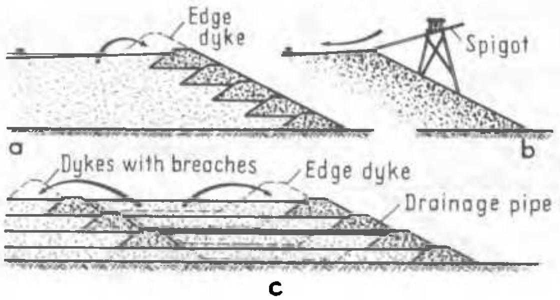

Fig.7 Upstream Method of Construction: a - with compacted dykes; b - by spigotting; c - with double contour dykes

initial drains become out of order, by some drains at several intermediate heights. Even in saturated condition, coarse material at shallow depth may not be liquefied under static loading, as confining stresses are low.

Finer material in the pond, even if unliquefiable, has a lower shear strength, a great capacity of water retaining, eventually remaining a long time in underconsolidated state. However, in normal (good) drainage conditions and usual rates of tailings dam height increasing, it is not expected that excess pore pressure would be of concern for stability (Nelson et al, 1977).

For drawing up design charts, the simplified scheme in Figure 8,a has been considered. The phreatic line has been assumed to be the same as the boundary between the two types of material: fine and coarse; as angles of shearing resistance for the two materials, two pairs of values, more frequently encountered, have been taken into account; pore pressure in every point of slime mass has been considered to correspond to the same piezometric water level as the phreatic line above the point.

Charts can be used both in preliminary design and for the stability checking up of existing tailings dams. So, e.g. in the hypothesis of more resistant materials (Figure 8,b) it results:

- if the shallow stability corresponds to a safety factor $F_1 = 1.5$ (according to the infinite slope method $m = F_1 \cot\phi'_1 = 2.14$), the stability corresponding to deep failure surfaces is ensured with the same safety factor if the beach (confirmed by piezometric measurements) is 0.92 H;
- for a smaller safety factor in the case of deep possible failure, at the same slope, i.e. m = 2.14, the needed beach has 0.70 H in width;
- if the slope coefficient is $m = 2.5$ ($F_1 = m / \cot 35° = 1.75$), $F_2 = 1.3$ is ensured if the beach width is 0.62 H, and $F_2 = 1.5$ if B = 0.85 H.

For a better understanding of the usefulness of such charts, Figure 9 explains the procedure followed for their drawing up. If all deposit had been formed by (wet) fine sand, the safety

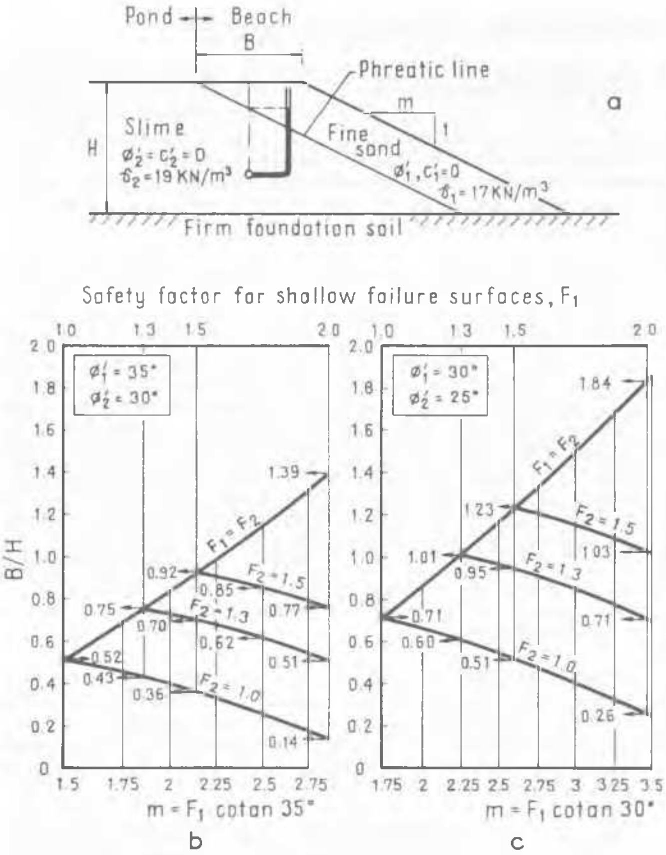

Fig.8 Design Charts for Upstream Method: a - considered cross section; b - graph for materials with more favourable strength properties; c - graph for materials with less favourable strength properties

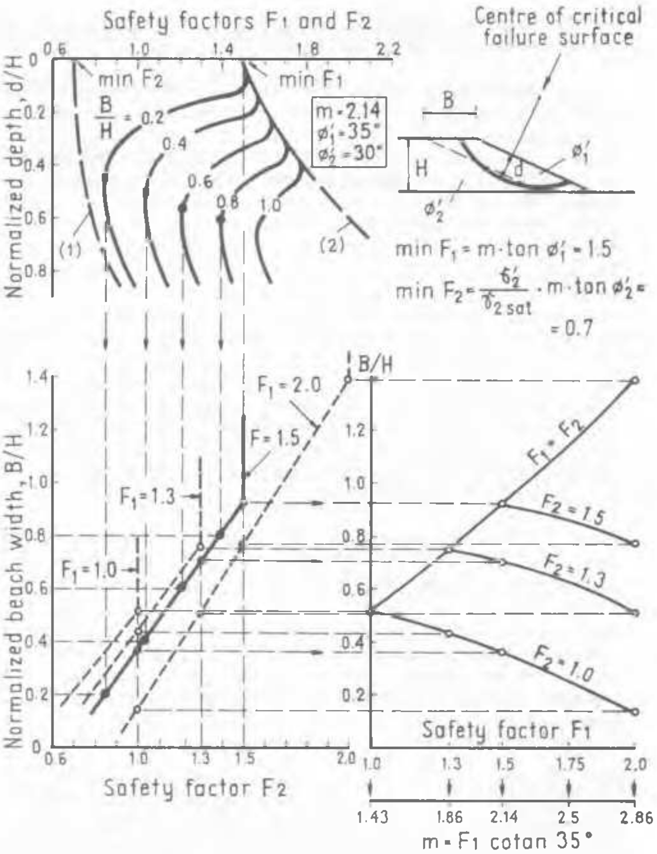

Fig.9 Procedure for Graphs Drawing up: starting from the initial graph (up, left), passing through the intermediate graph (down, left), to the final graph (down, right)

factor variation with depth of the assumed slip surface would have had the shape of curve (1), with a minimum value for the shallowest surface (1.5 for m = 2.14). If only (saturated) slime had been in deposit, with seepage lines parallel to the slope, the safety factor variation would have corresponded to curve (2), with the minimum value (0.7) according to the stability of a particle on the surface principle also.

The actual variation links the two curves, the positions of inflexion points depending on the beach width (B). The minimum values of safety factors for different B-values served to the plotting, in the left lower part of Figure 9, of a curve (a polygonal path in fact) of variation of minimum safety factor with normalized width of the beach (B/H). In the Figure this plotting is exemplified for a safety factor at the surface of F_1 = 1.5 (i.e. m = 2.14). This curve has been used to obtain the three points corresponding to F_1 = 1.5 (and F_2 = 1.0, 1.3, and 1.5 respectively) in the final graph. Performing calculus for other slopes (m = 1.43; 1.86; 2.86) the other representative points of the graph have been obtained.

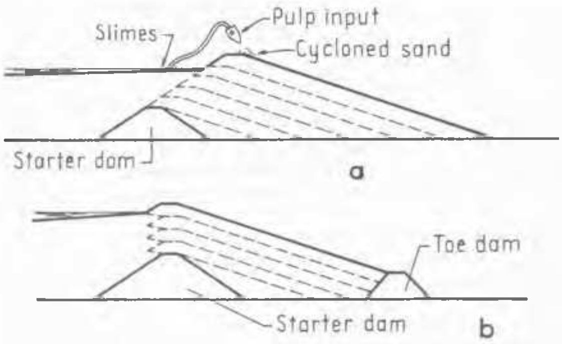

Fig.10 Downstream Disposal of Tailings: a - downstream method; b - centerline method

Inpoundment downstream developed

The downstream deposition of coarser material obtained by cycloning, that theoretically lead to a stable deposit of any height, can be applied in two main variants, as the discharge point from cyclones is successively moved to downstream or on a vertical (Figure 10).

It is generally considered that the downstream method is better than the centerline one from the seismic stability point of view. In practice, the downstream method is seldom adopted, as it requires great quantities of cycloned sand, which makes it possible in very favourable site conditions (narrow valley at the starter dam, but large reservoir). On the other hand, in sensitive seismic areas, the main danger is that of liquefaction; therefore, the better the drainage the safer is the resisting structure. In the case of downstream method the pond edge moves downstream, so that the seepage water is more and more difficultly intercepted by the starter dam or by the other drains provided at the foundation soil level. Our opinion is that, for this reason, the centerline method should be prefered as against the downstream one in any seismic conditions.

Even in the hypothesis of similar draining conditions, stability increase provided by the downstream development is not important. This is illustrated in Figure 11 for an actual case. Stability analysis has been performed by the wedge method and had in view partial liquefaction due to shear strain under high confining stress at the deposit bottom. Determining an average value of the mobilizable angle of internal friction (ϕ'_m, according to equation 2) led to the conclusion that the given deposit can be designed with 3.5 : 1 slope and the centerline method in the desired safety condition (F $\geq$ 1.5). It is expected that relying on field measurements during operation it will be possible to steepen the slope to 3 : 1.

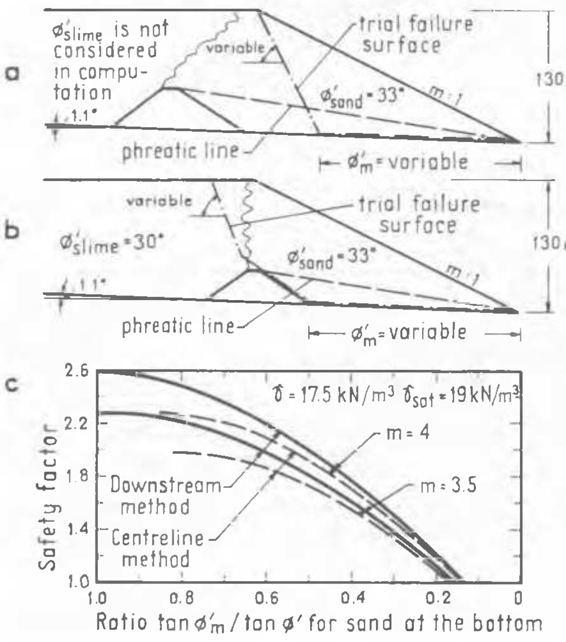

Fig.11 Variation of Safety Factor with Liquefaction Degree at the Deposit Bottom: a - scheme for downstream method; b - scheme for centerline method; c - comparison between results obtained by calculus

CONCLUSIONS

As tailings disposal is not a lucrative activity, the corresponding construction works must be of a minimum cost, in the same time observing safety and environmental preserving requirements. Therefore, it is imperiously necessary to use in the greatest part of the resisting structure just the material to be deposited, that generally is easy liquefiable.

Among the causes that can induce failure of tailings dams, liquefaction is the only one not implying previous signs (cracks, large or sudden settlements, wet spots, alarming rise in phreatic surface). Therefore, it is very important to take liquefaction into account in stability analyses, regardless of the seismicity degree of the zone where the dam is located. There are many well - known failures of tailings dams following liquefaction, with catastrophic consequences due to their suddenness: Barahona - Chile, 1929, El Cobre - Chile, 1965 and Mochikoshi - Japan, 1978, following earthquakes (cyclic liquefaction); Buffalo Creek - U.S.A., 1972, following overtopping; Aberfan - Great Britain, 1964 and Certej - Romania, 1971, during static loading (proper liquefaction).

Proper liquefaction, as the cyclic one, can be taken into account in stability analyses performed by conventional methods (pseudo-statical), by introducing a fictitious parameter, the mobilizable angle of internal friction, ϕ'_m, defined by equation (2).

Charts in Figure 8,b and c, or those similar to them, are useful both for preliminary design and for a rough estimate of the safety of tailings dams in operation, relying on control measurements. In the case of important works it is necessary to periodically verify the safety from the stability point of view, as the dam is raising, using similar graphs developed for the very cross section and the actual strength parameters.

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