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SYNOPSIS The factors governing the geotechnical stability of copper tailing dam Żelazny Most, the largest in Europe, have been discussed. The efficiency of pumping wells barrier against outflow of contaminated ground water has been predicted for a period of next 15 years.

## INTRODUCTION

The tailing disposal reservoir, Zelazny Most (Fig. 1), is placed near the town Lubin in West Poland, approximately 100 km from the German border. The reservoir is the most important link of the Polish copper production chain. Since 1977 the reservoir has been storing the flotation wastes from the mechanical processing plants of all four Polish copper mines. It is known that more than 90% of the all material becomes waste as a result of the flotation process. The daily production of waste is about 80 000 tons. The waste is continuously transported hydraulically and deposited in the reservoir with sub-aerial method. After the sedimentation process is completed, the water used for hydraulic transport is clarified, impounded in the central part of the reservoir and is returned in the flotation system. The reservoir provides also retention of mine waters. The excess of water is periodically discharged to the Odra river.

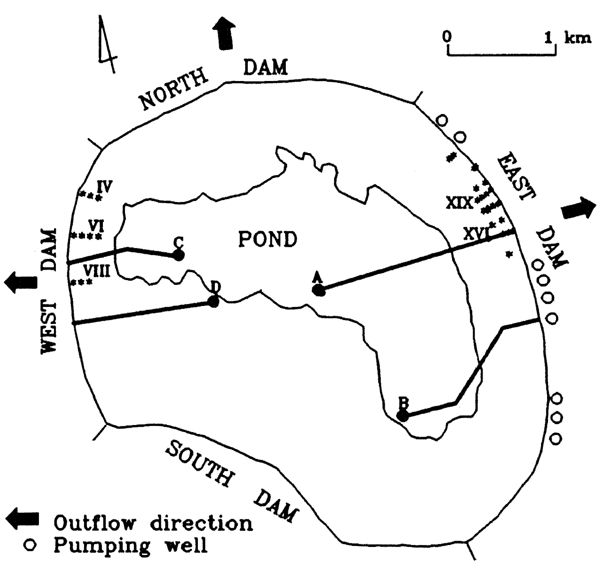


**Fig.1** Copper tailing disposal reservoir Żelazny Most

Because of its size i.e. area 12.3 km$^2$, actual max height of dams - 40 m, planned 100 m, underground mining works close to the reservoir and its location, the reservoir may be hazardous to the population, mines and other plants in its vicinity. Stability failure of the reservoir dam could be catastrophic to the neighboring cities and villages. A possible pollution of the ground water will also be a great hazard.

An interruption of the waste deposition will cause stop of the mining work and finally copper production, which will have enormous economical consequences. It is therefore important to find technical solutions to optimize the use of the reservoir while still maintaining a high safety margin with regard to dam stability and environmental pollution.

## DAM CONSTRUCTION

The general characteristics on 31 July 1992 were as follows:

| | | | |
|---|---|---|---|
| * | total volume | - | 228 000 000 m$^3$ |
| * | tailings volume | - | 214 000 000 m$^3$ |
| * | pond water volume | - | 14 000 000 m$^3$ |
| * | reservoir area | - | 12.4 km$^2$ |
| * | pond area | - | 5.9 km$^2$ |
| * | pond water level | - | 145.9 m a.s.l. |
| * | max. pond depth | - | 5.0 m |
| * | dam crest level | ≈ | 150.0 m a.s.l. |
| * | rate of tailing deposition | - | 1.3 m/year |

Assuming the same annual tailings production, the total volume of tailings is expected to be 350 millions m$^3$ and the tailings level 156.0 m a.s.l. near the year 2000.

The tailings reservoir is situated in the natural valley between moraine hills on the north and south-west sides. It is surrounded by starter dams, constructed from borrow medium grained sand and later upgraded from tailings using upstream method (Fig. 2). The starter dam height variate depending on the ground surface level. It is lower where the ground surface level is higher. The maximum East Dam starter dike height is 24 m, and the minimum North and South Dam starter dike is approximately 4 m. The geometry of the tailing dikes is the same for the whole dam, i.e. bank between subsequent dikes ~10 m, slope inclination 1:2.5, height 5 m, divided into 2 steps.

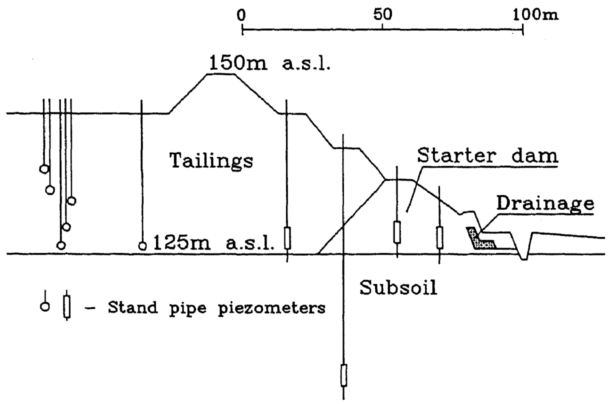


**Fig.2** Cross-section VI, West Dam

The discharging installations consist of pipelines 800 mm in diameter on the crest of the dam and spigots 200 mm in diameter at 20 m spacing along the pipelines.

Discharging is carried out in sections of average length of 500 - 700 m at a time. Tailings sedimentation takes place on a beach between the spigot outlet and the pond. A minimum beach length of about 200 m has been prescribed. The real average beach inclination is about 1%.

Water is drained from the tailings pond by the 5 decant towers and 4 water pipelines (A, B, C, D).

During the lifetime of the reservoir the following routine monitoring is executed:

- ground water level observations (pond level, ground water level in standpipe piezometers, piezometric head in tailings and subsoil using stand-pipe and vibrating-wire piezometers);
- infiltration of contaminated water (quantity of outflow and water sampling for chemical analyses);
- displacement measurements of the dams and original groundsurface;
- meteorological observations.

## GEOTECHNICAL CONDITIONS

The subsoil conditions in the Zelazny Most region have developed mainly by glacier action in the Pleistocene. Roof of Tertiary deposits consisting mainly of clay, clayey and silty sand is locally near to the ground surface and it is folded and discontinuous with inclination in southern direction. Quaternary deposits consist of Pleistocene glacial material in the form of moraine clay, sandy loam, fluvioglacial sand and gravel, lake sediments and Holocene river deposits.
Generally, the subsoil is characterized by high shear strength values. In the maximum dam height region (East Dam, cross-sections XVII - XIX) the subsoil consists mainly of sand with good foundation conditions. On the opposite side (West Dam, cross-sections VIII - IV) the subsoil is created by Quaternary moraine clay - sandy loam, with relatively small permeability.

Results of PCPT - insitu and lab tailing investigations indicate, that the deposit of tailings is characterized by the random distribution of lamination in the vertical direction and by the changes of physical and mechanical properties in the pond direction due to sedimentation processes. Geotechnical properties of tailings are strictly depending on grain size distribution (see table I).

TABLE I. Tailings grain size distribution

| Tailing group | Content of particles, % | | |
|---|---|---|---|
| | sand | silt | clay |
| I | > 90 | < 10 | < 2 |
| II | 90 - 70 | 10 - 30 | < 2 |
| III | 50 - 70 | 50 - 30 | < 2 |
| IV | > 90 | | < 10 |
| V | < 90 | | > 10 |

The mean value of angle of internal friction for the I to III group of tailing is about 30°.
Geotechnical properties of the groups IV and V are presented in Fig. 3, as a function of normalized liquidity index (from fall cone test).

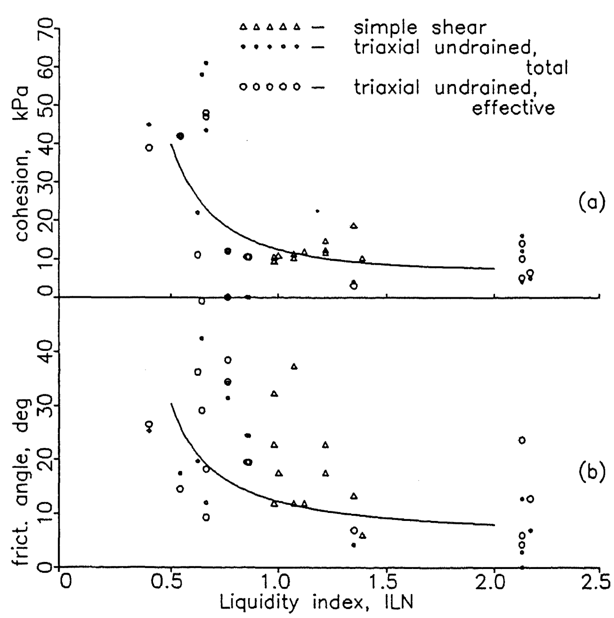


**Fig.3** Strength properties of IV and V tailings groups

Typical CPT profile ($R_f$ and $Q_c$) with layer division and estimated for each layer geotechnical properties is shown in Fig. 4.

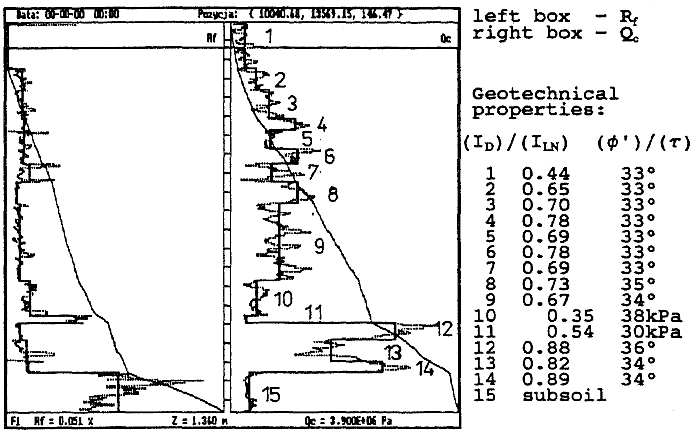


**Fig.4** Interpretation of typical CPT profile in tailings

## SEEPAGE

The seepage process from the pond through the mass of tailings and dam is generally determined by two factors: the water head and the permeability properties of tailings and subsoil layers. Both factors vary with the subsequent process of tailings deposition.

Based on the piezometric measurements, no influence of the pond water level on the ground water surface outside the reservoir was observed, excluding the early stage of tailings discharge, so now the ground water surface is determined only by the existent streams.

But in fact the seepage through the tailing mass will never be in steady state due to the fluctuation of the pond dimensions and continuous increase of the pond level. For example, during 6 months in 1991 the length of the beach was changing up to 400 m and the water level increased about 0.77 m. On the other hand the liquid mass of tailings (1 volume of solid particles and 5 volumes of water) is periodically discharged to the reservoir in different sections of the dam, causing additional vertical infiltration through the unsaturated tailings mass.

The seepage process is determined by the heterogeneous permeability properties of tailings that are caused by the random distribution of laminations in vertical direction and decrease of the mean grain size in the pond direction due to the sedimentation process.

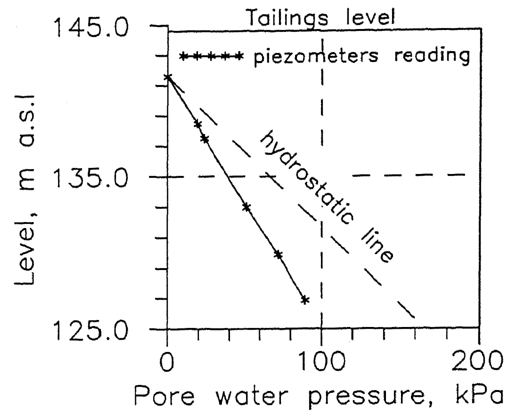


**Fig.5** Observed pore water pressure distribution

The observation in a region of clay subsoil (West Dam) indicates that the pore water pressure in the tailing mass is smaller than hydrostatic pressure (Fig. 5). Also observed hydraulic gradient has a vertical component much greater than the horizontal. Similar observation was done by Staufer et al. (1988) for another copper tailing dam as a result of drainage conditions and relatively slow loading rates.

## STABILITY ANALYSIS

Stability of the tailing dam is a function of dam geometry, subsoil, geotechnical properties of tailing mass, location of phreatic line and pore water pressure distribution. In addition, the seismicity due to mining works and deformation of the dam will also influence the stability. In comparison to the classical hydroengineering dam, the tailing dam is continuously upgraded and thus all the mentioned factors are varying in time. This means that it is impossible a'priori to select representative critical cross-sections valid during the reservoir lifetime.

Stability assessment was done for the tailings level 156 m a.s.l., which is expected near the year 2000.

Results indicate that for a pessimistic subsoil and tailing mass shear strength and hydrostatic pore water pressure distribution, the static stability factor is higher than $F_s = 1.43$ for the East Dam.

For the West Dam, founded on the subsoil characterized by a low permeability, assuming realistic shear strength of the subsoil and 50% of hydrostatic pore water pressure in unsaturated tailing mass, the minimum static stability factor is equal to $F_s = 1.83$.

The influence of mining seismicity and possibility of tailings liquefaction were checked for the West Dam by means of the combined quasistatic stability analysis and analysis of one-dimensional, nonlinear site response to known earthquake motions. The analyses were based on the assumptions of seismicity coefficient k = 0.02, 50% of hydrostatic pore water pressure in tailings, soil damping ratio varying in the range 0.015 to 0.03 and shear modulus $G_{max}$ (based on typical CPT results) as a function of depth with maximum value of 50 MPa.

Results of dynamic analysis indicate that for the above assumptions, there is no possibility of tailings liquefaction and subsequent loss of dam stability. The estimated value of stability factor for seismicity coefficient $k = 0.02$ is equal to $F_s = 1.6$ for tailing dikes, and $F_s = 1.7$ for whole dam. It should be noted, that liquefaction of saturated tailings and subsequently loss of stability cannot be expected for seismicity coefficient lower than 0.05, as can be seen from Fig. 6.

The obtained stability factors are very high in comparison to the safety factor equal 1, which is normally assumed acceptable with respect to the dynamic analysis, provided there is no danger of liquefaction.

The stability calculation also shows that due to the reservoir upgrading in the future, other regions of the dam can be expected to become more critical. This will be caused by the changes in relation between the size of the starter dam and the whole dam. This note is valid mainly for the regions where the subsoil is characterized by a low permeability.

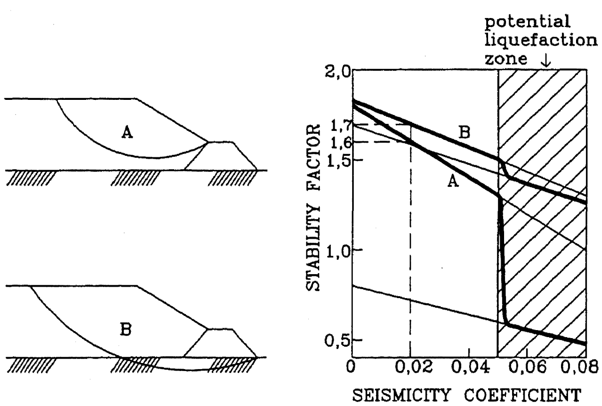


**Fig.6** Stability factor

## GROUNDWATER CONTAMINATION

The total mineralization of the pond water, i.e. weight of solid particles remaining after water evaporation, since 1980 has oscillated around 16000 mg/l. The three directions of the contamination outflow from the Zelazny Most reservoir are observed in the East, West and North Dam.

Measurements of ground water samples, seem to indicate that there are high salt concentrations in the ground water outside the dam. However, the samples outside the dam did not contain high concentration of heavy metals.

In 1990 and 1991 set of pumping wells was installed to decreasing the reservoir influence on the environment, what created a quite new element in water conditions. Average discharge of wells is in a range of 0.1 - 1.0 $m^3$/min.

The efficiency of pumping wells influence was predicted for the East Dam based on computation of contamination transport using a two-dimensional model of solute and dispersion in ground water (MOC computer program). A prediction for a period of the next 15 years (Table II) demonstrates that there is no significant effect of the pumping wells downstream of the East Dam.

TABLE II  Predicted chemical mass balance in 2005

| Mass in tons | No wells | 9 wells |
|---|---|---|
| in boundaries | 81377 | 185520 |
| out boundaries | -32297 | -32944 |
| pumped out | - | -134692 |
| Inflow - outflow | 46077 | 23551 |
| Initially dissolved | 30925 | 30925 |
| Dissolved in 2005 | 76869 | 65689 |
| Excess of mass dissolved | 45944 | 34765 |

Finally it should be stated, that the pumping wells in operation are mixing the contaminated water from the reservoir with clean ground water. This water is pumped into the large water circulation system in a process of copper extract production. It means that additional polluted water will have to be discharged into the Odra river.

## CONCLUSIONS

Based on the case history of the Żelazny Most tailing reservoir, the largest in Europe, which is under development since 1977, the following conclusions can be formulated:

- Sub-aerial method of tailings deposition used with upstream method of tailing dam construction is reliable and safe method in Polish copper field conditions;

- Stability of the tailing dam is a function of dam geometry, subsoil, geotechnical properties of tailing mass, location of phreatic line, pore water pressure distribution, and the seismicity due to mining works. These factors are varying in time, because of Żelazny Most tailing dam is continuously upgraded.

- The static and dynamic stability analysis for tailings level 156 m a.s.l., i.e. total volume of tailings 350 mln $m^3$, indicate that the factor of safety is adequate.

- Plumes of salt water are presently polluting the groundwater outside the dam and the efficiency of applied pumping wells barier is questioned. In this case alternative methods of protection are required.

## REFERENCES

Stauffer, P. A. and J. R. Obermeyer (1988), "Pore Water Pressure Conditions in Tailing Dams", Hydraulic Fill Structures, Proc. of ASCE Spec. Conf.: 924-939.