Importance of Shear Stress Anisotropy and bottom drainage on Tailings Dam Stability: a Case History

Importance de l'anisotropie de la résistance au cisaillement et du système de drainage sur la stabilité des terril: une étude de cas

Jean-François Vanden Berghe,
Fugro Engineers SA/NV, JFVandenberghe@fugro.be

Jean-Christophe Ballard
Fugro Engineers SA/NV, JCBallard@fugro.be

Richard A. Jewell
Fugro Engineers SA/NV, RJewell@fugro.be;

Marc Pirson
Solvay SA, Marc.Pirson@solvay.com

Uwe Reh
Solvay Chemicals GmbH, Uwe.Reh@solvay.com

ABSTRACT

In February 2007, a tailings dam used as sedimentation pond of lime particles failed. As a result, an estimated volume of 150,000m^3 of tailings flowed from the breach in the dam slope. Forensic investigations were carried out to determine the causes of failure, so that suitable changes could be made for the future safe operation of the tailings disposal facility. The investigation identified several features of the tailings material and dam behaviour that it is considered contributed significantly to the slope failure. Among them, a marked anisotropy in the effective shearing resistance of the tailings material and the water accumulation in the tailings were identified as important factors in the failure. The origin of the anisotropy is the method of tailings deposition per layer, and results in a much lower shearing resistance on horizontal planes. The water accumulation was the consequence of a permeability of the tailings being higher than expected due to shrinkage fissures and a significant reduction in drainage efficiency from below the tailings. This loss of drainage was due to precipitation of calcite that lowered dramatically the permeability of the granular soils. The objective of the paper is to illustrate through back-analysis of the tailing dam failure how the shear resistance anisotropy and the efficiency of the drainage system influences the safety factor of the tailings dam.

RÉSUMÉ

En Févier 2007, un terril servant de bassin de décantation s'est rompu soudainement. Cette rupture a entrainé l'épanchement d'un volume 150,000m³ de boue. Une étude détaillée s'en est suivie visant à déterminer les causes de la rupture de telle sorte que les changements appropriés pour une exploitation plus sure des terrils puissent être implémentés. L'étude a identifiées plusieurs éléments qui conjointement ont contribué à la rupture. Parmi ceux-ci, l'anisotropie de la résistance au cisaillement du matériau et un niveau d'eau élevé dans le terril se sont avérés être les paramètres les plus importants. L'anisotropie trouve sont origine dans la méthode de déposition du chlorure de calcium par couche créant ainsi des plans horizontaux à plus faible résistance. L'accumulation d'eau dans le terril résulte, d'une part, de la perméabilité élevée du terril en partie due à la présence de fissures de retrait et d'autre part, de la perte d'efficacité du système de drainage consécutif de la précipitation de calcite dans les drains. L'objectif de cet article est de montrer comment l'anisotropie de la résistance au cisaillement et l'efficacité du système de drainage influence la stabilité du terril.

Keywords : Embankment, tailings dam, slope stability, anisotropy

1 INTRODUCTION

A slope failure occurred in February 2007 at one of the tailings ponds operated by Solvay in Bernburg, Germany, about 70km North-West of Leipzig. The failure involved about 150,000 m³ of tailings material which flowed through a breach in the dam slope. A detailed investigation was carried out to determine the causes of the failure, so that suitable changes could be made for the future safe operation of the facility.

The Solvay chemical plant at Bernburg produces soda ash (sodium carbonate) from salt brine and limestone. The main waste product of the Solvay process is calcium chloride in aqueous solution. This material is delivered hydraulically to the tailings ponds where the particulate matter is progressively deposited.

2 SITE AND DAM DESCRIPTION

The tailings dams are built on flat or slightly sloping ground and require confinement around the entire periphery. Production at the plant started in 1883 and over the intervening years several tailings deposits of increasing height were gradually built. The ponds that are currently in operation were commenced in the 1960s and have a height ranging from 15m to 30m. The construction sequences for these tailings dams are as follows (see Figure 1):

1 Installation of base drainage layer

A series of drainage pipes is buried about 1m deep in the natural foundation soil of about 1m of fine-grained soils overlying silty sands. The purpose of these drains is to collect leachate that permeates downward from the tailings impoundment, and to transport it to a collector drain at the dam toe.

2 Construction of the Pioneer Dam

A Pioneer Dam is then constructed from natural soil and establishes the toe of the future tailings pond, Figure 2.

3 Filling of the pond and consolidation

The tailings material is delivered hydraulically along the periphery of the dam crest. A drainage outlet at the centre of the dam evacuates the overflow of decanted water. During normal operation, the tailings liquid flows from the periphery towards the center of the pond. The level of the central outlet is adjusted so that a pool is created, to permit settlement of smaller sized particles. When the pond is full, the tailings pond is left for a period of about 2 years to permit consolidation.

Proceedings of the 17th International Conference on Soil Mechanics and Geotechnical Engineering
M. Hamza et al. (Eds.)

doi:10.3233/978-1-60750-031-5-1626

4 Dam heightening
After consolidation, the dam is raised for the next phase of usage by building a new embankment with the coarser tailings material deposited close to the dam periphery. This material is excavated from a trench located close to the dam crest. The dams are raised in stages of 1.5m height.

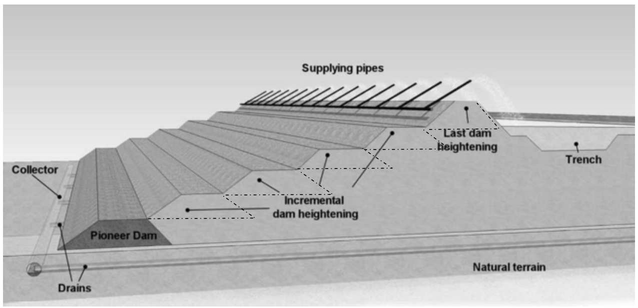


Figure 1 – Dam profile

3 A REVIEW OF THE SLOPE FAILURE

After a typical consolidation period of about 2 years, the tailings dam where the failure occurred was at a height about 22m above foundation level and deposition of tailings material behind a new retaining bund was restarted. The slope failure occurred after 20 days and about 150,000 m^3 of slurry had been placed. An aerial photograph of the failure is shown on Figure 2. Unfortunately the dam was not instrumented in this area. Except for some leakage visible in the slope of the dam, indicating a high water level, there was no warning of the slope failure.

3.1 *Mechanics of the failure*

It has been deduced that the failure started by an outward sliding of rigid blocks over a well defined and substantially horizontal shear surface. There were 2 blocks of the dam slope that apparently moved almost horizontally by about 30m to 40m and remained almost intact. The presence of distinct blocks that remain intact, and a steep back scarp, suggests an initial "blocky failure", or rupture of essentially intact material over distinct shear surfaces.

The failure apparently happened quite suddenly and quickly. The dam material at the slope surface, which is brownish due to oxidation with the air, slid and displaced but remained essentially intact. The part of the sliding block that suddenly came to rest on the Pioneer Dam broke into pieces with the shock loading, while the pioneer dam itself remained in place.

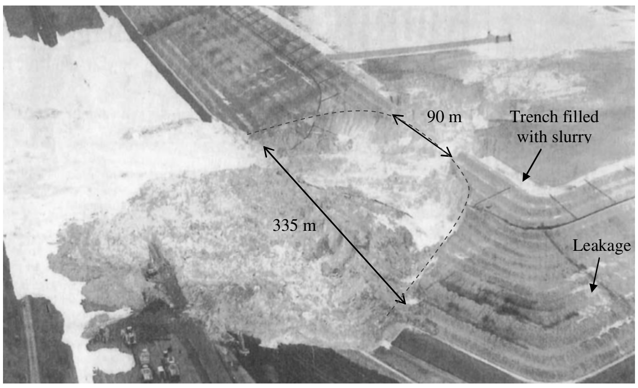


Figure 2 – Aerial photograph of failure

The "breach" opened by the initial slope failure permitted a progressive loss of material deep into the tailings deposit. It is conjectured that blocks of white tailings material (several meters high) would slide or topple, and break into smaller pieces of material which could "flow" down-slope on lubricated interfaces and surfaces caused by remoulding. Deep cracking within the tailings material, as observed in the intact material remaining, would permit such a toppling failure of blocks. After significant remoulding in such a flow slide, the tailings material becomes closer to a liquid than a solid. This type of mechanism would generate a flow of tailings material that could escape through the dam opening and flow out to the adjacent road, as shown in Figure 2. The eventual movement and flow of the tailings material appears to have been a consequence of the initial slope failure, rather than a cause of the failure.

3.2 *Initial shape of slip surface*

The initial slip failure was confined to the slope of the dam itself, rather than extending behind the dam crest. The shape of the initial failure mechanism is illustrated by the red dotted line on Figure 2. The failure mechanism is about 335m wide at the toe and 90m wide at the crest of the dam.

A cross-section of the initial failure mechanism is shown in Figure 3. The slip surface is composed of a vertical segment of about 3.5m and another segment inclined at about 40-50° from the horizontal. The vertical segment is likely to be due to tension cracks that developed before the failure occurred.

The base of the failure mechanism was hidden by the flow of liquefied tailings that took place following the initial failure, but this was investigated by trial pits and cone penetration tests, as well as simple excavation of the slide material. A clear junction was found between disturbed and undisturbed tailings material, and this slip surface was substantially horizontal and located within the tailings just above the natural terrain.

The Pioneer Dam remained in place and was not part of the initial failure. This implies that the failure surface did not follow the natural soil all the way to the toe of the slope but rose up to avoid the (relatively strong) Pioneer Dam.

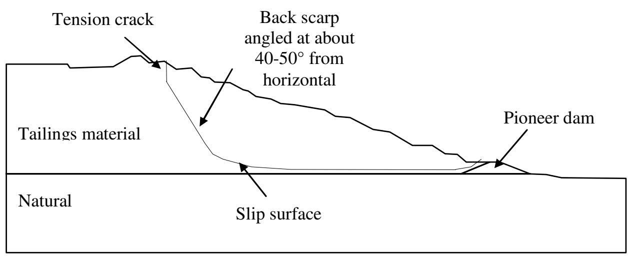


Figure 3 – Schematic view the initial slip surface

3.3 *Water conditions*

The groundwater level and pore water pressure at the time of failure are likely to have been a significant factor in the failure. Unfortunately the water pressure in the slope close to the failure was not monitored by instrumentation, so there is little quantitative data on the water pressure.

On the remaining scarp at the back of the failure (intact tailings) there are clear traces of water that has flowed out of the tailings at about 3.5m from the top of the tailings. This might correspond to the maximum position of the water level at the time of failure at the back of the slip surface.

4 GEOTECHNICAL PROPERTIES OF THE TAILINGS MATERIAL

4.1 *Basic indentification*

The intact tailings material has a high water content of about 200 to 270%. The bulk unit weight increases slightly with depth in a range of about 11 to 13kN/m³, with an average of 12kN/m³. The corresponding dry density of the material is very low, between 3 and 4.5 kN/m³, and the specific gravity of the particles is comparable to that of natural soil at about 2.65.

The tailings material has a plastic limit around 95% and a liquid limit around 165%, and plasticity index about 70%. Such values plot below the "A-line" in a plasticity chart, in the region designated as "silt of extremely high plasticity". The liquid limit of the tailings material is above the normal range for most natural soils.

The natural water content of the tailings material is higher than the liquid limit giving a liquidity index greater than unity. Indeed the liquidity index is typically of the order of 2. Soils with a liquidity index greater than unity are usually regarded as sensitive soils, and contain more water than normal for the given state of consolidation. Once disturbed, such a material could move relatively rapidly towards a more stable state, with expulsion of excess water.

4.2 *Drained shear strength*

A strong horizontal layering was apparent in the intact tailings material exposed by the slope failure. Many planar discontinuities can be observed in the material, both in broadly horizontal and vertical orientations, as illustrated in Figure 4. This tendency for the material to "break" or "cleave" on well defined planes and surfaces is likely to be a result of the deposition process used for the tailings, or it may be an intrinsic characteristic of the tailings material itself. This structure would suggest possibly anisotropic shear strength conditions. A lower shearing resistance on near horizontal planes through the tailings would also be consistent with preferential sliding along a bedding plane.

By analogy with fissured clay, it should be expected that the tailings material might have an "intact" shear strength, and a lower shear strength applicable for shearing on a fissure or horizontal bedding plane. Taking the analogy further, the main difference between the two shear strength values might be a "cohesive" component of shearing resistance present in the intact material and largely absent along a fissure or bedding plane.

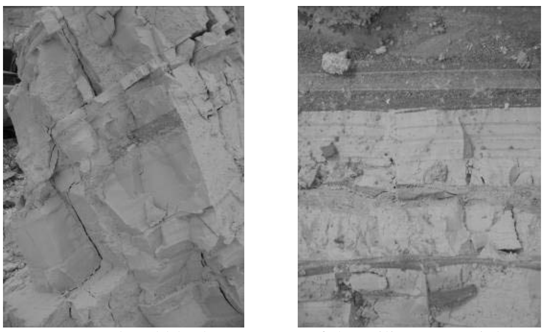
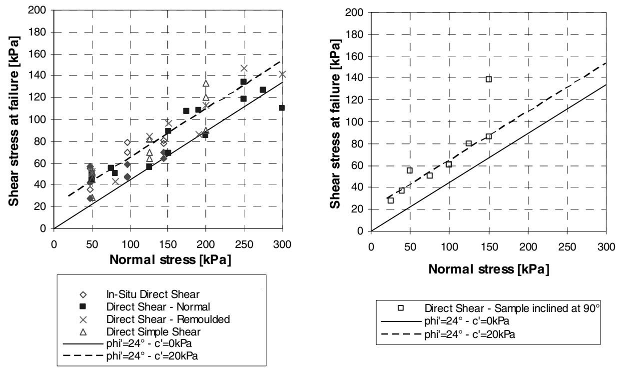


Figure 4 – Layered and blocky structure of the tailings material

The field and laboratory testing program for the site investigation was selected to try to identify the shearing resistance that might exist on the planes of discontinuity. Among the different tests performed to measure shearing resistance were large scale in-situ direct shear tests (0.5m x 0.5m), laboratory direct shear tests and laboratory direct simple shear tests.

For the relevant range of effective stress investigated (predominantly less than 200kPa), a shear strength envelope defined by a friction angle ϕ'=24° and a cohesion c'=0kPa was found to provide a lower estimate to the measured peak strength, as shown on Figure 5a. This may be considered applicable for shearing along fissures or discontinuities. An additional cohesive component of shear strength is applicable for shear through intact material, and may be represented by a simplified shear strength envelope with a friction angle ϕ'=24° and a cohesion c'=20kPa, as also shown on Figure 5a. At low effective stresses a tension crack is assumed to form at the crest of the slope.

A number of direct shear tests was completed on samples rotated by 90° to represent shearing on inclined surfaces through the tailings, across the natural stratification of the material. The data from these tests are plotted on Figure 5b and correspond quite well with the shear strength envelope assumed for the intact tailings material, Figure 5a.



a)shearing parallel to bedding planes b) shearing across bedding planes

Figure 5 – Drained shear strength measured in various types of tests

4.3 *Permeability*

Standard permeability tests performed in the laboratory may underestimate the field permeability because they are performed on small samples that do not include macro features such as fissures, drainage layers and shrinking cracks. An in-situ permeability test (well pumping test) was therefore performed to analyze the effect of these features and measure a representative permeability for the tailings material. The permeability measured in-situ (k_h~2.10^{-7}m/s) was observed to be about 40 times higher than the one measured in the laboratory (k_h~5.10^{-9}m/s) in standard permeability tests. This difference is expected to have been even higher at the time of the failure when the production just restarted after a period of consolidation and drying. At this time, the tailings material is extremely fissured with deep tension cracks.

5 PERMEABILITY OF FOUNDATION SOIL

There appears to be some form of chemical reaction (Calcite deposition) between the tailings material and the natural soil, resulting in a cemented and relatively low permeable layer at the top of the foundation soil (where this was observed to occur). This hard "crust" formed on top of the natural terrain and around the drainage pipes, makes unlikely that the drainage pipes buried 1m below ground level would have operated effectively. Permeability tests were performed on samples of the "crust" (or hardpan) and permeability of about 10^{-9} m/s was measured. An investigation by electron microscope showed calcite deposition within the soil voids.

6 BACK-ANALYSIS OF FAILURE

A slope failure can provide useful and direct data on material and slope behaviour, and improve the knowledge and understanding of slope stability in the field. Because the slope has actually failed, a factor of safety of one should be computed in the back-analysis for stability at the point of failure. Using this knowledge, combined with the data and knowledge of the properties of the tailings material and the foundation soils, and taking into account the physical evidence of the location and shape of the triggering failure mechanism, it should be possible to "calibrate" the stability analysis with a relatively high degree of confidence.

A set of parameters was found for the slope failure at Bernburg that provides: (1) a good match between the observed and back-calculated failure mechanism, (2) a good match with the measured properties of the tailings material and the foundation soils, and (3) a safety factor close to unity in the back-analysis of the slope failure.

A drained analysis was considered most relevant for the initial slope failure because: (1) the dam was raised sufficiently slowly to ensure full dissipation of excess pore pressures, and (2) there has been no rapid loading event, such as an earthquake, that could have triggered undrained failure.

Steady-state seepage analyses and slope stability analyses were performed using SEEP/W and SLOPE/W (Geostudio, 2004). The main assumptions used in these analyses were the following:

- 3.5m deep tension crack at the crest of the slope,
- Tailings unit weight $\gamma = 12\text{kN/m}^3$,
- Effective shear strength for steeply inclined shearing through the tailings material $c' = 20$ kPa and $\varphi' = 24°$,
- Effective shear strength for predominantly horizontal shear on planes of weakness $c' = 0$ kPa and $\varphi' = 24°$,
- Tailings permeability $k = 2.10^{-7}$m/s, and
- Natural soil composed of 2 layers. The first layer is 1m thick and has a permeability $k = 10^{-9}$ m/s, and the second layer a permeability $k = 10^{-5}$ m/s.

The position of the water level resulting from the steady-state seepage analysis is close and mainly parallel to the dam slope, as shown on Figure 6. This is in line with the observations made on site (i.e. leakage at about mid height of the dam, traces of water at about 3.5m from top of dam).

The slip surface found from stability analysis (assuming the pore water pressures computed from the seepage analysis) captures many observed features of the slope failure. The slip mechanism is illustrated on Figure 6 and the important features include:

- A slip surface within the slope of the dam rather than extending behind the dam crest,
- A steep inclined back-scarp,
- A horizontal plane following the natural soil, and
- A Pioneer Dam that remains in place

Most importantly, the stability analysis indicates a minimum factor of safety close to unity (0.972) for the slope implying limiting equilibrium and expected failure conditions.

If no strength reduction on horizontal planes is considered, with all the other parameters and assumptions unchanged, then the safety factor increases to about 1.7. The most critical failure mechanism is then rather circular and does not look like the deduced failure mechanism.

7 CONCLUSIONS

The main cause of the tailings dam failure was higher than expected pore water pressures in the tailings and lower than expected shear strength in the tailings material along horizontal planes resulting from the sequence of deposition in the tailings dam.

Higher than expected pore water pressures developed in the tailings for the following reasons:

- The in-situ permeability of the tailings material is significantly higher than the permeability measured in standard laboratory tests most likely due to the presence of macro features such as fissures, shrinking cracks and drainage layers,
- Some form of chemical reaction (Calcite deposition) seems to occur between the tailings material or leachate and the natural soil, creating a relatively low-permeability "crust" that acted as a flow barrier and reduced the efficiency of the included drainage system, and
- The sequence of construction with a water filled trench at the crest of the slope provides a damaging source of free water to the slope.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the active support and encouragement by Solvay in both the investigation of the slope failure at Bernburg, and implementation of recommended improvements to the practice of tailings disposal at the site to minimize the risk of any future such failure. Permission to publish details of this investigation so that it may be of benefit to the profession is gratefully acknowledged.

REFERENCES

Alonso E. E. & Gens A. (2006), « Aznalcollar dam failure. Part 1 : Field observations and material properties », Géotechnique 56, No. 3, 165–183.

Duncan J.M. & Wright S.G. (2005), "Soil strength and slope stability", John Wiley & Sons Inc.

GeoStudio (2004), Geotechnical engineering software, GEO-Slope International.

International Commission on Large Dams (1996), "A guide to tailings dams and impoundments – Design, construction, use and rehabilitation".

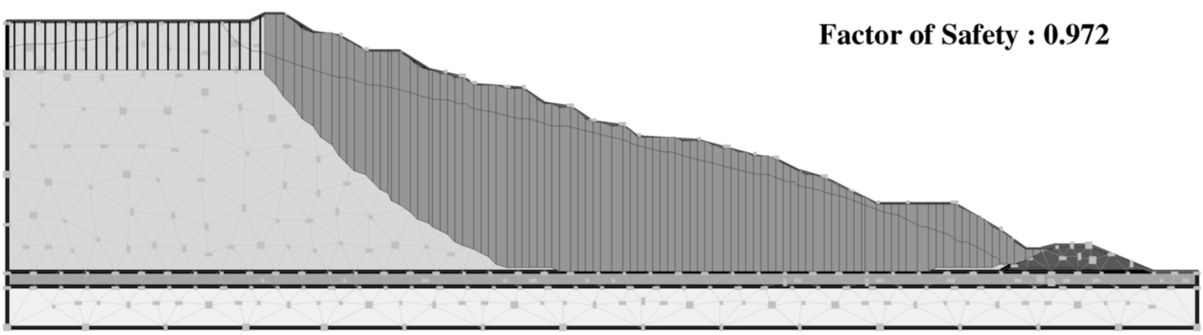


Figure 6 – Failure back-analysis