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Geotechnical Risks Related to Tailings Dam Operations

J.-F. Vanden Berghe[1], J-C. Ballard[1], J-F. Wintgens[1] and B. List[2]

Fugro GeoConsulting, Brussels, Belgium[1], Fugro GeoServices, Calgary, Canada[2]

Abstract

Tailings dams are geotechnical structures that are increased in height with time. Several factors typical of tailings dams cause a higher risk of failure compared with other earth structures. The factors that influence the risk of tailings dam failure are discussed in this paper. Important factors include a high water level in the tailings, dam slope, lack of monitoring, inappropriate site investigation and a lack of understanding of the mechanical behaviour of the tailings material. An approach to mitigate and/or control these risks is then proposed based on appropriate site characterization, design analysis adapted to the tailings characteristics and a sufficient monitoring system that is rigorously used.

Introduction

Tailings dams are common in several chemical and mining industries. This type of geotechnical structure is increased in height with time and can reach heights of more than 30 metres. The main characteristics of tailings dams are the length of construction, which may be spread over 40 to 50 years or more, and the repeated application of new maximum loading conditions. As a result, tailings dams cannot be physically tested under maximum loading conditions and, as such, the risk of slope failure increases with time.

Broadly, 2 to 5 out of the 3,500 tailings dams in the world experience major failures each year (Lemphers, 2010). Two examples of recent tailings dam failures are shown on Figure 1. In both failures, spectacular quantities of tailings material escaped from the breach that opened in the dam resulting in severe consequences.

Tailings dams are more than 10 times more likely to fail than other conventional water retaining dams (Lemphers, 2010). Operating a tailings dam involves risks that need to be identified, quantified and mitigated. The main risks of slope failure are discussed in this paper and a methodology to mitigate these is proposed based on the authors' experience.

(a) Kolontárt Devecseri tailings dam, Hungary (2010)

(b) Bernburg tailings dam, Germany (2007) (Ballard, 2008 and Vanden Berghe, 2009).

Figure 1: Two examples of recent tailings dam failure

Tailings dam construction and operation

A tailings dam is generally a structure containing a pond where the by-products from the mining or chemical industry are disposed. In most cases, the tailings material is delivered hydraulically from the periphery of the dam (Figure 2). The tailings sludge then flows towards the centre of the pond where a water outlet system evacuates decanted water (European Commission, 2009). The level of this outlet is adjusted so that a pond is created, to permit deposition of fine particles. As a result, a high water level is maintained within the containment structure. Water flow is also induced through the containment structure and the foundation soil. An efficient drainage system that prevents the water table from approaching the dam slope is generally essential (ICOLD, 1996). A network of drainage pipes connected to a main collector pipe is often installed at the bottom of the pond to drain the tailings leachate.

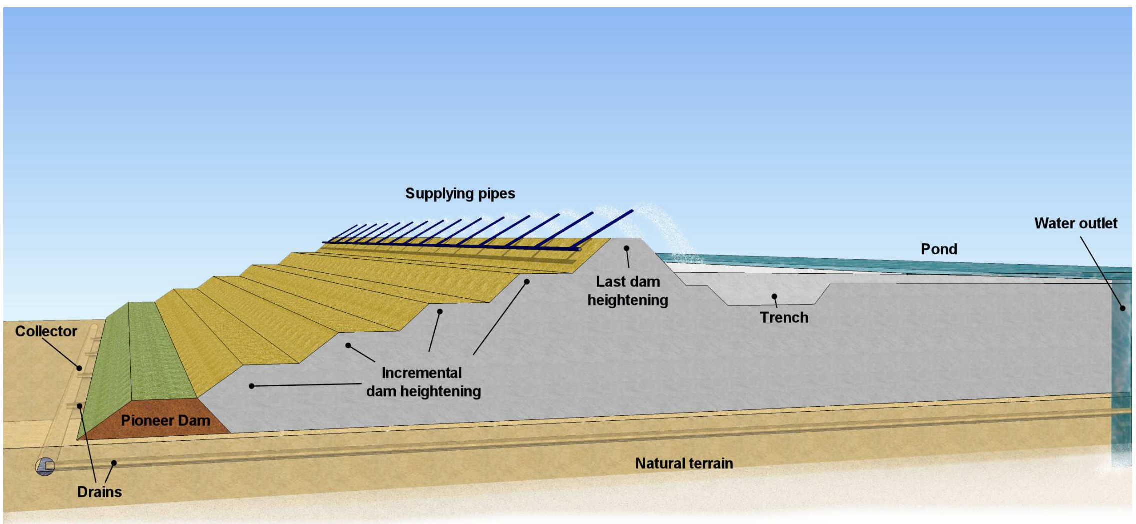
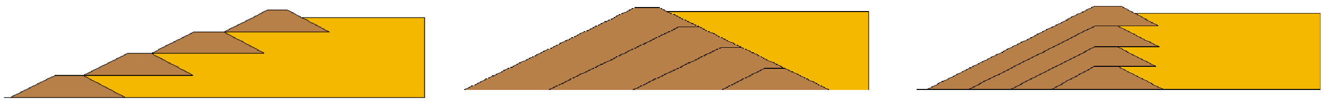


Figure 2: Example of tailings dam profile

The process begins with the construction of a starter dam (Pioneer Dam on Figure 2), which may only be a few metres high. When this initially generated volume is filled, the starter dam is heightened. There are 3 broad types of methods for raising a tailings dam (ICOLD, 1996):

- Upstream method (Figure 3-a): this method consists of building each new levee on the tailings material that has consolidated. The new levee could either use the tailings material itself or an imported material. This approach is the most cost-effective as it maximizes the storage volume and minimizes the volume of imported material. However, it is also the least robust, especially in case of earthquakes, as the tailings material itself is relied upon for stability.
- Downstream method (3-b): this method consists of raising the dam by enlarging the retaining structure. The levees are built with imported material, generally selected for its good drainage and shearing properties. In this case the tailings material does not contribute to the dam stability. This approach is the most robust but also the most expensive in terms of imported material. The storage volume is also reduced.
- Centreline method (3-c): this method consists of increasing the height of the structure with imported material placed on top of the existing dam. This approach is an intermediate approach; one between the upstream and downstream methods.

It is also common to find combinations of these different techniques. The most common combination is to build the lowest part of the dam through downstream or centreline construction and the last raisings using the upstream method.



(a) Upstream **(b) Downstream** **(c) Centreline**

Figure 3: Broad types of methods for raising tailings dams

Tailings dam operation: a risky work?

Tailings dams are subjected to many hazards that directly influence their stability. These hazards need to be properly identified and assessed. This section lists and discusses the main hazards potentially influencing the dam stability. The list is based on the authors' experience and is not meant to be exhaustive. Each identified hazard is located in a risk matrix provided on Figure 4.

- Water retaining dams and embankments are generally built over short periods and are tested under maximum load at the end of construction prior to starting production. Tailings dams are raised slowly. As a result, they experience new maximum loads for which they were never tested on a daily basis. Therefore, the risk of slope failure increases with time as the dam is raised.
- The duration of the tailings dam construction is long and can be spread over more than 40 years. People who started the construction and all their knowledge and experience may not be available at the end of the tailings dam development. The original design and dam history is sometimes also not properly documented.
- Because tailings dams are sometimes existing structures that needs to be raised, design is sometimes modified well into the operational life of the facility, resulting in a final height of the dam well above the initial plan.
- Some tailings dam operators tend to underestimate (geotechnical) risks associated with tailings dams and not to consider them as part of the industrial process with specific risks that need to be controlled.
- Tailings materials are not natural soils and may behave differently. They have a different chemical constituency and experience a different depositional process. As a result, they may develop special properties potentially affecting the performance of the dam. For instance, they may have anisotropic shear strength and permeability properties (Vanden Berghe et al, 2009). An in-depth understanding of the fundamental behaviour of the material and a correct modelling of the key aspects is therefore essential (Chang, 2011).
- Water levels in the dams are generally very high as the product is deposited in a liquid phase. The water flow through the dam generally represents the most critical and most uncertain destabilizing load. During the design of the dam, seepage modelling will impact the risk assessment significantly. Operating procedures are also very important in order to minimize the amount of free water at the crest of the dam.
- The drainage system is an essential part of the design to prevent any pore pressure build-up close the dam slope. The system efficiency may reduce with time for several reasons and needs to be controlled.

- The chemical content of the tailings material is not neutral. Several chemical reactions could occur after deposition with the air, the natural water, added chemicals or the foundation soil. This may lead to an unexpected behaviour of the dam. For instance, undesired chemical reactions may alter the efficiency of the drainage system (Ballard et al, 2008).
- A good monitoring system is very important during operation. An inadequate system will not highlight the potential problems and could lead to the dam failing without warning.
- Tailings dams could be subjected to geohazards such as earthquakes, fault movements, hydrogeological hazards, etc. If not properly addressed because they are not identified or poorly characterized, these hazards could have severe consequences on the dam stability. In the case of earthquakes, the risk of liquefaction or cyclic degradation of the strength of the tailings material is a central question.

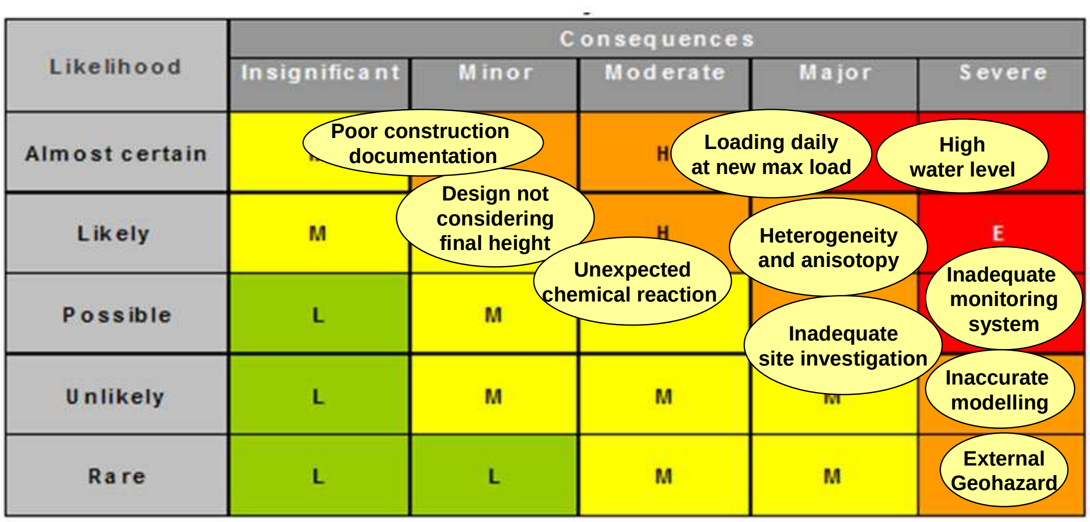


Figure 4: Main risks affecting directly the dam stability

Mitigation of Failure Risks

This section proposes a methodology based on the author's experience on how to mitigate the risks of tailings dam failures based on data collection, analysis, proper design and monitoring. This experience was mainly built on studies performed of several existing European tailings dams used to store waste product coming from the chemical production. More details can be found in Ballard (2008).

Data collection/analysis

The determination of the most critical slope failure mechanism is a fundamental step in the risk analysis and the determination of mitigation measures.

Each risk analysis should start with a preliminary desktop analysis based on available data. The objective is to evaluate the quality and reliability of the available data with regard to the determination of the most critical slope failure mechanisms. Parametric analyses are useful to identify the governing parameters. At this stage, the natural geohazards should also be identified, the most critical of which is earthquakes. Depending on available information, a Probabilistic Seismic Hazard Assessment (PSHA) may be required. This analysis will determine, based on an analysis of past earthquakes, the probability of occurrence of an earthquake of given intensity at the tailings dam location. It will also provide the induced surface accelerations based on the local geology. Other geological risks such as fault (active or not) or karstic dissolutions should be addressed as they can also directly or indirectly influence the dam integrity.

Based on the outcomes of the preliminary desktop analysis and geo-hazard review, an optimized site investigation program should be set up. The objective will be to know the governing parameters with a sufficient level of accuracy. The program will as a minimum include the determination of (1) the geotechnical parameters of the tailings material and the foundation soil which will be directly used in the stability analysis and (2) the intrinsic properties of the tailings material. The second set of data is critical in tailings dam design in order to verify that the tailings material behaves like a soil and that standard soil models can be used for the dam design. In most cases, the behaviour of the tailings material is similar to a natural soil but it may present some specific particularities that need to be taken into account (e.g. anisotropy, high permeability, chemical reactivity, etc.). Special attention should be paid to the chemical interaction of the tailings leachate with the foundation soil and dam material (Ballard, 2008 & Chang, 2011).

The type of tests should be chosen carefully taking into account the particular nature of the tailings material. The main geotechnical tests are discussed in the following sections. These tests are mainly applicable to test existing facilities those stability needs to be reassessed and/or that need to be raised.

Boreholes

Boreholes performed in an existing tailings dam will provide valuable information on the stratigraphy of the tailings and the foundation soil. Samples should be taken for laboratory testing. Since tailings deposits are generally very soft, special attention should be paid to the sampling techniques and handling practices. High quality samplers should be used to minimize disturbance. Ladd et al (2003) provides recommendations for drilling, sampling and handling procedures for very soft soils. Boreholes should reach the foundation soil such that it can also be properly characterized. Chemical reactions of the tailings leachate with the foundation soil may induce a modification of its properties with time. Therefore, re-evaluating those as the dam height increases is important.

In situ testing

Given the generally soft behaviour of the tailings material, a combination of Cone Penetration Test (CPT) and in-situ vane tests is generally very efficient. CPT will provide detailed information on the stratigraphy and the variation of resistance with depth while in-situ vane tests will measure the tailings undrained shear strength at specific locations. These tests have the advantage of being reasonably quick and both types of tests can be performed with the same testing rig. Unfortunately, CPT and vane tests will not provide precise information on the drained shear resistance of the soil/tailings and its potential anisotropy.

More specific in-situ tests are sometimes required to test larger volume of tailings material. The tailings material sometimes presents a blocky, fissured or highly layered structure (Alonso, 2006). In this type of structured material, the macroscopic behaviour may differ from the behaviour observed in small element tests. Large scale shear box tests, pumping tests and vertical loading tests are useful tests to determine the in-situ drained shear resistance, the mass permeability and the in-situ stiffness, respectively (Ballard, 2008).

Laboratory testing

Two types of laboratory testing are generally required: characterization tests and shear strength tests. The characterization tests include unit weight, water content, particle size distribution, Atterberg limits, chemical content and micro structure analysis. Even if all the results from these tests are not directly used for the stability analyses, they are essential for drawing parallels with natural soil and identifying special features. The drained and undrained shear strength of the tailings material, the foundation soil and the dam body can be determined using classical direct shear tests, direct simple shear tests and triaxial tests. Since the in-situ testing generally gives a more reliable measurement of the undrained shear strength, laboratory testing should focus on the measurement of the effective stress parameters.

Due to the depositional process by sedimentation, tailings material may exhibit an anisotropic behaviour with a lower shear resistance along horizontal planes. In this case, direct and simple shear tests are preferred to triaxial tests. A design based only on triaxial test results may be un-conservative (Ballard, 2008).

As previously discussed, tailings materials are generally very soft and samples should be prepared carefully and tests executed with special caution. Recommendations for sample preparation in very soft soil are provided in Ladd et al (2003). The sample should be extruded from the sampling tube directly in the testing devices with a minimum of manipulation. X-ray of the sample tubes should also be performed to visualize the sample quality and determine the best part of the sample for testing.

Design

Design is the backbone of the entire risk management system of tailings dams. It allows the quantification of the risk level and is the link between the different elements that enter into the analysis. From the Author's experience, three aspects are particular to tailings dams and need to be carefully addressed as examined in the following sections.

Selection of adequate safety factors

Given the consequences of a tailings dam failure and the uncertainties related to the fact that the material is not a natural soil, higher safety factors should be adopted for tailings dams than for standard earth slopes (Duncan, 2005). The adopted safety factors should comply with codes of practice but should also incorporate the limitations of these codes regarding the particular case of tailings dam stability. For example, the most recent codes proposing a partial safety factor approach do not request explicitly the application of a partial factor on the pore water pressure although it is often the main (and the most unpredictable) destabilising load for a tailings dam.

It is proposed to design the dam for a global safety factor in drained condition of at least 1.5 and authorize lower values only if a very efficient and proved monitoring and management system is in place. The safety factor should never be lower than the applicable standard. For the Eurocode and the DIN Standard, the equivalent minimum global safety factor is 1.25 in drained condition. A comparison of the safety factors used in Europe (EU commission, 2009) indicates similar values.

Calculation method compatible with failure mode

The traditional Bishop approach (Bishop, 1955) assuming a circular slip surface to compute the slope safety factor may not be appropriate in all cases. For instance, in the case of anisotropic shear strength properties, as sometimes observed in tailings dams due the depositional process, the most critical failure mechanism is not a circular one. Commercial software programs are available to check the factor of safety for non-circular mechanisms.

Drained versus un-drained analysis

The raising of a tailings dam is generally completed sufficiently slowly to allow pore water pressure dissipation to occur. Therefore, the calculations should focus mainly on effective stress analyses (c', ϕ'). However, undrained failure in fine-grained sediments can be triggered by a quick external loading such as an earthquake. In this case, the main question to answer is whether or not the tailings material is susceptible to liquefaction or cyclic degradation.

Monitoring

Monitoring comes naturally from the risk analysis discussed above. Stability analyses of the dam determine the most critical failure modes and the governing parameters. Depending on how confident we are about these parameters, the monitoring provides a continuous control and defines action plans in case increased risks are detected.

Monitoring strategy

Any monitoring needs to be based on a monitoring strategy: what do we want to monitor and why? The quality of the monitoring strategy will determine the quality of the entire monitoring system.

The main risk that could compromise the tailings dam stability in a drained condition is generally a water level that is too close to the slope surface. If the water level exceeds a certain limit, the dam is likely to fail. This risk increases as the dam height increases and the water level is difficult to predict in advance. The other parameters directly influencing the slope safety factor are the shear strength and the unit weight of the tailings, the dam body and the foundation soil. If the site investigation program is properly defined, these parameters should be known with a sufficient level of confidence.

In many cases, slope failures are preceded by a series of anomalies that, if detected and well interpreted, could presage the incident. These anomalies are generally the apparition of tension cracks and accelerating displacements. These could be monitored by a regular visual inspection of the dam and by measuring the dam displacements. The difficult task will be to differentiate critical situations from normal ones.

A monitoring plan has no value without alarms levels and action plans. For each monitoring location, different levels of alarm should be defined. With each alarm level, a clear and simple action plan should be defined. For example, alarms levels on the measured water level could be linked to the associated factor of safety (FS) as illustrated in the table below.

Table 1: Example of alarm levels and corresponding actions for water level monitoring

FS range	Alarm level	Corresponding action
FS > 1.5	No alarm	➔ Continue production
1.5 > SF > 1.25	Alarm 1	➔ Change/adjust deposition location ➔ Increase measurement frequency ➔ Measure closely dam displacements
FS < 1.25	Alarm 2	➔ Stop production in this pond ➔ Measure closely dam displacements ➔ Reassess stability based on actual measurements

To summarize, a monitoring strategy should include:

- Stability analysis with a discussion on the key parameters.
- A list of the most critical failure modes and the parameters to monitor.

- A monitoring plan with the measurement locations, the monitoring equipment, the measurement frequencies, the data treatment and transfer.
- Alarm levels and associated action plans.
- Follow up plan including reporting and back-analysis to maintain the vigilance and increase the knowledge level.

The monitoring strategy should also be well documented with a good report control system such that the monitoring system can be maintained in the long-term, including after the decommissioning of the pond.

Monitoring operations

As discussed above, monitoring of tailings dam is generally based on:

- Visual inspections
- Observations of the water level
- Measurements of slope displacements (at the surface as well as at depth with inclinometers)

Visual inspection

The visual inspection should be conducted by an experienced operator on a regular basis. The inspection frequency varies from site to site based on dam height, production type and dam structure. The inspection should mainly focus on cracks, sources of liquid and abnormal behaviours but any other anomaly should also be reported. Generally, the main difficulty of the visual inspection is with the treatment of the observations. It is generally difficult to define simple and clear alarm levels. The operator reporting the anomaly generally does not have the background to assess the gravity and the associated risks. Therefore, it is crucial to set up an excellent reporting system that guarantees that the information is communicated to the person who can assess the risks and take the required actions.

Measurement of the water level

Monitoring the water level aims at controlling one of the most critical triggers of drained slope failure. Therefore, it plays an important role in the management of the pond and the planning of the production. Two types of equipment are generally used: standpipes and piezometers. Standpipes have the advantage of averaging the water level on a large volume. It can also easily be controlled and inspected. The measurement is normally performed manually but the standpipes can easily be equipped with automatic pressure transducers.

Control and inspection of the equipment on a regular basis is very important. Standpipes can be tested regularly by infiltration/pumping tests. This should guarantee that the water/tailings fluid can freely flow towards the instrument. Inspection is especially important for equipment installed in tailings material at risk of chemical reactions through the tailings fluid, the drainage system of the standpipe and where the air in the standpipe is relatively high. These reactions can sometimes clog the perforated sections of the standpipe. Water monitoring is, unlike the other mentioned monitoring operations, a real risk prevention measure. Alarm levels are commonly reached before deformation or damage occurs.

Measurement of the displacements

The objective of monitoring the displacement is to follow the dam reaction to the continuous loading. Deformations are normal and thus the difficulty of the monitoring is to distinguish a normal deformation from a critical one. There are two types of measurement methods: the surface displacement measurement and the measurement of the dam body displacement.

(1) Surface displacement

Surface displacements can be measured manually by a surveyor equipped with a GPS type of system. There are also continuous dam surface measurement tools such as the InSAR technique. InSAR is based on an interferometric technique that provides data on object displacement by comparing phase in-formation, captured at different times, of reflected waves from the object. Data acquisition could be based on satellite images or ground-based installations that follow the displacement of reflectors installed on the dam. Accuracy is in the order of millimetres. The main difficulty for this type of monitoring is to determine alarm levels and acceptable displacements. In practice, it is not possible to define acceptable total displacements. The alarm level should be based on the displacement rate. An acceleration of the displacement may indicate an imminent risk of failure. Mitigation measures and a rapid action plan should be prepared and tested for such occurrences.

(2) Inclinometer

Inclinometers are the preferred equipment to detect slope displacements. These instruments have the advantage of measuring the distribution of displacement with depth. Simple data processing allows deducing the cumulative shear strain at any depth (Figure 5). The maximum shear resistance for most of the soils and tailings materials is mobilized for a shear strain of the order of 10%. The measured cumulative shear strain should therefore be compared with this value to give an idea of the failure risk. The main limitation of this method is that the installation of the inclinometer can be performed only when the dam has reached a certain height. Therefore, the measured zero shear strain (measured when the inclinometer is installed) is not the actual zero as the dam has already deformed. For this reason, it is strongly recommended to install the inclinometer as soon as it is permitted by the dam height. Considering the uncertainty on the zero value and the required safety factor, it is proposed to define an alarm level for a cumulative shear strain of the order of 1 to 2%. A second alarm level should also be defined on the displacement rate. Any acceleration in the displacement should be analysed carefully. Inclinometers can be measured manually on a regular basis or in the case of an incident they could also be equipped with permanent measurement devices that can be continuously monitored.

Data transmission and treatment

The quality of the monitoring system will strongly depend on how the measured data is treated and transferred. An easy and efficient way is to centralize the measurements in one unique system that could be accessible via a web portal interface (Figure 5). Predefined alarm levels can also be implemented and compared with actual data in real-time. The web interface also permits quick response in the case of an incident as all the different parties involved in the process have immediate access to the data.

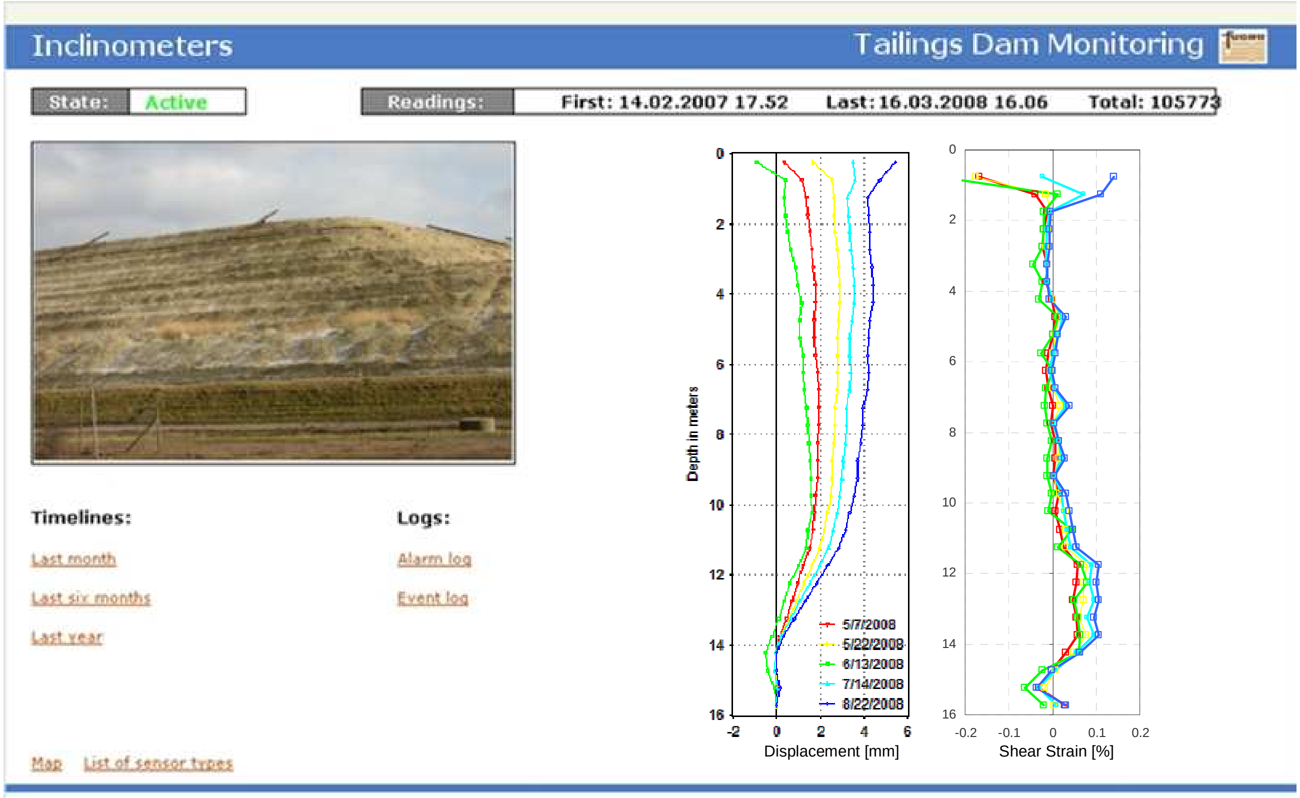


Figure 5: Example of Web portal interface with inclinometer measurement data

Conclusions

Tailings dams are industrial structures having their own particularities. They are life structures that are continuously loaded to the maximum load. Some displacements are thus normal. Often, tailings material is highly heterogeneous and may present anisotropic properties.

There are many factors that could influence the dam stability and the risk of failure. An approach based on a good data collection system, appropriate design and an efficient monitoring system was proposed. Monitoring is a key tool in this process and should be based on a clear and simple monitoring strategy that defines the risks to be monitored, the alarm levels and the associated actions to be taken in the event of a problem. The monitoring needs to be reliable in the long term and the instruments regularly inspected and controlled. On a regular basis, monitoring data also needs to be back-analyzed in order to check the design assumptions and to define the future heightening strategy.

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