1. INTRODUCTION

In mining industry, the most fine-grained residues normally referred as tailings, need to be managed in safe, environmentally and economically manner. This can be handled by impoundments, normally surrounded by tailings dams.

Tailings dams can be constructed in various ways, all depending on the mining- and site conditions. They differ from traditional water retention dams as there is continuous deposition of material in the impoundment, leading to non-static conditions. Since the impoundment level is raised, the dams need to be raised as well.

(*) Utilisation de la modélisation numérique pour la mise en place de niveaux d’alerte lors de l’instrumentation des digues de bassins de résidus miniers stériles.
The safety of dams (in terms of slope stability), can be estimated either by limit equilibrium methods or by numerical modeling (for example finite element methods) [1]. In order to maintain stability for this type of constructions, there are numerous guidelines and literature dealing with the subject, c.f. [2], [3], [4].

Methods for dam surveillance and monitoring of dam behavior are for stability aspects proposed in many guidelines [2], [3], [5]. Benefits of using instrumentation in the geotechnical field are described by Dunnicliff [6], who highlights the need for prediction of soil behavior before installing instruments. Without anticipated values, no abnormalities will be recognized from the field data.

There are different reasons for field monitoring. An often used approach is to evaluate measurements from instrumentation in terms of trends. Measurements can then be used to notice changes with time that may indicate dam safety risks [7]. Based on deformation records, warning criteria can be established in different ways, e.g. by deformation rates [8].

Another approach is to use instrumentation data for soil parameter determination (back-analyses) c.f. [9], [10], [11]. This can be used in observational methods [11] or in cases where future deformations are to be estimated [10].

Deformation monitoring in field, can be used for indication of large movements and strains, thus indicating near failure conditions (slip surfaces). These failure volumes can then be evaluated in terms of safety by e.g. limit equilibrium methods [12], [13]. A drawback with the limit equilibrium method is that there will be no information about the deformations at a certain degree of safety.

Cases where numerical modeling are used in order to estimate deformations for geotechnical activities, such as retaining structures or consolidation settlements are presented in [14] and [15] respectively. This methodology is not applicable for embankment dams nor tailings dams, and the interpretation of field measurements are therefore hard since there are limited available reference values (predictions) for comparison. Neither can measured data be used to validate the dam’s stability.

This paper presents a case where numerical modeling (finite element method) has been used in order estimate deformations and pore water pressures that can prevail in a dam for a certain degree of safety. A method for determining early warning (alert) levels for measured parameters from instruments is proposed. The methodology is in accordance with Dunnicliff [6] who used the three colors green, yellow and red warning levels.
2. AITIK TAILINGS DAM

Aitik mine is an open pit copper mine owned by Boliden AB, and located outside Gällivare in northern Sweden. The annual production rate is approx. 36 Mtonnes, and after mineral extraction more than 99 percent of the material is considered as waste which is hydraulically transported to the tailings impoundment. The tailings impoundment has been in use since 1968 [16], and is surrounded by topography and four dams: dam A-B (with extension dam A-B2), dam C-D, dam G-H and dam E-F (with extension dam E-F2), see Fig. 1. The impoundment covers an area of approx. 13 km², and the tailings are deposited by the spigot method [17] from the dam crests. The dams are raised in the upstream direction by 2.5-3 m/year [18]. A cross-section of dam E-F dam is presented in Fig. 2.

![Fig. 1](image1.png)

**Fig. 1**
Layout view of Aitik tailings impoundment and dams (red line indicates the cross-section presented in Fig. 2)

*Disposition des digues de stériles du bassin d'accumulation de résidus miniers de la mine d'Aitik (la ligne rouge indique la section transversale présentée dans la Fig. 2)*

![Fig. 2](image2.png)

**Fig. 2**
Cross-section of dam E-F (year 2013)

*Section transversale de la digue E-F (en 2013)*
In the Aitik dams, different instruments are used for dam surveillance, such as standpipes, piezometers and inclinometers. According to Swedish dam safety guidelines [2], the level of surveillance is basically dependent of the consequence class (dams are classified into four consequence classes, i.e. 1+, 1, 2 and 3). Class 1+ represents dams with most serious consequences and 3 the least serious consequences. The dam studied in this paper (dam E-F) is classified as consequence class 1.

Up until today, monitoring data have mainly been evaluated in terms of changes with time, and is according to the authors the most common method when it comes to dam surveillance. Evaluating in terms of measured changes with time is a good method to get indications of sudden changes in the dam body. However, it cannot tell whether constant changes are in the serviceability state or not. Due to the continuous raise of the dam embankments and impoundment level, normal deformations in the serviceability state (that do not affect the stability negatively) are not easy to estimate. Predictions with the help of more sophistical methods by using numerical models are therefore needed.

3. FINITE ELEMENT MODELING

Previous stability analyses for the dams in Aitik, have been performed by both limit equilibrium analyses [19] and by finite element modeling [20], [21]. In [20] a method for dam strengthening by rockfill embankments on the downstream slope of upstream tailings dams was proposed. By using finite element modeling, the time aspect of the stability for continuous raised constructions can be taken into consideration with staged construction computations. Additionally, the effect of excess pore pressures that might develop during construction is considered in the proposed method in [20].

In 2013, geotechnical investigations were performed in the Aitik tailings dams. Cone penetration tests (CPTu) showed that the tailings in the impoundment are stratified in nearly horizontal layers with both "loose" and "dense" properties [22]. Undisturbed samples of tailings were taken with a thin-walled piston sampler (ø50 mm) and brought to the laboratory at Luleå University of Technology [23].

Based on laboratory results, parameters for the constitutive model “Hardening Soil” were evaluated for the tailings [24]. Hardening Soil has the Mohr-Coulomb failure criteria (described with strength parameters such as cohesion and friction angle), but utilizes additional stiffness parameters in order to simulate soil deformations more accurately than the linear-perfectly plastic Mohr-Coulomb model [25].
A model of a cross-section (dam E-F) was built in PLAXIS 2D, with assumption of plane strain conditions. PLAXIS is a finite element program, developed for the analysis of deformation, stability and groundwater flow in geotechnical engineering [25]. The geometry was based on as-built drawings (history of dam constructions), airborne data surveys (performed every second year, giving history of the impoundment level) and CPTu-results (the tailings stratigraphy in the impoundment). Future dam raises by 3 m per year are planned in the upstream direction. These will be constructed with a downstream slope of 1:6 (V:H) according to Fig. 3.

![Fig. 3](image)

**Fig. 3**

Geometry (cross section dam E-F)

Géometrie (coupe transversale de la digue E-F)

Each geometry region (soil layer) was given material properties obtained in laboratory tests. Tailings materials were simulated with "Hardening Soil" model, and dam materials such as moraine, filters and rockfill support were simulated with Mohr-Coulomb model [26]. All materials were simulated with undrained behavior where computations were performed as effective stress analyses. For these settings effective parameters for stiffness and strength are used as input, which allow excess pore pressures to build up and dissipate during consolidation calculations.

Computations were performed to model the staged constructions. The initial stage chosen was the geometry that prevailed 1992. This year was the first year from where airborne data is available (for the authors). The rate of raise at that time was also low, assuming no occurrence of excess pore pressure in the construction. According to documented history of dam activities between 1992 and 2013, such as embankment constructions, increased impoundment levels and remedial works, stages for these events were created in PLAXIS.

From 2013 and onwards, raisings, beach constructions (increased impoundment level) and resting phases were simulated by using a “standard year”, based on planned events at the dams [18]. The construction of the embankments is assumed to be performed in 15 days, starting at the 15th of August. This is followed by a resting phase of 15 days (representing the time were the embankment has been built but the spigot system still have not been rebuilt). From here a month of deposition (spigotting) is assumed, followed by a new resting phase until the 1st of May the following year. This resting phase represents the time with no spigotting due to risk of freezing. From the 1st of May, three months of deposition is assumed (spigotting), followed by 15 days of rest
and then, again, followed by construction of a new embankment. This “standard year” was used for ten years ahead in order to simulate future behavior of the dam. An illustration of the activities during the year is presented in Fig. 4.

For all stages, the phreatic line was assumed to be located at the ground surface in the tailings impoundment. From the dam crest, the phreatic line was assumed more or less linear down to the starter dike, from which it is horizontal due to downstream water level (clarification pond).

In addition to stresses and strains (deformations), the global factor of safety was computed for every stage of construction. According to Swedish dam safety guidelines [2], the factor of safety should be at least 1.5 under normal conditions. The proposed way of strengthening by [20] was used, where a plan for future need of support was created by adding rockfill berms on the downstream slope of the dams in order to maintain a global factor of safety at 1.5.

By following this rockfill support plan at site, the calculated stability of the dam is maintained for the period of the present study. At the same time, the numerical modeling can, for each construction event, give information about the expected dam behavior. These data was used for determining alert levels for dam instrumentation.

4. ESTIMATED BEHAVIOR AND ALERT LEVELS

The output from the modeling, i.e. results from specific points in the dam where instrumentation is installed, is compared with observed field measurements. In this paper focus is directed to simulated and observed pore water pressures and horizontal deformations.
4.1. PORE WATER PRESSURE

Pore water pressure has a major influence on the dam stability. In Fig. 5, excess pore water pressures and the calculated most probable failure mechanism are presented for a situation just before embankment construction 2015. Comparison can be made with Fig. 6, where the embankment construction 2015 just has been finalized. As can be seen in Fig. 6, excess pore pressure is developing under the added embankment and affects the failure mechanism and the global factor of safety. Before construction of the embankment, the failure mechanism covers the whole dam and has a calculated factor of safety at 1.58. After construction, failure mechanism is influenced by the excess pore pressures concentrated to the upper part of the slope, with a corresponding factor of safety at 1.49. After consolidation and corresponding dissipation of excess pore pressure, the effective stresses are increased and the safety is again increased.

By adding rockfill support according to [20], the safety of the dam is maintained even though excess pore pressures exist. Field measurements of pore water pressure can therefore be used to control the dam’s stability.

Excess pore water can be tolerated in the dam, but should be kept under further surveillance. A proposed alert level is therefore the limit between hydrostatic pore water pressure, based upon the phreatic line at the ground surface, and total water pressure exceeding hydrostatic pressure. Measurement values that exceed this level are said to be in the yellow stage since excess pore water pressures prevail. Values that are lower than this level are said to be in the green stage.

The proposed third alert level is defined as the total pore water pressure computed by the numerical modeling that represents a global factor of safety of 1.5. Measured values that exceed this level are said to be in the red stage as the factor of safety then is below 1.5. A schematic presentation of the alert levels used in Aitik is presented in Fig. 7.

Piezometers that are used for pore pressure monitoring in the studied cross-section are presented in Fig. 8. Simulated pore water pressures at the same locations obtained by the numerical modeling are presented in Fig. 9. The dashed lines represent the yellow alert levels for the instruments, and the continuous lines represent the red alert levels. For the dashed lines, changes are due to changed groundwater level (static) when the impoundment level is raised. Even though the phreatic line in the impoundment is raised for every beach construction stage, there are fluctuations along the slope of the dam. This can be seen in Fig. 9. For the first beach construction stage (15th of September to 15th of October), there is a small decrease, and for the second beach construction stage (1st of May to 31st of July) there is an increase. A graphical explanation for these occurrences is presented in Fig. 10. The continuous lines include excess pore
pressures, which develops during dam construction, and then dissipates with time.

Fig. 5
Before embankment construction 2015. Upper: Excess pore water pressure. Lower: Most probable failure mechanism (factor of safety 1.58)

Avant la construction du remblai 2015. En haut : pression de l'eau interstitielle excessive. En bas : le mécanisme de rupture le plus probable (facteur de sécurité de 1,58)

Fig. 6
After embankment construction 2015. Upper: Excess pore water pressure. Lower: Most probable failure mechanism (factor of safety 1.49)

Après la construction du remblai 2015. En haut : pression de l'eau interstitielle excessive. En bas : mécanisme de rupture le plus probable (facteur de sécurité de 1,49)
Fig. 7
Schematic presentation of alert levels for pore water pressure
*Représentation schématique de niveaux d'alerte de pression d'eau interstitielle*

Fig. 8
Cross section with piezometers (names are according to Boliden AB)
*Section transversale avec piézomètres (dénommés par Boliden AB)*
Fig. 9
Simulated pore water pressure for the used "standard year", season 13/14
(locations of instruments are presented in Fig.8)
Pression de l'eau interstitielle simulée pour « l'année normale » utilisée, saison 13/14 (les emplacements des instruments sont présentés sur la Fig. 8)

Fig. 10
Changes of the phreatic line at different stages. Upper; Before embankment construction. Middle; After beach construction. Lower; Before embankment construction (following year).
4.2. **HORIZONTAL DEFORMATIONS**

While the pore water pressures in the dam can be seen as the *cause* behind possible stability problems, deformations can instead be regarded as the *effect* of possible stability problems [6]. The deformations that are evaluated from inclinometers can therefore be regarded as the result of stress changes in the dam. By monitoring, and comparing with predicted deformations, the measurements give a good indication on how the dam behaves in relation to what have been simulated by changed loading and time. Based on this, conclusions can be drawn regarding the “in situ” dam stability.

The inclinometer used in this study was installed in November 2007. The location is presented in Fig. 11. The bottom of the inclinometer casing is installed 0.5 m below the bedrock surface beneath the tailings impoundment. The casing penetrates 5.5 m of glacial till (underground), 27 m of tailings, 7 m of compacted till and lastly by 1 m of rockfill support. The inclination of the casing with respect to the vertical, have been measured twice a year since the installation. The rockfill support has recently been placed here, meaning no measurements at this elevation to compare the simulations with. From the inclinations along the depth, deformations are evaluated (assuming a fixed position in the bottom). Details about inclinometer evaluation is given in [6].

![Fig. 11](image.png)

Cross section with location of inclinometer casing

*Coupe transversale avec emplacement de boitier d'inclinomètre*

Comparison between evaluated field data (dashed) and simulated deformations for the inclinometer in dam E-F is presented in Fig. 12 (left). From the numerical results obtained by PLAXIS, it is clear that the simulated deformations in the underground is too large, and is most probably due to underestimation of its stiffness (which is described with the Mohr-Coulomb model). By focusing on the tailings only, the underground deformations can be neglected and fitted to the field data-curve just above the underground, see Fig 12 (right). Here, the agreement between field data and numerical results is better but it still overestimates the deformations in the upper part.

According to this principle where underground deformations are neglected, future deformations can be predicted. In Fig. 13, deformations for a year ahead...
are presented. These are the predictions that field data should be compared with in order to validate the stability of the dam.

Fig. 12
Horizontal deformations. Left: field data (dashed) and results from PLAXIS (continuous). Right: field data (dashed) and results from PLAXIS where deformations in the underground are neglected (compensated for installation depth)

Déformations horizontales. À gauche : données de terrain (en pointillés) et résultats de PLAXIS (continu). À droite : données de terrain (en pointillés) et résultats de PLAXIS où les déformations souterraines sont négligées (compensées pour la profondeur de montage)
Fig. 13
Predictions of horizontal deformations
Prévisions des déformations horizontales
5. DISCUSSION

This paper presents a case study where finite element modeling has been performed for estimation of pore water pressures and horizontal deformations in a tailings dam. The estimated values represent a state of the dam behavior, where the stability is described by a global factor of safety at 1.5 calculated by PLAXIS.

Good agreement between field data and numerical results in terms of horizontal deformations has been reached, but it should be noticed that only one inclinometer has been used for the comparison here. Other inclinometers in the dams nearby are recently installed, and do not have any results to compare with. The numerical model seems reliable on describing the dam behavior at this location, and is considered to be used for prediction of future deformations. For better understanding of the dam behavior in situ, and to validate the model used, similar comparisons for other inclinometers in the dams are desirable.

Pore water pressure has a major influence on the dam stability as it affects the effective stresses. It has been shown how the excess pore water pressure effect the stability, which indicates the need of good field monitoring. Monitoring and corresponding evaluation helps the dam owner to relate field behavior to dam stability. From the numerical modeling, alert levels for pore water pressure instruments (piezometers) have been proposed. This is performed by using three levels (green, yellow and red).

The proposed methodology, where finite element modeling is used to relate pore water pressure and deformations to a certain degree of safety, can be used in dam safety operations in general. A benefit with this methodology is that dams can be evaluated in terms of how they should behave, and not only how the normally do behave. Evaluating measurements in terms of changes with time is a good method to indicate sudden changes in dam behavior, but it cannot tell whether constant changes are in the serviceability state or not. According to the authors, there is a lack of methods where field measurements not only are evaluated in terms of changes with time. For some cases constant rate of deformations may be in the serviceability state, not affecting the stability. For other cases, constant rate of change may seem non-problematic, as it may constantly reduce the stability. A better safety evaluation method is to do theoretical simulations first, and then use field measurements to evaluate how the specific in situ value is related to the computed value. With the proposed method, predictions on “normal” behavior can be estimated.

In numerical modeling the results are highly affected by the input. For this study, effort were spent on describing the constitutive behavior for the tailings (relations between stresses and strains), which facilitate the modeling of deformations in the dam. Making this effort for material description is of course desirable. But even for analyses where there is lack of laboratory data, numerical
modeling with a less advanced constitutive model would still give hints about dam behavior, which helps evaluating field data. This is not at all possible with limit equilibrium methods.

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SUMMARY

In dam safety operations for tailings dams, surveillance has an important role as these dams are raised with time. Methods for stability analyses and how to set up monitoring programs are covered in many guidelines. But in order to relate the field data to the stability of dams, measured data need to be compared with expected dam behavior.

Evaluation of field measurements is commonly performed by comparing values with previous data to see changes with time. This method is good for indication of sudden changes, but cannot be used to relate to the dam stability.

With the use of numerical modeling, expected behavior and stability of dams can be simulated and then in situ measurements can be compared and related to the theoretical values. In this paper, a case study is presented where finite element modeling has been used for estimation of pore water pressures and horizontal deformations in Aitik tailings dam in northern Sweden. Estimated values represent a certain degree of safety, so values can be used as alert-levels in monitoring programs. Proposed method can be used in dam safety operations in general.
RÉSUMÉ

Pour les opérations de contrôle de sécurité des digues de bassins d’accumulation de résidus miniers, la surveillance a un rôle important du fait que ces digues sont progressivement surélevées. Les méthodes pour les analyses de stabilité et les instructions pour la mise en place de programmes de surveillance sont définies dans de nombreuses directives. Mais afin de mettre en relation les données de terrain et la stabilité des digues, les données mesurées doivent être comparées avec les prévisions du comportement de la digue.

L’évaluation des mesures de terrain est généralement effectuée en comparant les valeurs mesurées avec les données antérieures pour observer les évolutions temporelles. Cette méthode est appropriée pour l'indication d'un changement soudain, mais ne peut pas être utilisée pour évaluer la stabilité des digues.

Avec l'utilisation de la modélisation numérique, le comportement et la stabilité des digues peuvent être simulés et les mesures in situ peuvent être comparées et associées aux valeurs théoriques. Dans cet article, une étude de cas est présentée où la modélisation par éléments finis a été utilisée pour l’estimation des pressions interstitielles et des déformations horizontales dans les digues du bassin d’accumulation de résidus miniers de la mine d’Aitik dans le nord de la Suède. Les valeurs estimées représentent un certain degré de sécurité, de sorte que les valeurs peuvent être utilisées comme niveaux d’alerte dans les programmes de surveillance. La méthode proposée est générale et peut être utilisée dans les opérations de sécurité des barrages.