Importance of tailings properties for closure

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Abstract
Managing tailings facilities often includes stability and deformation analyses from both short- and long-term perspectives. Behind these analyses, geotechnical theories are applied on the studied material.

Design for closure is often considered to cover a period of 1,000 years, during which time the closed tailings facility should be stable, both physically and environmentally. Since the use of tailings facilities only covers about 100 years back in time, there are still no data on how tailings behave in the long term. In Sweden, correlations to natural formations have been used to predict the long-term stability of tailing dams. Natural formations that have been stable since the latest ice age (approximately 10,000 years ago) are considered good examples of long-term stability. These are mainly formed by glacial till, a natural material that has been subject to erosion, transportation, and sedimentation processes. Tailings material, however, is artificially created and differs in some respects from natural soils.

Recent laboratory work on tailings from one mine in Sweden indicates unexpected behavior during shearing. In direct (simple) shear tests, contractant tendencies were initially observed, but these were followed by a remarkable compression after maximum shear stress was reached. Pore-water pressures were measured correspondingly and indicated an increase parallel to the decreased sample volume. The reasons behind the unexpected deformations after reaching maximum shear stress are not fully understood and explained, but they are assumed to be attributable to particle breakage and rearrangement in the soil skeleton. The geotechnical theories normally used for tailings might therefore need an upgrade to cover the phenomena recent laboratory tests indicate.

This paper discusses possible effects of the observed change of tailings properties with regard to closure of tailings management facilities.

Introduction
Mining operations generate mine waste. Fine-grained mine waste, that is, tailings, have been managed in tailings management facilities (TMFs) for about 100 years. As the long-term perspective considers
design for closure over a period of 1,000 years, there is lack of experience regarding the long-term behavior of tailings.

TMFs are generally surrounded by dams, to which classical geotechnical theories are applied. Bjelkevik (2005) discussed factors for long-term stability of tailings dams. Jantzer (2009) studied natural analogies to dam construction: Naturally formed structures, formed by glacial till during the last ice age, were compared with tailings dams. In Sweden, naturally formed structures have been used to predict long-term stability. It has been concluded that it is basically possible for an embankment dam to withstand a certain hydraulic gradient over long times.

The same conclusions cannot be made for mechanical properties, as the natural formations differ from tailings in terms of particle type, shape, mineralogy, and so on. The mineral extracting processes, that is, mainly crushing and grinding, leaves tailings particles more angular than particles in natural soils (Rodriguez and Edeskär, 2013). This phenomenon is known to influence mechanical properties (Cho et al., 2006). Other differences, like different types of chemicals and additives in the tailings, are also present.

Recent laboratory work on seven samples with a total of 28 direct shear tests on tailings from one site in Sweden indicates unexpected deformations of the soil skeleton during shearing. In the direct shear tests, a constant vertical compression rate was observed after the point of maximum mobilized shear stress. It was also observed that this influenced measured pore water pressure in the samples. If these phenomena are caused by particle breakdown or collapse of the soil skeleton, this could affect dam stability in the long term.

After closure, tailings might be exposed to creep behavior, that is, deformation at constant load. These deformations lead to shearing and deformations in the soil skeleton. Creep is an important factor for securing the long-term stability of tailings facilities, and should therefore be considered.

This paper presents a discussion regarding tailings properties and their potential effects on TMFs after closure.

**Important factors for soil behavior**

**Behavior during shearing**

When shearing soils, two types of deformation are expected, depending on whether the soil skeleton is densely or loosely arranged. For dense soils, dilatancy is probable; that is, after an initial compaction, the volume increases as the shearing progresses. The increased volume results in a looser state of the soil with an increased void space.

Alternatively, for loose soils, contractancy is probable; that is, the volume of the soil decreases as the shearing progresses. For a contractant soil, the volume normally reaches a stable value after initial
compaction with no further volume change. The decrease in volume results in a denser state with reduced void space.

For saturated fine-grained soils, the change in void space has a major influence on the strength of the soil. For contractant material, a reduction of void space results in increased pressure in the water. If the pore water pressure increases, the effective stress decreases accordingly, resulting in reduced shear strength. The phenomenon is opposite in dilatant soils, as the void space increases and suction might be developed in pore water with correspondingly increased strength.

**Particle shape**

Particle shape, size, and angularity all affect the roughness of a shear plane in a soil (Knappett and Craig, 2012). Large and angular particles generally create a rougher shear plane (i.e., higher strength) than small and rounded particles.

The angularity of a soil mainly depends on the erosion and transportation processes to which it has been subjected. Natural soils in Sweden have been exposed to erosion and transportation by glaciers since the last ice age, resulting in relatively rounded particles. Tailings, on the other hand, are man-made materials that are crushed and ground during production processes. This results in highly angular materials. (See Rodriguez and Edeskär, 2013 for image analyses of tailings particle shapes.)

**Laboratory work**

**Methods and materials**

A comprehensive geotechnical investigation was performed in 2013 at a TMF in Sweden. During the investigation, shear tests were performed on undisturbed samples from deposited tailings materials. Seven samples from different positions and depths were used for shear tests in the laboratory. In total, 28 direct shear tests were carried out. The main purpose of these tests was to determine the relevant parameters for the numerical modeling of the dam and its behavior during deposition, drainage, consolidation, and so on. The sampling positions were based on initial CPT test results carried out with the goal of determining the stratigraphy of the deposited material and potentially soft layers, which might influence the stability of the dam bodies. Depths for undisturbed sampling were chosen based on the CPT results. The undisturbed sampling was performed using a thin-wall piston sampler, giving undisturbed samples in cylindrical tubes with a diameter of 50 mm and a length of 170 mm. The chosen sampling locations were regarded to represent different layers in the deposit and especially the loose layers identified by the CPT tests. These layers were regarded to be of central interest for the study. The identified loose layers had a thickness of several meters.
The deposition took place decades ago, and therefore particle size distribution curves were determined for all samples taken. The results are shown in Figure 1, with the border lines for all curves determined. The material is classified as clayey silt with low plasticity according to the Swedish Standard Institute (SIS) (Larsson, 2008).

Direct shear tests were performed on the samples, either as consolidated drained or consolidated undrained tests with a Geonor Direct Shear apparatus. The specimens, being cylindrical with a diameter of 50 mm and a height of 20 mm, were mounted in a steel reinforced rubber membrane with porous filter stones at the lower and upper flat ends of the sample. The filter stones enable drainage during consolidation and drained shearing. After consolidation (for stresses close to in situ effective stresses), the specimens were sheared with a constant rate until a predefined shear displacement was achieved. During the tests, vertical and horizontal stresses, pore water pressure, and sample heights were recorded.

All samples were water saturated from the time of sampling until the laboratory testing. Samples had water content in the range of 15–44%. The bulk density was 1.66 to 2.12 t/m$^3$. Porosity and void ratio were calculated based on particle density and found to be 41.9–58.5% and 0.72–1.41, respectively.

**Results from laboratory work**

All shear tests were performed with a constant deformation rate of $3.1 \times 10^{-4}$ mm/sec. During the tests, unexpected deformations were observed. At the initial stage, the material indicated a hardening behavior (see Figure 2) with a corresponding compaction. During shearing, the sample volume thus decreased,
which was all expected for this loose material. The observed behavior thus indicated a contractant material in line with what was expected.

When the shear stress reached its maximum (and more or less perfect plasticity occurred), the vertical deformations started to increase with a corresponding sample volume reduction. Because of volume reduction, the void space decreased and load was transferred to the pore water with a corresponding increase of pore water pressure even in the drained tests. Results showing these behaviors (from drained tests) are presented in Figures 2 and 3 and are typical for the test series. Clogging of the material and filters probably explains why any pore water pressure at all was observed in the drained tests. Even though the pore water pressure increment is small, the same type of curve was indicated for all drained test. Similar behavior was observed for undrained tests, but in these cases, the pore water pressure rise was larger than that in the drained tests.

**Figure 2: Shear stress and sample height vs. shear strain**

**Figure 3: Pore water pressure and sample height vs. shear strain**
Discussion

The presented laboratory results indicate unexpected deformations during shearing of the samples tested. When shearing a soil with a loosely arranged skeleton, contractancy is expected, where the particles arrange into a denser state and the volume correspondingly decreases. This can be expected for tailings because of their normally loose state. In the presented results, initial compaction was observed as expected in the direct shear tests, but a remarkable volume decrease was initiated at the moment when maximum shear stress was reached. This behavior was unexpected and requires explanation. The authors have long experience with tailings materials but have never observed this phenomenon with tailings from other sites or the same site, even though several similar tests have been carried out.

Hamidi et al. (2011) conducted direct shear tests on natural material with the same grain size as the tailings in this study. They showed the expected behavior during shearing, with approximately the same shear stress behavior as in this study, but the change in vertical deformation took the form of contractant behavior without a sudden change in deformation as in the presented study.

As additional sample volume decrease takes place (after maximum shear stress is reached), the void volume has to decrease. The consequence is that the pore water pressure increases. This phenomenon is confirmed by the increase in pore water pressure as shown in Figure 3. The reasons for this unexpected behavior are not fully understood. Possible reasons might be

- particle breakage;
- re-arrangement of the skeleton due to irregular particle shapes;
- re-arrangement of the skeleton due to particle breakage (combination of the bullets above).

Particle breakage of tailings might be due to micro-joints in the grains, which could be logical, as the material is crushed and ground during the extraction process. A small study, performed in laboratory and based on image analysis of the particles, shows that the tailings particles are very angular as expected. With angular particles, there is risk of breakage due to high contact forces between particles; this is amplified, as the particles in this case are full of micro-joints. Another reason might be brittle rock types that easily crush. It is assumed that brittle rock type is not the only reason for the observed behavior but might be a part of the explanation.

Several processes with erosion, transportation, and sedimentation have taken place in natural geological materials formed during and after the latest ice age. Rounded particles have therefore been formed, and possible micro-joints have already resulted in breakage. This is probably why natural soils reaches a critical state during shearing with no further change in material properties, as in the study by Hamidi et al. (2011). Additional processes such as weathering might also be of importance, but this will not be discussed further here.
Since no critical state was reached during the performed tests, there are still unanswered questions regarding further potential deformations and corresponding further increase in pore water pressures. If the presented behavior were to go on for a long time, the pore water pressure might reach a level at which the effective stresses are too low to provide enough strength to maintain the stable structure. This phenomenon can then be regarded as a type of static liquefaction.

Even though there is no additional loading on the tailings after closure, creep behavior might occur with time. Creep results in shear stresses, and therefore the behavior observed in the performed direct shear tests could show up in the TMF. If drainage conditions are low, and the pore pressure increases, there will therefore be a risk of reaching static liquefaction. In order to understand how tailings behave in the long term, this phenomenon has to be studied in more detail.

If a degradation process of the skeleton prevails, but at a slow rate (long-term perspective), there is a chance that excess pore water pressure could generate at a rate slow enough for dissipation to take place. In this case, the risk of failure due to excess pore pressure is reduced but will still lead to continuous deformations. Settlements or horizontal deformations can, for example, affect the closure of a TMF by affecting the TMF cover, or the drainage layers or filter layers designed to maintain low pore pressures in the embankment. The change of tailings material properties in the long term needs to be considered in the design phase of the TMF.

**Conclusion**

Indications of unexpected deformations during shearing of tailings have been observed in laboratory tests. The observed behavior differs from what would be expected from natural soils. As the study is based on a limited number of tests from one site, further investigations are needed to verify the observed behavior. If the behavior can be shown to be valid for tailings in general, changes to the constitutive relationships used today will have to be implemented in the design of TMFs, including TMF closure, in order to secure their long-term stability.

**References**


