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Permeability Variation Analysis in the Raising Steps of Tailings Deposits

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Abstract. This paper presents the findings of a consolidation test program carried out on mining tailing samples. Using a standard consolidation apparatus, along with head flow tests, it was evaluated the void ratio and permeability variations of the tailings according to the loads imposed by the raising steps into a disposal dam. Two kinds of mining materials were analyzed: gold tailings, which are more granular and do not exhibit plasticity; and bauxite tailings, that are finer and exhibit plasticity. Remolded samples were studied in both cases, as also, one undisturbed sample for the bauxite tailings, obtained through Shelby sampler. Results show the correlation between void ratio variation and permeability, against the load imposed by the raising steps at the dam, evidencing the influence of increasing loads in the reduction of permeability coefficient on the bottom layers. Our findings reveal the importance of permeability variation during the life-cycle of tailing deposits, which should be considered in the development of safer designs.

Keywords. Permeability, mining tailings, dam, raising steps.

1. Introduction

The mining activity is significant for the economy of countries, as an example, such activity was responsible for 5% of Brazil's industrial GNP, in 2014 [1]. However, at the same time technology improves the production of metals and minerals there is an increase of tailings, a fine-grained waste produced during the ore beneficiation process. The big challenge is to find out an efficient and safe method for storing a large amount of tailings resultant from the mining process. Generally, the tailings are produced in a slurry form, and thus, the hydraulic disposal is the most common and less expensive method.

In this hydraulic storage method, tailings are contained by dams made of natural soil, or even by tailings material itself; using one of the three distinct raising steps deposition methods: upstream, centerline, or downstream. This is due to the attractiveness of raising the dam size according to the production demand. The counterpart of hydraulic disposal is that it makes the tailings into the reservoir have a large quantity of water; being thus a fundamental concern for the dam stability under both static and seismic loading conditions [2, 3].

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According to Robertson (2010) [4], flow liquefaction triggered by excesses of pore water pressure is one of the main concerns in the design of mining tailings dams. The liquefaction is the loss of the shear resistance of low plasticity and saturated soils, caused by a sudden excess of pore water pressure triggered by a monotonic or cyclic load. The flow liquefaction is associated with large deformations occurred after liquefaction, spreading material over extensive areas with disastrous damage [5-7]. The nature of mining tailings and the hydraulic disposal create ideal conditions to the occurrence of flow liquefaction phenomenon: the presence of granular particles, low plasticity of tailings, a high degree of saturation and low density. The World Information Service on Energy [8] highlights four mining dam failures at 2018, all of them related to drainage conditions and excess of pore water pressures.

Therefore, one of the base targets in the design of mining tailing dams is to provide an adequate internal drainage system; helping the maintenance of the phreatic water surface into the reservoir and avoiding the excess of pore water pressure that can affect the dam stability. This drainage system can be installed inside or beneath of the reservoir and usually consists of chimney drains and blanket drains. The correct operation of this system depends on factors like permeability, compressibility, grading and density of the tailings [2, 3]. As the raising increases, the tailings material close to the bottom drainage system compresses, and the void ratio reduces. This phenomenon improves the shear strength of the tailings, but on the other hand, it reduces permeability on the internal drainage system vicinity.

Singh et al. (2008) [9] emphasize that most permeability measurements of soil samples are obtained by laboratory tests under no surcharge, as such, the results represent the flow only for the specific void ratio. As the permeability is a function of void ratio, when soils receive different surcharge stages, like raising steps, the permeability reduces as well as the void ratio. These researchers evaluated the permeability of hydraulic fills under surcharge using oedometer tests through permeability readings and found a considerable variation on permeability with the vertical effective stress increase. With the same concern, Xu et al. (2016) [10] analyzed characteristics of tailings permeability considering the chemical and physical clogging of drainage systems. They also correlate the physical clogging with the reduction of the void ratio of tailings near the drainage systems.

This paper focuses on permeability measurements of mining tailing samples at different loading stages. The behavior of two types of tailings (gold and bauxite) is evaluated using a standard consolidation apparatus, along with head flow tests. It is possible to correlate void ratio, permeability, and effective vertical stresses for reconstituted samples with different initial void ratios. In addition, the same correlation is realized using one undisturbed bauxite sample.

2. Experimental Program

The experimental program splits into two parts. First, Section 2.1 presents a characterization of the two investigated tailing materials (i.e., bauxite and gold). Next, Section 2.2 describes the experimental methods, including the details of performed consolidation tests with head flow tests for varied initial void ratio specimens of bauxite and gold mining tailings.

2.1. Materials

The bauxite and gold tailings considered in this study were taken from tailing disposal sites situated in Brazil. Disturbed samples were collected in sufficient amount to complete all tests and one undisturbed bauxite sample was obtained through Shelby sampler. Table 1 presents the physical properties of bauxite and gold tailings. It is possible to observe that the bauxite tailing has smaller grains than the gold tailing and presents plasticity. The bauxite tailing is very sensitive to water content, so the liquid limit (LL) and plastic limit (PL) values are close and the plasticity index (PI) is low. According to USCS classification, from ASTM D 2487 [11], both bauxite and gold tailing were classified as low plasticity silt (ML), even with a large amount of clay-size particles in the bauxite tailings. Probably, the bauxite plasticity is an artificial property that results from chemical elements interactions of the ore beneficiation process.

The mining tailings have high specific gravities because of the presence of metallic ores, including aluminum and gold. The maximum dry unit weight for standard Proctor compaction effort was smaller for bauxite tailing than for gold tailings; moreover, the optimum moisture content was higher for bauxite tailings. This characteristic corroborates with the sensitivity of the bauxite tailings to the presence of water.

Table 1. Physical properties of tailings.

Property	Bauxite Tailing	Gold Tailing
Liquid Limit (LL) (%)	32.2	-
Plastic Limit (PL) (%)	29.9	-
Plastic Index (PI) (%)	2.3	Non-Plastic (NP)
Specific Gravity (G)	2.88	2.86
Fine sand (0.075 mm < diameter < 0.425 mm) (%)	3.7	28
Silt (0.002 mm < diameter < 0.075 mm) (%)	63	71
Clay (diameter < 0.002 mm) (%)	33.3	1
Mean particle diameter, D_{50} (mm)	0.005	0.06
Maximum dry unit weight for standard Proctor compaction effort (kN/m³)	14.2	17.0
Optimum moisture content for standard Proctor compaction effort (%)	32.2	17.0
USCS Class	ML (low plasticity silt)	ML (low plasticity silt)

2.2. Methods

The performed consolidation tests relied on cylindrical specimens with 50 mm in diameter and 20 mm in height. A standard consolidation apparatus was used to the measurements of specimen deformations for different load steps and, at the same time, a graduated burette coupled to consolidation cell allowed to take the specimen permeability. The burette was connected to the specimen from the center of the bottom porous stone into the cell consolidation. By monitoring the water level into the burette over time, it was possible to define the permeability along specimen.

In the case of bauxite tailings, there were conducted four tests, three on reconstituted specimens and one on an undisturbed specimen. For the reconstituted samples, a target void ratio was established for each specimen. These samples were mold at optimum moisture content presented at Table 1, and from these samples, the tested specimens were obtained. Table 2 depicts the properties summary of the tested specimen. Note that the specimen named “Reconstituted 1” has similar properties to the undisturbed specimen, this is for assessing the influence of sample reconstitution on tailings properties definition. With the purpose of evaluating the behavior along loading steps during raising, the other two reconstituted specimens have void ratios smaller than *in situ* conditions (undisturbed sample).

The gold tailings have a large amount of sand particles sized and do not present plasticity (Table 1). Those characteristics makes difficult to extract undisturbed samples, and because of that, most of conducted researches in this material rely on reconstituted samples [11], [12]. Thus, this paper analyses three reconstituted specimens molded at different void ratios. According to previous researches [11], [12] the estimated *in situ* void ratio is 1.2, so one of the specimens was molded with this void ratio, one with a larger void ratio, and one with a smaller void ratio. Table 2 also presents the summary of gold tailing specimens.

Table 2. Properties of tailings specimens.

Tailing	Sample	γ_d (kN/m^3)	e
Bauxite	Undisturbed	13.30	1.21
	Reconstituted 1	13.32	1.20
	Reconstituted 2	13.70	1.10
	Reconstituted 3	14.47	0.99
Gold	Reconstituted 1	12.00	1.50
	Reconstituted 2	13.70	1.20
	Reconstituted 3	14.10	1.15

After molding the specimens, they were taken to the consolidation cell and was saturated. For each load stage the deformations were measured for 24 hours and permeability readings were taken along all test.

3. Results

3.1. Variation of Void Ratio by Loading

Figure 1 shows the variation of void ratio by loading for bauxite mining tailings specimens. The maximum load applied for all specimens was 1600 kN/m^2, which is equivalent to a surcharge that corresponds to a raising of about 90 m, considering a natural specific weight of 18 kN/m^3 for the bauxite tailings, obtained from physical properties of the undisturbed sample.

In general, there is a reduction of void ratio with the increase of load for all the specimens and as the initial void ratio reduces the compressibility of the material also reduce, thus, the difference between the initial and final void ratios become smaller. It is interesting to note that the curves for the reconstituted specimens have a similar shape, only translated according to the initial void ratio value. By comparing the undisturbed specimen curve with the reconstituted specimen curve, using the same physical properties of the undisturbed one, it is possible to observe that the undisturbed specimen curve presents a linearity at the beginning, which can indicate a possible natural slight cementation that was not reproduced in reconstituted sample. The lower void ratio achieved at the end of the loading on undisturbed sample can be related to the heterogeneity of natural tailing and to a possible breakdown of natural cementation.

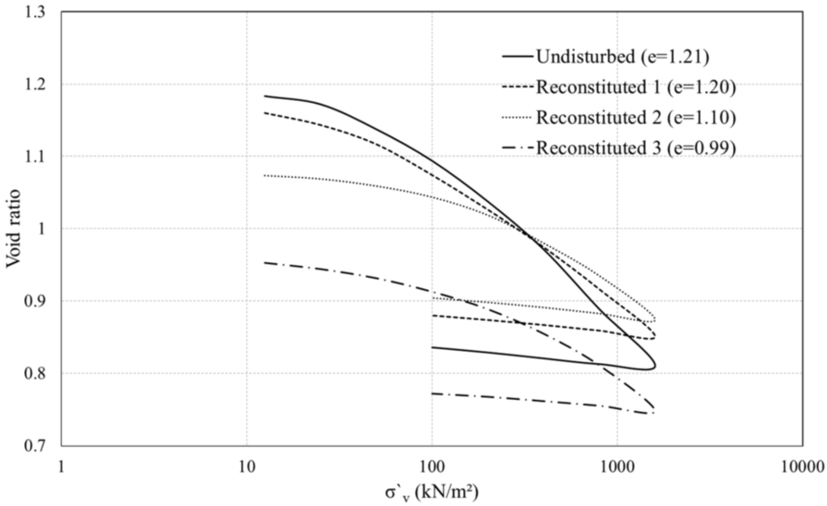

Figure 1. Consolidation curves for bauxite tailing specimens.

Figure 2 shows the void ratio variation of gold mining tailings specimens according to the vertical effective stress. While the maximum load applied for specimens with an initial void ratio equal to 1.5 and 1.2 is of 400 kN/m^2, the specimen with an initial void ratio equal to 1.15 received a maximum load of 1600 kN/m^2. Thus, considering a natural specific weight of 20 kN/m^3 -- as cited by previous researches [11, 12] -- these loads are equivalent to a surcharge of a raising of 20 and 80 m, respectively. Regarding the curves behavior, the measurements show that as the effective stress closes to its maximum, the curves appear to achieve almost the same void ratio. If the maximum load for specimen "Reconstituted 3" was 400 kN/m^2 probably, the final void ratio for all specimens will be very similar. The variation of the void ratio by loading for gold tailing at the space evaluated on Figure 2 appear to be linear, and for the loads analyzed it was not possible to identify crushing of particles.

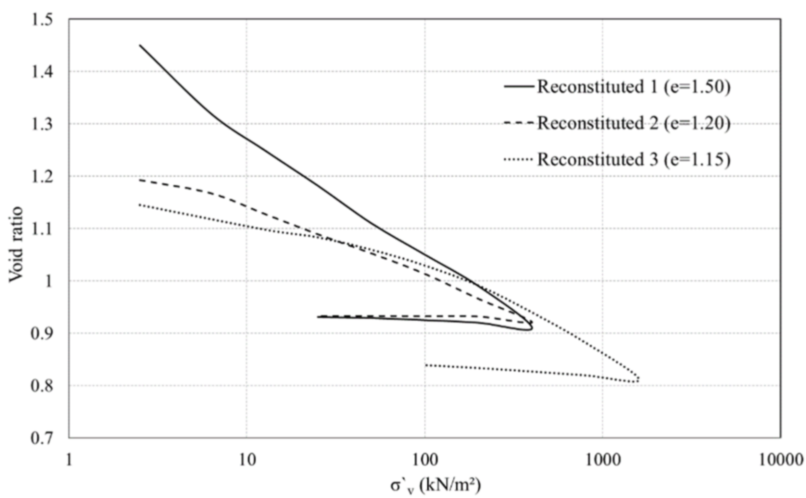

Figure 2. Consolidation curves for gold tailing specimens.

3.2. Variation of permeability by void ratio

Figures 3 and 4 present the variation of permeability coefficient (k) by the void ratio for bauxite and gold mining tailings specimens, respectively. In all the cases, as the load increases, the void ratio decreases consequently reducing the permeability. For the bauxite tailings, the permeability coefficient varies from 10^{-9} m/s, at the beginning of load, to 10^{-10} m/s at the end of loadings. These low values probably are due to a large amount of fine particles present in this material. On the flip side, the gold tailing present permeability coefficient varying from $5x10^{-6}$ m/s, at the beginning of load, to 10^{-7} m/s at the end of loadings. As discussed in Section 2.1, gold tailings are coarser than bauxite tailings, and because of that, this kind of material tend to have higher values for the permeability coefficient.

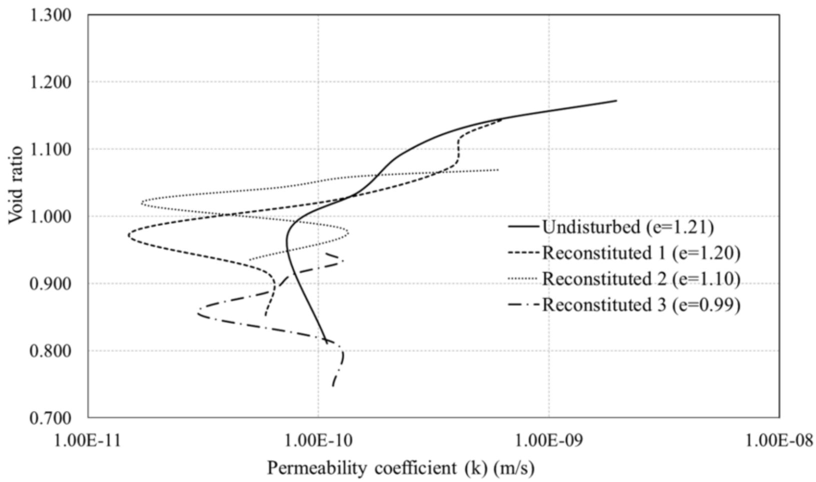

Figure 3. Permeability coefficient *versus* void ratio for bauxite tailing specimens.

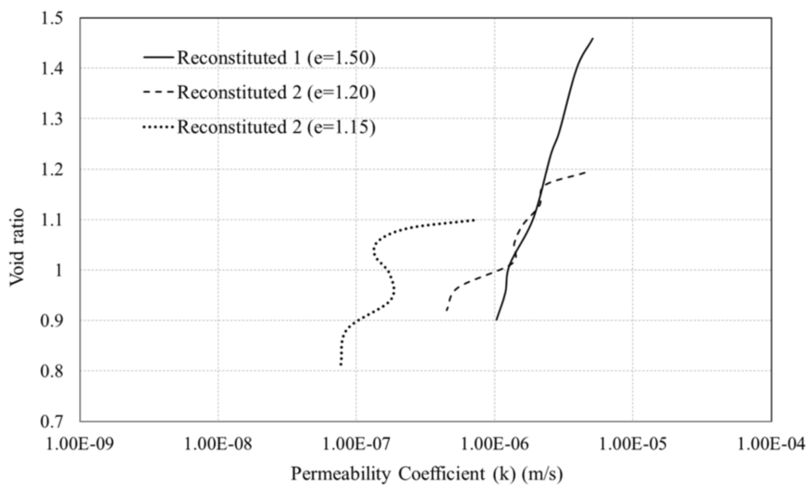

Figure 4. Permeability coefficient *versus* void ratio for gold tailing specimens.

As discussed above, the permeability coefficient at the end of the load is about ten times smaller than the initial permeability coefficient for both the analyzed tailings. This situation indicates that the variation on the permeability during the life-cycle of tailing deposits is very important for safe designs. It is also interesting to note that, for bauxite tailings, the more significant variation on permeability coefficient occurs at the begging, with small variations on the void ratio. For lower void ratios, the permeability coefficient tends to be more stable. Such analysis indicates that even low raising steps can significantly affect the permeability of the tailings at the bottom and, consequently, cause material saturation. For the gold tailings, the initial reduction is less pronounced; however, it is evident that the load imposed by the raising cause a reduction on the permeability capability of the tailings.

4. Conclusions

Considering the presented results, which are limited to evaluate the permeability variation induced by surcharges imposed by raising steps on tailings deposits, the following conclusions arise:

- The consolidation curves for reconstituted bauxite specimens present similar shape, and the curve of the undisturbed specimen indicates possible slight cementation that cannot be reproduced on reconstituted specimens;
- For gold tailings specimens, the void ratio at the end of loading appears to be independent of the initial void ratio and is very similar for all specimens;
- The permeability coefficient for both tailings have a significant reduction when subjected to an increasing load, indicating that raising steps can modify this property considerably and affect deposits stability;
- For bauxite tailings, the larger variation on permeability coefficient was verified for low loadings, which indicates that even small raising can affect the permeability of tailings.
- The variation of permeability coefficient must be evaluated according to the raising steps to develop safe tailings deposits designs, and the permeability coefficients defined to a specific void ratio must be carefully evaluated.

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