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The mechanics of a silt-sized gold tailing

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ABSTRACT

Tailing dam failures result in irreversible environmental impacts and cause fatalities. In recent years the mechanical behaviour of tailing geo-materials has received more attention by the geomechanics and engineering geology communities in an attempt to understand better their behaviour in the light of designing safer tailing dams. In this study, the mechanical behaviour of a gold tailing from Brazil is thoroughly investigated by conducting a series of compression and shearing tests as well as dynamic element tests. Fabric effects from the sample preparation method, the susceptibility to liquefaction and the possibility of any transitional behaviour are presented and discussed within a soil mechanics framework. Comparisons are made between the present gold tailing and previously published data on other tailings, giving a general view of the mechanics of tailings and the effects of grading. The results show that for this tailing the rate of convergence for different initial densities to the normal compression line is slow, and so the depositional density would affect the volume to far higher stresses than the material would be expected to experience in-situ. For this tailing any fabric effects from the sample preparation method were found to be very small to negligible with respect to small-strain behaviour and critical state behaviour. For different tailings, even if the particle sizes may cover a wide range, the susceptibility to static liquefaction, as determined by the location of the horizontal asymptote of the critical state line in the specific volume-log stress plane, shows no consistent variation. So it can be concluded that neither the pond nor the upper beach tailings are more susceptible.

1. Introduction

Tailings are the by-products after the mining processes to extract the valuable fractions from ores. The mineralogies, gradings and particle morphologies of tailings vary a lot due to the different composition of the parent ores as well as the different extraction processes they undergo. The most common method to dispose of the tailings is impounding a slurried material within a tailings dam, usually being built with the coarser disposal products. Due to the relatively small particle size and high water content, tailings materials often have a high risk of failure due to liquefaction, caused by either static or seismic loading. Even when the tailings liquefaction is not directly responsible for the initial failure, it can exacerbate a failure because its loss of strength causes it to apply a large hydrostatic force to the dam (e.g. Gens and Alonso, 2006). If the dam fails catastrophically the runout of the tailings can be fast and fatal (e.g. Chandler and Tosatti, 1995). Between 1912 and 2014 there were > 240 tailings dam incidents (WISE, 2014). The stability performance has therefore concerned many researchers studying the mechanics of tailings/tailing dams (Okusa and Anma, 1980; Fourie et al., 2001; Zandarin et al., 2009; Carrera et al., 2011; Chang et al., 2011; Bedin et al., 2012; Ozer and Bromwell, 2012; Schnaid et al., 2013; Coop, 2015; Zhang et al., 2015).

In this work, detailed laboratory tests were designed to investigate the mechanical behaviour of a silt-sized gold tailing. Comparisons are then made between the present results and reported data in the literature on different tailings to obtain a general view of their behaviour, covering a broader range of mineralogies, particle characteristics and types of tailing materials. The analysis/comparisons are made within a soil mechanics framework. Emphasis is given to the compression and shearing behaviour, static liquefaction, the possible occurrence of transitional behaviour (as defined by e.g. Martins et al., 2001; Altuhafi and Coop, 2011; Xu and Coop, 2016), sample preparation effects as well as their small-strain stiffness/stiffness anisotropy.

2. Materials and procedures

A silt-sized (gold) tailing material, collected from the Fazenda Brasileira disposal plant in Northeast Brazil, was tested in the study in

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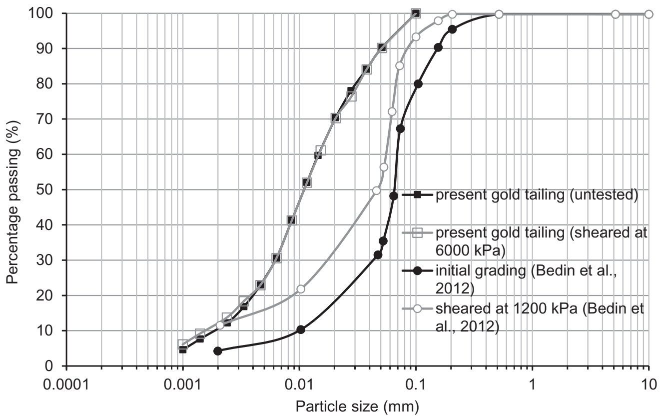

Fig. 1. Particle size distributions of the present and Bedin's gold tailings.

its "natural" or in-situ grading. The grading curve of the soil is given in Fig. 1. The tailing has a fractal grading with fractal dimension D_F of 2.19, obtained using the method proposed by Tyler and Wheatcraft (1992). Fractal gradings can represent a broad range of geological materials often found in nature in terms of grain size distribution (Vallejo, 1996; Hyslip and Vallejo, 1997), and have been reported to have complex behaviour (e.g. Altuhafi and Coop, 2011). In the same figure, the tailing tested by Bedin et al. (2012) and Schnaid et al. (2013) is also given for comparison. The latter comes from the same tailing impoundment but is coarser, which resulted in noticeable particle breakage from the shearing tests reported by Bedin et al. (2012).

The parent ore vein is located within the Rio Itapicurú Greenstone Belt (RIGB). Gold, which is present in a very small percentage, is the benefited ore in the vein, with gangue minerals predominately of quartz, albite, chlorite and sulphides. Ore-dressing, such as crushing and grinding, is done first to expose the beneficial minerals for metallurgical extraction, in which the gold is extracted chemically through a heap leaching system. Several methods for hydraulically placing gold tailings are used: the cyclone system, the spigot system, and even (occasionally) open-end discharge behind the containment wall. The sequence of placement changes continuously using one or other of the downstream, centreline or upstream placement techniques. X-ray diffraction (XRD_D8 Advance) analysis (see Fig. 2), was conducted at the Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. The voltage and current used are 40 kV and 40 mA respectively, and the angular range is between 3° and 70°. The Reference Intensity Ratio (RIR) method was used to determine the mineral composition percentages, which indicates that the major minerals within the tailing are quartz (22.1%), albite (25.0%), chlorite (47.1%), and calcite (5.9%). The present finer gold tailing contains twice the quantity of chlorite

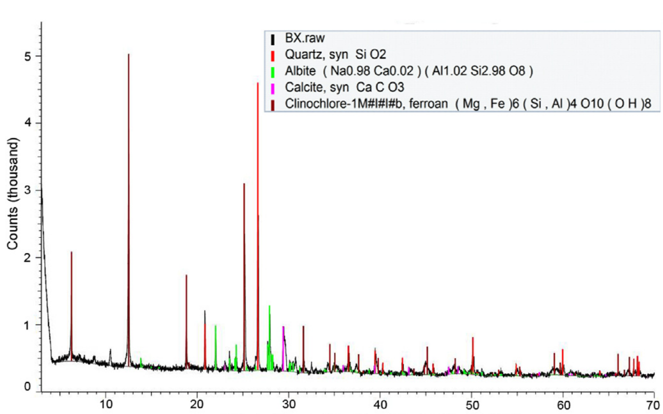

Fig. 2. XRD analysis quantifying the mineral composition of the gold tailing.

Table 1
Characteristics of different types of tailings.

Tailings type	D_{50} (mm)	C_u	C_z	G_s	C_c	φ'_{cs} (°)
Gold (in this study)	0.011	7.3	1.4	2.89	0.30	34.8
Gold (Bedin et al., 2012)	0.065	7.0	2.3	2.89–3.20	0.44	33.0
Gold-UB (Chang et al., 2011)	0.095	24.1	2.2	2.72	0.11	31.1
Gold-MB (Chang et al., 2011)	0.053	10.5	0.8	2.69	0.30	33.6
Gold-PO (Chang et al., 2011)	0.006	2.6	1.6	2.75	0.49	31.5
Copper (Li, 2017)	0.031	5.1	1.5	3.75	0.22	35.2
Iron-UB (Li, 2017)	0.22	10.4	2.6	3.37	0.38	34.6
Iron-MB (Li, 2017)	0.035	10	1.1	3.14	0.32	33.7
Iron-PO (Li, 2017)	0.023	6.7	2.2	3.11	0.19	34.8
Fluorite-sand (Carrera et al., 2011)	0.180	2.5	1.1	2.72	0.19	35.0
Fluorite-9010 (Carrera et al., 2011)	0.169	2.7	0.8	–	0.18	–
Fluorite-7030 (Carrera et al., 2011)	0.125	9.3	1.8	–	0.11	–
Fluorite-5050 (Carrera et al., 2011)	0.075	11.5	1.0	–	0.10	–
Fluorite-3070 (Carrera et al., 2011)	0.044	10.0	1.1	–	0.09	–
Fluorite-silt (Carrera et al., 2011)	0.026	9.7	2.6	2.83	0.10	33.0

Note: D_{50} mean particle size. C_u and C_z coefficient of uniformity and curvature. G_s specific gravity. C_c compression index. φ'_{cs} angle of shearing resistance at critical state. UB, MB and PO tailings taken from the upper beach, middle beach and pond of a tailings dam respectively. 9010 90% sand and 10% fines. 7030, 5050 and 3070 similar with 9010 but different sand and fines contents.

(which belongs to clay-sized minerals) as the coarser one tested by Bedin et al. (2012), but it did not give any plasticity to the soil. Table 1 gives a summary of basic grading characteristics of the present tailing as well as a number of tailings from previous works which were re-analysed and compared with the results of the present study to obtain a general view of the mechanical behaviour of tailings.

A series of oedometer and triaxial tests was conducted on the gold tailing (summarized in Tables 2 and 3) using front loading oedometer frames. The diameters of the rings used were 50 mm and 30 mm, the latter having a floating ring design in order to reduce wall friction (Rocchi and Coop, 2015; Okewale and Coop, 2017), giving resultant maximum vertical stresses of 7 MPa and 20 MPa, respectively. This helped to investigate better the compression behaviour of the soil at greater pressures. The initial specific volumes are the mean values calculated from the measurements of initial weights, dimensions and water contents (for saturated samples) as well as final ones, accounting for the volume changes during the tests (similar to the calculation procedure described by Rocchi and Coop, 2014). For the triaxial tests, most of the samples were tested in a conventional apparatus, with maximum working cell pressure of 700 kPa. A high pressure triaxial with a maximum cell pressure of 7 MPa was also used for a limited number of tests to examine the behaviour over a broader range of pressures. For both apparatus, the sample size was 38 mm in diameter and 76 mm in height. The samples were first saturated with initial flushing using CO_2 to accelerate the process and then they were isotropically compressed and sheared under conventional drained (CID) or undrained (CIU) conditions. Reconstituted samples were used since intact ones were not possible to obtain from this tailing structure. Three different sample preparation methods were adopted to identify any effects of fabric: dry compaction, wet compaction and slurry (details are given in Tables 2 and 3). Even though the intention was to reproduce in-situ states, the construction of samples with different preparation methods gives some more general insights.

A number of samples was also prepared and tested with bender elements inserted in a Bishop and Wesley (1975) apparatus. Details of the samples are given in Table 4. The bender elements were configured in three different directions, allowing the investigation of elastic stiffness and stiffness anisotropy (details in Li and Senetakis, 2017). The