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The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

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Sample reconstitution for evaluating the cyclic liquefaction resistance of iron ore tailings

Reconstitution d'échantillons pour évaluer la résistance à la liquéfaction cyclique des résidus de minerai de fer

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ABSTRACT: The behaviour of ore tailings under monotonic and cyclic loading remains poorly understood, as suggested by the serious disasters occurring in tailings dams around the world, which put at risk the safety of people, properties and environment. The urgent need to solve this problem will be even more pressing in the future, because the needed future energy transition based on the so-called low-carbon paradigm will significantly raise the demand for minerals and metals. Therefore, a geotechnical engineering approach needs to be undertaken to characterize ore tailing in order to support sustainable and safe mining in the future. This paper discusses the problem of slurry-based reconstitution of ore tailings samples, considering the most relevant physical, identification and mechanical properties of undisturbed and reconstituted samples. An experimental validation of the method is carried out, using iron ore tailings from a Portuguese mining site, taking into account the main physical and identification properties of the samples and its response under monotonic triaxial compression loading in undrained conditions and cyclic triaxial loading in undrained conditions able to induce cyclic liquefaction.

RÉSUMÉ : Le comportement des résidus de miniers sous chargement monotone et cyclique est encore mal compris, comme le suggèrent les graves catastrophes survenant dans les barrages de retenue de résidus à travers le monde, qui mettent en danger la sécurité des personnes, des propriétés et de l'environnement. Le besoin urgent de résoudre ce problème sera encore plus pressant dans un futur proche, car la future transition énergétique nécessaire basée sur le paradigme dit bas-carbone augmentera considérablement la demande de minéraux et de métaux. Par conséquent, une approche basée en génie géotechnique doit être entreprise pour caractériser les résidus miniers afin de soutenir une exploitation minière durable et sûre à l'avenir. Cet article traite du problème de la reconstitution à base de coulis d'échantillons de résidus minier, en tenant compte des propriétés physiques, d'identification et mécaniques les plus pertinentes d' échantillons non perturbés et reconstitués. Une validation expérimentale de cette méthode est réalisée, en utilisant des résidus minier de fer d'un site minier portugais, en tenant compte des principales propriétés physiques et d'identification des échantillons et de sa réponse sous chargement triaxiale monotone de compression non drainée et chargement triaxial cyclique en conditions non drainées capables de provoquer la liquéfaction cyclique.

KEYWORDS: tailings, sample reconstitution, slurry, physical properties, undrained mechanical behaviour

1 INTRODUCTION.

The behaviour of ore tailings in the field under monotonic and cyclic loading is still poorly understood, as shown by the serious disasters that occurred around the world in tailings dams under different conditions, including but not limited to those imposed by earthquakes. In fact, catastrophic events such as the 2019 Brumadinho tailings dam collapse in Brazil and others (Liu & Henderson, 2020) or the different failures observed as a result of the 2010 Maule Earthquake in Chile (Verdugo et al. 2012) suggest that further research needs to be carried out to improve our current understanding on the behaviour of ore tailings under generalized undrained loading conditions, namely those causing complex liquefaction-related phenomena in the field. Moreover, there is an urgent societal need with respect to the safety of people and property and to the environmental protection in regions where old and new tailings dams exist. Actually, failure of tailings dams in the past had very serious and regrettable costs, ranging from substantial loss of lives, which reached a total number close to 3 hundred in the case of Brumadinho tailings dam collapse, large social and economic costs and broad and long-lasting environmental impacts. In fact, the recent 2019 Brumadinho tailings dam tragic failure is considered by Rotta et al. (2020) the worst human and environmental disaster in Brazil.

Unfortunately, the challenges to the human and environmental safety posed by tailings dams will certainly become more demanding in the future, not only because the society is increasingly more aware of this problem but also because of the required future energy transition in the society based on a so-called new low-carbon paradigm. This approach requires extensive electrification of the economy to reduce greenhouse-gas emissions through the use of renewable energy, which will significantly raise the demand for minerals and metals that must be obtained through sustainable mining. In fact, electric cars and onshore wind plants, for example, require various times the mineral resources of conventional cars and equivalent sized gas-fired power plants, respectively. Therefore, a geotechnical engineering approach is needed to characterize ore tailings in detail, so that appropriate design can be performed to support sustainable and safe mining under future challenging conditions that will have to be matched by the mining industry, including appropriate safety in seismically active regions.

2 SAMPLE RECONSTITUTION OF IRON ORE TAILINGS

Poor characterization of the behaviour of ore tailings results primarily from the fact that ore tailings are a waste product of the mining industry, often deposited in very large and often heterogeneous piles with limited engineering involvement. In addition, ore tailings have not always been treated as a geotechnical material and, as a result, have only rarely be characterized in detail under generalized loading conditions and using suitable geotechnical engineering principles.

Table 1 compiles some physical and identification properties of iron ore tailings dams from two different sites: Córrego do Feijão (Dam 1), in Brazil, and Yuhezhai (fine iron tailings), in Yunnan, China. From the geotechnical point the view, the iron ore tailings shown in the table can be described as a non-plastic to low plasticity material having uniform to well-graded grain size distributions mostly containing sand and silt. According to the Unified Soil Classification System (ASTM 2011), the tailings from Table 1 are usually classified as silty sands (SM), although they can be classified as sandy lean clay (CL) in the case of some finer tailings from Yuhezhai. With respect to the in situ state, the iron ore tailings in Table 1 confirm the large heterogeneity frequently exhibited by these materials, namely with respect to the void ratio, which varies within a large range typical of granular to low-plasticity materials, as a result of the variation of the depositional processes in tailings dams. Another singular feature of iron ore tailings dams is the unusually high values of the density of solid particles (G_s). In fact, because iron ore tailings often contain 10 to 50 % of iron, whose density (G_s around 7.9) considerably exceeds that of common soil particles (G_s around 2.65), it is not surprising that the density of iron ore particles tend to reach values significantly above 3 and in some cases around or even slightly above 5.

A basic problem that needs to be solved in order to assess the behaviour of ore tailings under generalized loading conditions is the ability to assess the behaviour of comparable samples tested under different conditions. Because "undisturbed" tailings samples are usually heterogeneous and also expensive and difficult to collect in many cases, reconstituted samples may provide a reasonable solution to this problem. However, the reconstitution process must be established so that the resulting samples are uniform and homogeneous while qualitatively representing the physical properties and the mechanical behaviour of "undisturbed" samples, which should be confirmed through comparison of the response of reconstituted and "undisturbed" samples under similar loading. In addition, the reconstitution procedures should result in similar samples in successive occasions and irrespective of the researcher involved.

Table 1. Geotechnical properties of two different iron ore tailings dams

Properties	*Córrego do Feijão iron ore tailings Dam I (Silva 2010)*	*Yuhezhai iron ore tailings (Hu et al. 2017)*
e_0	0.30 ~ 1.07*	-
w_0 (%)	16 ~ 20	43 ~ 54
w_P (%)	14 ~ 24	0 ~ 19
w_L (%)	18 ~ 33	0 ~ 28
PI (%)	4 ~ 10	0 ~ 9
G_s ()	4.02 ~ 5.11	3.08 ~ 3.23
D_{10} (mm)	-	0.005 ~ 0.051
D_{50} (mm)	-	0.030 ~ 0.120
C_u	-	3.11 ~ 8.82

* values obtained through inaccurate methods were dismissed

2.1 *Basic requirements for tailings samples reconstitution*

Reconstituted samples of ore tailings should, at least, be uniform and homogeneous and be produced using methods exhibiting good repeatability and reproducibility. In addition, the sample composition and the reconstitution procedures should replicate as close as possible any depositional and post-depositional processes affecting tailings in the field, so that the reconstituted samples have physical properties and a mechanical behaviour comparable to those exhibited by tailings in situ. Because tailings are usually recent deposits, time effects, typically impossible to mimic in reconstituted samples, should have minor importance.

Iron ore tailings consist of particles with very angular shapes (Figure 1) and unusually high average G_s values (Table 1), which vary significantly depending on the mineralogy. The most effective way to prepare reconstituted samples of materials having particles with unique shapes and compositions, as in the case of iron ore tailings, is by using disturbed samples collected in the field. This ensures that the sample composition replicates that of tailings in situ. Considering that tailings tend to be formed by deposition of a slurry, the slurry-based reconstitution procedures typically used in clayey soils may be a good solution, provided that the problems of segregation affecting tailings uniformity in situ are suitably dealt with. As a matter of fact, because iron ore tailings can contain particles with very different sizes and densities that are deposited as a fluid slurry that flows away from an outfall, natural segregation in the field is the main responsible for the heterogeneity of these materials in situ. The degree of segregation tends to decrease when the pulp fluidity of the slurry and the size range of ore particles decrease.

2.2 *Proposed method for iron ore tailings samples reconstitution*

Taking into account the specific characteristics of the particles forming iron tailings and the need to create representative and uniform reconstituted samples of these highly heterogeneous materials deposited in the field from a slurry, the reconstitution procedure proposed takes advantage of the low plasticity of these materials to avoid segregation. The procedure consists of:

a) select a representative amount of iron ore tailings particles collected in the field that represent the tailings that are the focus of the investigation;

b) assess the Atterberg Limits of the selected representative amount of iron ore tailings particles;

c) prepare a slurry with a liquidity index moderately above unity so that the mixture can be uniformly mixed while avoiding particle segregation with respect to size and/or mineralogy;

d) deposit the slurry in a consolidometer with a geometry that is suitable with respect to the number and size of reconstituted samples that will be required;

e) consolidate the slurry to a desired effective stress level using dead-loads for a suitable period of time

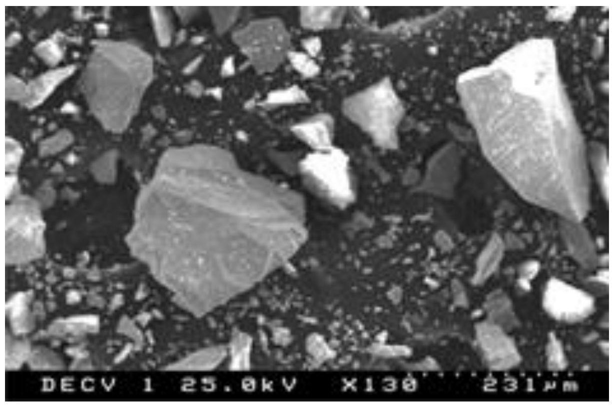

Figure 1. SEM images of powdered iron ore particles (Ofoegbu, 2019)

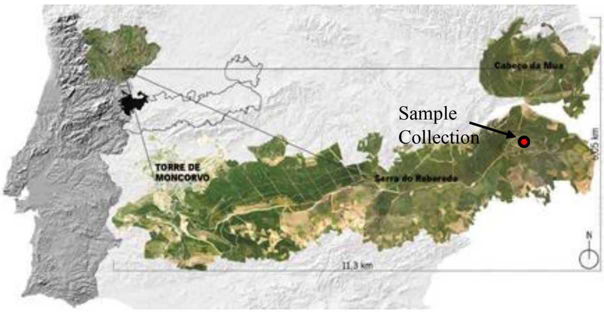

Figure 2. Location of sample collection at Moncorvo Iron Mine (adapted from Fevereiro 2015)


a)

b)

c)

Figure 3. Reconstitution procedure: a) create a uniform slurry; b) slurry deposition in the consolidometer; c) slurry consolidation under dead-load

2.3 *An example of iron ore tailings samples reconstitution*

The use of the proposed method in the preparation of large-sized reconstituted samples of iron ore tailings is herein examined.

2.3.1 *Iron ore tailings used in the reconstitution*

The ore tailings used in the reconstitution were collected from an old iron ore tailings deposit in the Northern Region of Portugal, namely from the old Torre de Moncorvo's Iron Mine (Figure 2), which operated in the region for more than 30 years and ceased its operation in the middle of the 80s, before reopening recently.

The iron ore tailings collected from the site were representative of the material deposited near the surface and apparently having larger iron proportions based on its colour. Most part of the material was collected with no particular caution to preserve the natural structure of the iron ore tailings. However, some "undisturbed" block samples were also collected and carefully transported and stored in the Geotechnical Lab of the University of Coimbra in order to assess the mechanical behaviour of the in situ material through laboratory tests.

2.3.2 *Application of the proposed reconstitution method*

After selecting a representative amount of particles from the collected sample, the organic remains and large-sized particles that were unrepresentative of the bulk material were firstly removed by hand and identification tests were carried out on representative samples of the remaining material. The results obtained show that the iron ore tailings selected for reconstituting the samples have a grain size distribution that mostly fits in the range 0.01 to 0.15 mm, which contains 90 % of the particles in terms of weight. The density of solid particles (G_s) is about 4.7, which confirms that the selected ore tailings still contain an appreciable amount of iron. The material is also moderately plastic, with a plastic limit (PL) and a liquid limit (LL) equal to 15 and 20 %, respectively, following BS 1377-2:1990 (BS 1990). The Plasticity Index (PI) equals 5 %, which reflects the moderate plasticity of the tailings. These values are fairly representative of the average properties of other ore tailings (Table 1), which probably reflects similar processing methods and particles composition found in these mines around the world.

Taking into account the properties of the selected material, namely its liquid and plastic limits, a slurry was prepared with a water content (23 %) slightly above the obtained liquid limit (LL) of 20 %. The slurry was then thoroughly mixed until a uniform and homogeneous viscous paste was obtained (Figure 3a). The slurry was subsequently transferred to a rigid 30 cm high cylindrical mould (ϕ= 11.5 cm) with a porous stones placed at the bottom for drainage of excess water from the bottom. Filter paper was used around the vertical walls of the contained to accelerate the consolidation process (Figure 3.b). After placing the slurry in the container and fill it fully except for the upper 3 cm required to place another porous stone and the loading plate on top, the slurry was consolidated up to an effective vertical stress close to 50 kPa for 3 weeks (Figure 3.c).

3 VALIDATION OF THE SAMPLE RECONSTITUTION PROCEDURE

The sample reconstitution procedure was validated by assessing the uniformity and homogeneity of the reconstituted sample and by evaluating the mechanical response of the reconstituted and undisturbed samples under monotonic and cyclic loading.

3.1 *Visual evaluation of the uniformity and homogeneity*

From a visual point of view, the proposed method results in quite uniform and homogeneous reconstituted samples, where no apparent particle segregation and/or macroscopic layering or other heterogeneous features are observed.

3.2 *Physical and identification properties*

A more quantitative approach towards the characterization of the uniformity of the sample was undertaken by comparing different physical and identification properties at different locations within the large reconstituted sample. Firstly, the grain size distributions determined at different locations showed that the distribution of the grains is quite uniform through the sample. In addition, the density of solid particles (G_s) measured across the sample is within the range 4.7±0.3, which is relatively constant, taking into account the variety of G_s in individual iron ore particles. Also, the water content measured at different locations varied within a narrow range (14%~16%). Therefore, the results confirm the uniformity and homogeneity of the sample. As expected, the average values obtained also match those measured in the iron ore tailings collected in situ. The void ratio of the reconstituted and undisturbed samples (0.65 versus 0.66) is also similar and close to the values found in real deposits (Table 1).

3.3 *Undrained mechanical behaviour*

To assess the validity of the sample reconstitution procedure, namely for the purpose of evaluating the cyclic liquefaction resistance of iron ore tailings, the undrained behaviour of the sample under monotonic and cyclic loading must be addressed.

3.3.1 *Reconstituted samples under undrained compression*

Firstly, the undrained triaxial compression response of 2 comparable specimens retrieved from the large reconstituted sample and consolidated under different isotropic consolidation stresses is compared. Reconstituted samples consolidated at 50 (Rec@50) and 200 kPa (Rec@200) are considered. In plane p'q (Figure 4), the stress-paths exhibited by the reconstituted samples are typical of moderately loose granular materials. Similarly, the increase in the effective confining stress increases the contractive tendency during the early loading stages, which is often related to the occurrence of the so-called static liquefaction. It is also possible to identify the stress ratios corresponding to the phase transformation (q/p'=1.1) and critical states (q/p'=1.7). The effect of the effective confining stress is clearer in the stress-strain response at low strains (Figure 5), a more rigid response being observed for higher effective confining stresses. Finally, Figure 6 confirms that the sample consolidated under lower effective confining stresses tends to contract less, both tending to similar principal effective stress ratios (~5) at large strains.

3.3.2 *Reconstituted samples under undrained cyclic loading*

In seismically active regions, cyclic liquefaction poses a serious threat to iron ore tailings deposits. The performance of the reconstituted samples under undrained cyclic triaxial loading was also assessed using a reconstituted sample fundamentally similar to the one tested under monotonic compression but with a slightly larger sand fraction. Figure 7 shows that the basic features of the response of iron ore tailings to undrained cyclic triaxial loading, in the p'-q plane, are similar to those of sandy soils. In fact, the progressive increase of excess-pore-pressure in each cycle, the stress-path reversals occurring in each loading stage when the phase transformation line PT(Rec) is crossed and the evolution of the stress-paths along the critical state line CS(Rec) after liquefaction triggering, at least on the compression loading stage, is typically observed in liquefiable sands under undrained cyclic loading. As expected, on the extension loading stage, the slopes of the phase transformation and, particularly, the critical state lines determined in undrained triaxial compression do not fit the stress-paths observed during cyclic loading. In fact, a slope of the critical state line in extension of around 1.33 would provide a better fit of the results. This corresponds to a ratio of the extension to compression critical state line slopes of about 0.78, which is slightly above the most usual range for silica sandy soils (Azeiteiro et al. 2017a).

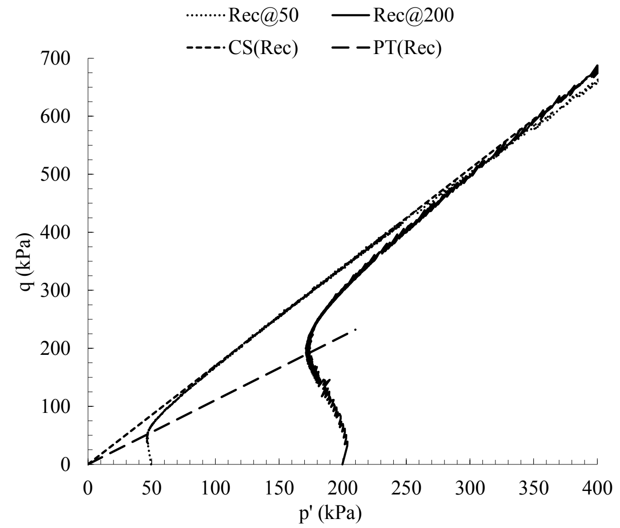

Figure 4. Effective stress-paths in plane p'-q of reconstituted samples under undrained triaxial compression

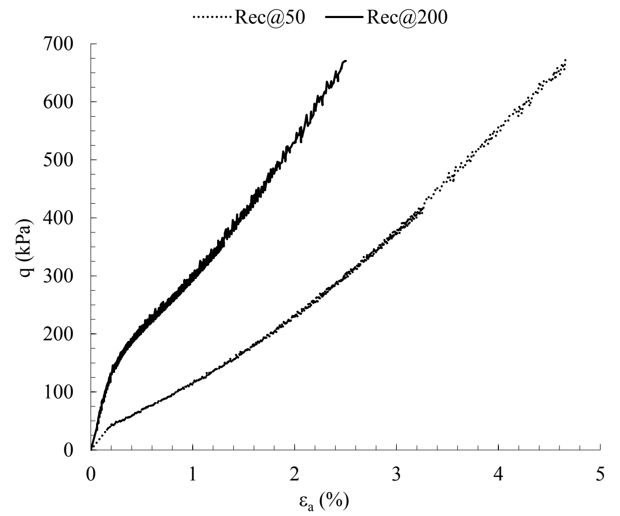

Figure 5. Stress-strain response of reconstituted samples under undrained triaxial compression

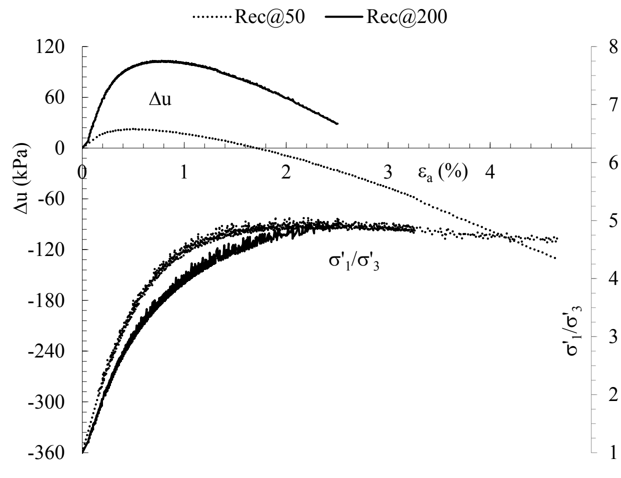

Figure 6. Excess-pore-pressure and principal stress ratio variation with strain of reconstituted samples under undrained triaxial compression

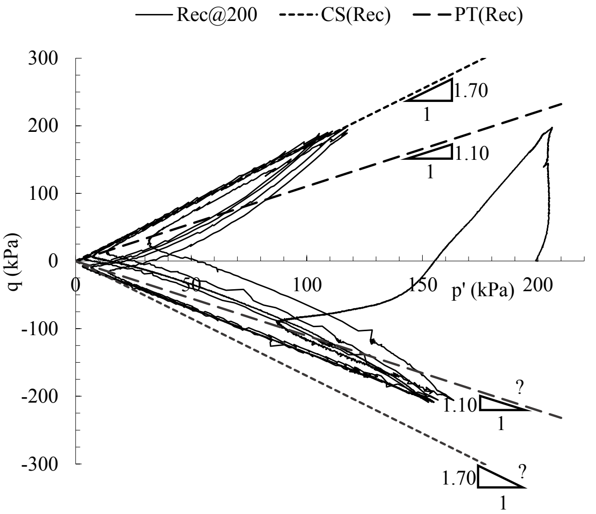

Figure 7. Effective stress-paths in plane p'-q of reconstituted samples under undrained cyclic triaxial compared and relation to the phase transformation and critical states determined in triaxial compression

The fact that a limited number of cycles is required to reach liquefaction is mostly due to the fact that a large cyclic stress ratio was applied from the first cycle, which has a large effect on the liquefaction resistance (Azeiteiro et al. 2017b). This may have been exacerbated by the fact that the slope of the phase transformation line PT(Rec) determined in triaxial compression slightly overestimates the slope of this line for the sample tested in cyclic loading, because this reconstituted sample has a slightly larger sandy fraction. In fact, as shown in Figure 7, the stress-path in the 1st compression loading stage seems to dilate before reaching PT(Rec) predicted based on the undrained monotonic compression response of the other reconstituted sample.

Overall, the stress-paths observed in undrained cyclic triaxial loading and their relation to the undrained response in triaxial compression suggest that the reconstituted sample offers a suitable approach to assess the behaviour of iron ore tailings susceptible to earthquake-induced liquefaction.

3.3.3 Comparison of the behaviour of reconstituted and "undisturbed" samples

To further validate the reconstitution procedure proposed for iron ore tailings, the mechanical behaviour of the reconstituted and undisturbed samples was compared for similar loading conditions. The comparison is based on the undrained monotonic triaxial compression behaviour observed in the reconstituted (Rec@200) and undisturbed (Und@200) samples consolidated at similar effective isotropic confining stresses (200 kPa).

When the stress-paths are compared (Figure 8), it is clear that the samples show qualitatively similar behaviour in undrained monotonic triaxial compression. However, the stress-path of the reconstituted sample is smoother, namely in the transition zones, and the slopes relative to the phase transformation, PT(Und), and critical state, CS(Und), slightly differ in the reconstituted and undisturbed samples. Actually, the slope of PT(Und) exceeds that of PT(Rec) while the slope of CS(Und) is smaller than that of CS(Rec). Thus, the stress ratios q/p' relative to PT(Und) and CS(Und) is much closer than in the case of the reconstituted sample, which may be an effect of the layering and/or fragility planes observed in the block samples from where undisturbed samples were cut, in some cases due to the depositional method in situ and in some others possibly due to sample disturbance caused by sampling. This suggests that reconstituted samples avoid the problem of sampling disturbance while qualitatively maintaining the in situ behaviour of iron ore tailings.

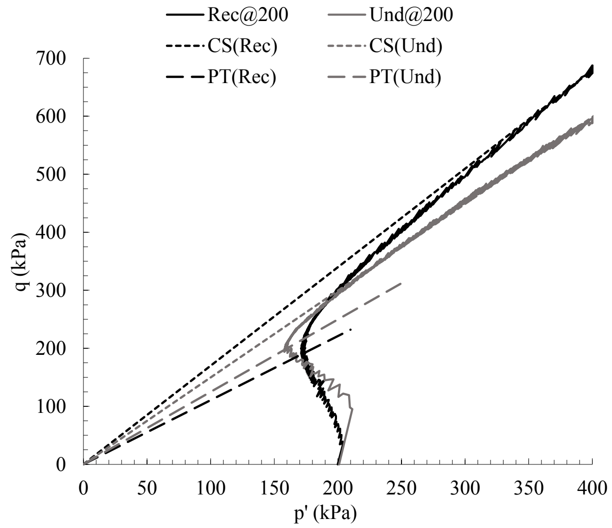

Figure 8. Effective stress-paths in plane p'-q of reconstituted and undisturbed samples under undrained triaxial compression

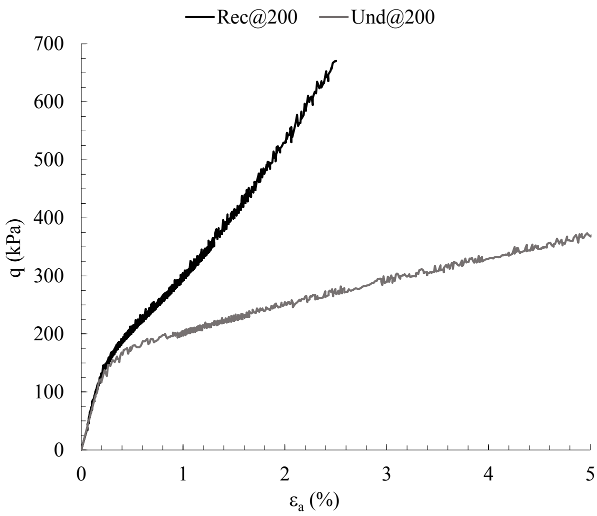

Figure 9. Stress-strain response of reconstituted and undisturbed samples under undrained triaxial compression

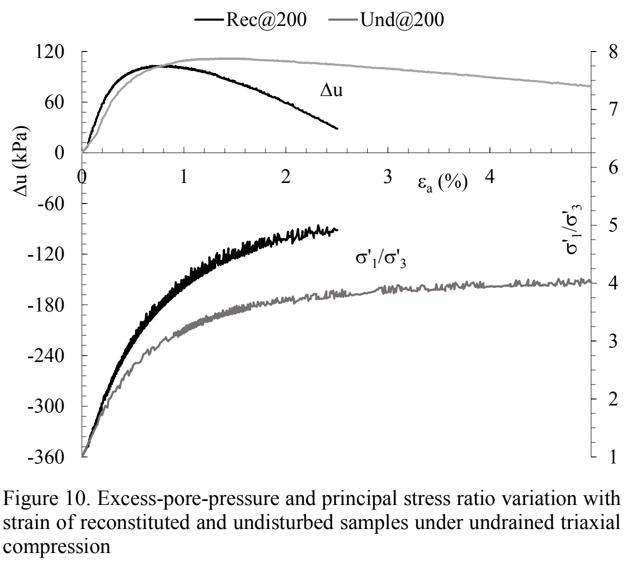

Figure 10. Excess-pore-pressure and principal stress ratio variation with strain of reconstituted and undisturbed samples under undrained triaxial compression

The slopes of the PT and CS lines also affect the response of the reconstituted and undisturbed samples when compared using different perspectives. When the stress-strain behaviour of Rec@200 and Und@200 samples are compared (Figure 9), for example, the response of the samples at relatively small strains is very similar, but as the phase transformation state approaches, the reconstituted samples starts dilating earlier due to the lower slope of PT(Rec). After this point, the stress-strain responses of the reconstituted and undisturbed samples diverge quite significantly. Similar observations can be derived from the excess-pore-pressure generation during undrained shearing in compression (Figure 10). In fact, after showing a fairly similar behaviour at low strains, the reconstituted sample starts dilating earlier and more evidently than the undisturbed sample. Figure 10 also shows that both samples tend to reach a constant principal stress ratio, σ'_1/σ'_3, for larger strains, the maximum value being larger in the case of the reconstituted sample, as expected, taking into account the observations of the stress-paths exhibited by the samples in p'-q plane and the slopes of CS(Und) and CS(Rec).

Overall, the reconstituted sample seems to qualitatively replicate the behaviour of the undisturbed sample under monotonic triaxial compression, the differences observed being probably a result of the natural layering or the sampling disturbance effects inevitably present in undisturbed samples. Considering this result and the conclusions derived from the undrained cyclic behaviour of reconstituted samples in comparison to the behaviour of these samples in undrained monotonic compression, the reconstitution procedure proposed to obtain representative samples of iron ore tailings seems suitable to carry out research on earthquake-induced liquefaction of iron ore tailings dams in the field.

4 CONCLUSIONS

The recent global demand for a more sustainable development based on a new paradigm of low-carbon energy will significantly increase the need for minerals and metals, geotechnical characterization of ore tailings being a crucial element for safer and sustainable mining in the future. Ore tailings heterogeneity often exceeds that exhibited by natural soils, because of the depositional processes and some particular characteristics of ore particles, namely the great variability of particles density. This problem, which is particularly relevant in iron ore tailings, requires the use of reconstituted samples to assess the behaviour of these materials under generalized loading conditions in the field, including undrained cyclic loading leading to liquefaction.

This paper proposes and discusses the use of a slurry-based method to prepare reconstituted samples of iron ore tailings through dead-weight consolidation in a large cylindrical container, using a material collected from an old tailings deposit in Northern Portugal. The results suggest that:

a) the reconstituted sample is uniform and homogeneous irrespective of the perspective of the analysis(visual observation, water content, grain size distribution or density of solid particles), providing similar smaller samples for lab testing;

b) reconstituted sample's average physical and identification properties match those found in iron ore tailings in the field;

c) the response of reconstituted samples in undrained triaxial monotonic compression under different effective confining stresses is coherent and compatible with the behaviour of sands, phase transformation and critical states governing the behaviour;

d) the undrained cyclic triaxial behaviour of reconstituted samples is also coherent with the results of undrained monotonic compression and is compatible with the behaviour of sands, both before and after cyclic liquefaction triggering;

e) the undrained compression behaviour of reconstituted and undisturbed samples is qualitatively similar, major differences being probably a result of the natural layering or the sampling disturbance effects inevitably present in undisturbed samples.

In conclusion, the reconstitution procedure proposed to obtain representative samples of iron ore tailings seems suitable to carry out geotechnical-based research on the generalized behaviour of these materials under monotonic and cyclic loading, including the effects of earthquake-induced liquefaction of iron ore tailings dams in the field.

5 ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution to this research by the company responsible for Torre de Moncorvo's Iron Mine, Aethel Mining, Ltd (previously MTI Ferro de Moncorvo SA), and express their gratitude to Mr. António Frazão and Ar. Carlos Guerra, who organized the iron ore tailings sample collection in the field.

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