Mining
Mineração

Impact of methods used to reconstitute tailings specimens on the liquefaction potential assessment of tailings dams

http://dx.doi.org/10.1590/0370-44672018720164

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Abstract

The aim of this research is to investigate the liquefaction susceptibility of silt sandy mining tailings by experimental laboratory techniques. The main aspect analyzed is how techniques of sample reconstitution impact the results obtained in static undrained triaxial tests. Different methods of sample preparation are reviewed, such as moist tamping (MT), air and water pluviation, and a newly developed one called the Slurry Deposition (SD) method. This research highlights the importance of the "fabric" or particle structural arrangement associated with the various specimen preparation techniques when liquefaction potential assessment is of concern. Two series of undrained static triaxial tests were performed on specimens prepared according to MT and with SD techniques on specimens in the loose and very loose state. Results have demonstrated that MT specimens have shown the whole spectrum of liquefaction resistance (total liquefaction, limited liquefaction, and no liquefaction) on increasing density, while the SD campaign has shown only liquefaction resistance even in the overlapping intermediate densities with the MT series, where the latter has shown liquefaction, although limited. This scientific study critically discusses the risk of taking laboratory results of replicated soil elements that may not correspond to the reality.

keywords: static liquefaction, fine silt sand mining tailings, specimen preparation techniques, triaxial test, undrained shear strength behavior.

1. Introduction

Laboratory tests play an important role in understanding the mechanical response of geomaterials. For this purpose, testing undisturbed samples obtained from field investigations is considered more appropriate for studying natural soil behavior, since it allows the structure of soil particles in situ, stress field, depositional history, etc. to be represented. However, the use of reconstituted samples of granular soils for laboratory testing has gained widespread acceptance in the past for a number of reasons, including (Khalili and Wijewickreme, 2008):

a) difficulties in obtaining high quality undisturbed non-cohesive field samples;

b) need to test essentially identical "homogeneous" test specimens (without variability commonly found in field samples); and

c) demand to characterize man-made engineering materials.

The use of reconstituted samples for liquefaction potential assessment of tailings deposits as proposed by this research can be easily justified by all three of these reasons. In addition, most of our fundamental understandings of the liquefaction phenomena in sands has been derived from controlled laboratory studies. However, previous articles on this issue have shown that each sample preparation method renders a specific fabric, which may result in distinct stress-strain characteristics and responses (Vaid and sivathayalan, 2000; Carraro and Prezzi 2007).

Sample reconstitution methods, such as moist tamping (MT), air pluviation (AP) and water pluviation (WP) are the most widespread methods in laboratory routines. In addition, Slurry Deposit (SD) is a newly developed preparation technique, derived from WP, which has been considered to yield the most realistic results for natural alluvial soils, and tailings deposits formed by disposed slurries. Table 1 summarizes the methods, their characteristics and applications.

Method	Type of Soil	Brief Procedure Description	Characteristics	References
Slurry Deposition	sand, silty sands, silt, clay, silt / clay / sand mixtures and materials with high fines content	Deposition of slurry prepared within an acrylic tube	incorporates some desirable characteristics from water pluviation technique, but less conducive to material segregation and most adequate for applications of tailings reconstitution	Carraro and Prezzi (2007)
Air Pluviation	Non-cohesive soils (sand)	Gravity particle deposition in air	preferential fabric which mimics natural alluvial deposits but fails when used with fine-grained sands, that causes segregation	Vaid and Negussey (1988);
Water Pluviation	Non-cohesive soils (sand)	Gravity particle deposition in water	greater homogeneity, but also conducive to segregation for fine-grained sands	Vaid and Negussey (1988); Miura and Toki (1982)
Moist Tamping	Non-cohesive soils (sand), silty sands, silt, clay, silt / clay / sand mixtures	Deposition of moist layered soil, which is compacted after deposition.	large range of specimen densities, produces non-homogeneous specimens and does not simulate fabric of alluvial deposits	Castro (1969); Casagrande (1979)

Table 1
Most common specimen reconstitution techniques.

2. Liquefaction assessment by laboratory tests

Soil liquefaction is one of the geotechnical engineering phenomena that has been researched for decades. Its consequences can be catastrophic, whether caused by dynamic or static loading. To this day, most research has been directed to the phenomenon occurrence under dynamic conditions, performed mainly in countries with constant records of seismic events. However, static stress-strain analyses of this mechanism of failure has recently received more interest especially in the context of tailings dam collapse disasters, such as Fundao TSF, in 2015, in Southeastern Brazil. This article deals exclusively with static liquefaction.

2.1 Influence factors

Silty sand liquefaction is known to be affected by the following factor: fines content, confining stress, test specimen preparation method, and (dry) density (Monkul and Yamamuro 2011).

Table 2 presents a summary of main research findings on liquefaction resistance while investigating those factors.

Table 2
Influence factors on liquefaction.

Variation	Resistance	Reference
fines content increases	increases	Monkul and Yamamuro (2011)
fines content increases	decreases	Zlatovic and Ishihara (1997); Monkul and Yamamuro (2011)
relative density increases	increases	Suhindra et al (1989)
confining stress increases	increases	Yamamuro and Lade (1997);
reconstituting specimen method	strength parameters not affected	Zlatovic and Ishihara (1997); Monkul and Yamamuro (2011)
loose deposits	more contractive	Kuerbis (1989)

3. Materials and methods

Experimental work comprised of performing two series of isotropic undrained consolidated static triaxial tests (CIU) on specimens prepared using either a moist tamping or slurry deposition technique, variable density (or void ratio), at 50 kPa and 300 kPa confining effective stress.

3.1 Sample Characterization

Material used in the study was silt-sandy tailings with non-plastic fines, from iron ore flotation processes, collected at a mine site in the Quadrilatero Ferrifero, in the State of Minas Gerais. Indexed property tests on this material rendered a mass density of 2.97 g/cm^3, minimum dry density of 1.55 g/cm^3 (according to ABNT MB-3324), and maximum dry density of 1.73 g/cm^3 (ABNT MB-3388). Microscopic mineral analysis identified quartz, hematite and goethite. From the grain size distribution curve, high fines content (% passing #200) above 50% (58% exactly) were detected, and material could be characterized as a fine sandy silt material.

3.2 Moist Tamping Method (MT)

Soil elements were recreated in the lab for the triaxial tests, firstly using the moist tamping technique (MT) with undercompaction, as suggested by Ladd (1978), in order to improve specimen uniformity. The main materials and equipment used in this technique were: a wood socket; latex membrane (Ø 71 mm x 255 mm and thickness 0.3048 mm); two porous stone discs (Ø 71.5 mm x 10 mm thick); a triaxial split mold (Ø 72.5 mm x 161 mm); 760 mm/Hg vacuum pump; a triaxial cell with base (Ø 62 mm x 30 mm) and a topcap (Ø 62 mm x 30 mm).

Triaxial tests performed with specimens prepared according to the MT technique initially followed a two-fold saturation procedure. First of all, they were submitted to a low hydraulic gradient flux outside the triaxial chamber using differential elevation heads between a water source and the specimen. This external saturation, although necessary and common in laboratory routines, was not very effective, since in the end, the Skempton B parameter was below 0.1 for all MT test specimens. Secondly, specimen saturation was pursued by backpressure incremental steps with the triaxial cell already assembled. This time the procedure was effective, although extremely slow, taking days to finish, and requiring high back pressure values, approximately 700 kPa. The specimens were then isotropically consolidated under a confining effective stress of 50 kPa or 300 kPa. For the undrained shearing phase (CIU), a shear rate of 0.16 %/min was determined based on consolidation data and tests lasting until axial deformation reached 20%, which means a two-hour test.

3.3 Slurry Deposition Method (SD)

Field soil elements were also recreated using the reconstitution technique for sandy soils with slurry deposition fines (SD), as suggested by Carraro and Prezzi (2007), with some modifications and additions of Wang *et al*. (2011), Abreu *et al*. (2016) and others developed in this research. The main materials and equipment used in this preparation were: a cylindrical acrylic tube (70.0 outer diameter and 60.0 inner diameter x 1000 mm height); 2 latex stoppers (70.0 x 55.0 x 67.0 mm), one with an attached valve on its center; a latex membrane (Ø 71 x 255 mm and thickness 0.3048 mm); two porous stones (Ø 71.5 mm x 10 mm thick); a triaxial split mold (Ø 72.5 mm x 161 mm); an aluminum collar; an aluminum tray; a 760 mm / Hg vacuum pump; a triaxial cell with pedestal (Ø 62 mm x 30 mm) and a top cap (Ø 62 mm x 30 mm).

After specimen preparation, SD specimens for triaxial tests were also saturated following similar laboratory techniques as described for MT samples. In this case, as expected, the initial percolation at low gradient rendered Skempton B values approximately 0.6, which is much higher than the ones obtained for MT specimens. Saturation was then completed by applying backpressure steps. The desired saturation, that is, B values around 0.95, was reached at backpressure values around 350/450 kPa, quite low as compared with the MT series, and much less time consuming. The specimens were then isotropically consolidated under 50 kPa or 300 kPa stress. The undrained test shear rate was set at 0.16%/min (CIU), based on the consolidation data, until the sample reached an axial deformation of 20%, which took approximately two hours.

4. Results

The main results of this research are related to the analysis of CIU triaxial tests performed on the silt sandy tailings, whose specimens were prepared according to the moist tamping (MT) and slurry deposition (SD) methods. The goal was to attempt to verify the impact of these specimen reconstituting techniques on liquefaction susceptibility.

4.1 Moist Tamping Triaxial (MT)

Figures 1 and 2 show CIU tests results for MT test specimens plotted in terms of stress path (p' x q) according to the MIT convention ranging from low (1.48 g/cm³ and 1.51 g/cm³), intermediate (1.56 g/cm³) and higher densities (1.59 g/cm³). Figure 3 replotted all 50 kPa tests together, and also one 300 kPa test.

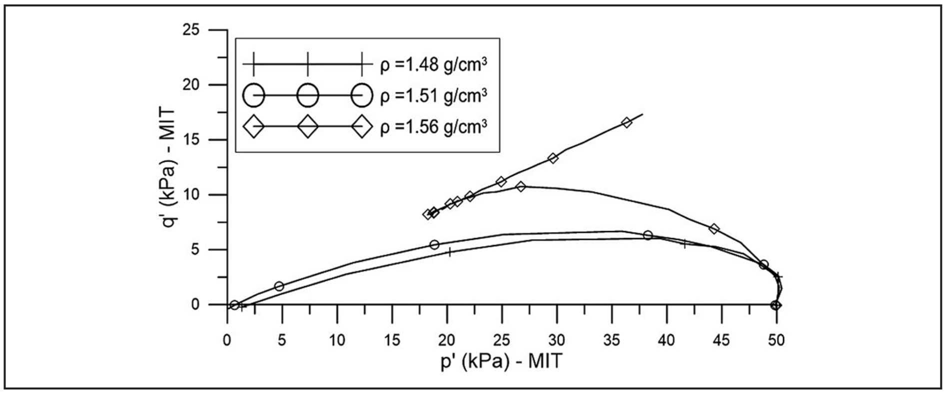

Figure 1
CIU triaxial test results stress path (MIT) for MT specimens with densities of 1.48 g/cm³, 1.51 g/cm³ and 1.56 g/cm³.

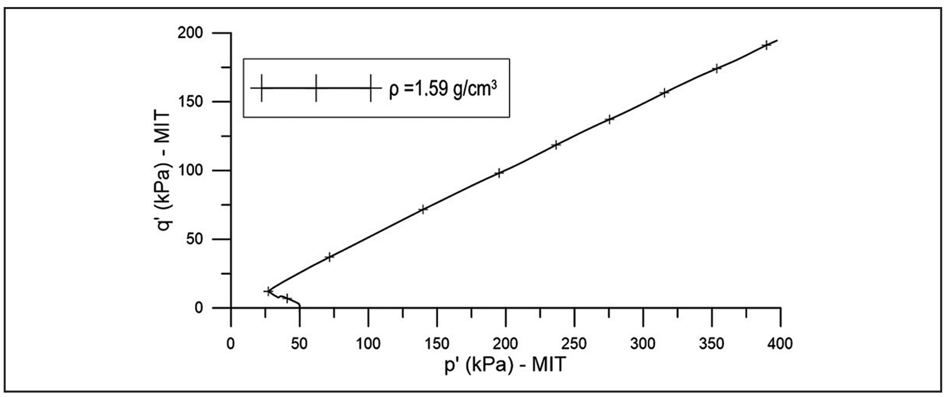

Figure 2
CIU triaxial test
results stress path (MIT) for MT specimens with densities of 1.59 g/cm³.

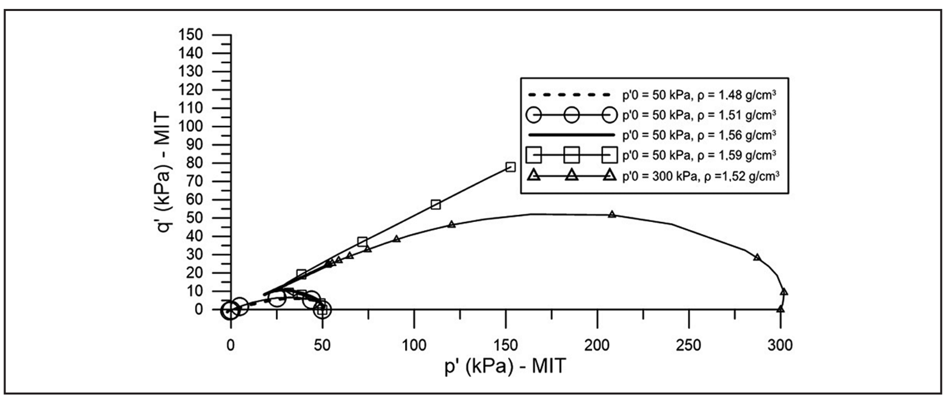

Figure 3
CIU triaxial test results stress
path (MIT) for all MT test specimens.

At low densities (Figure 1), a complete liquefied state is reached, differently from the intermediate range where a limited liquefaction state is observed (also in Figure 1, 1.56 g/cm³). For the test with the highest specimen density (Figure 2), high liquefaction resistance is configured. Briefly, the increase in density produces a change from contractive, softening (liquefiable) behavior, to a dilating and hardening (liquefaction resistant) pattern, including an intermediate state of slight softening (limited liquefaction). It is further noted that for the 300 kPa confining effective stress test (Figure 3), although it is performed on a low density (1.52 g/cm³) test specimen, softening behavior occurs, and general liquefaction does not occur. All of this corroborates previous studies, with influence factors density and confining stress playing important roles on liquefaction resistance (Yamamuro and Lade, 1997).

4.2 Slurry Deposition Triaxial (SD)

Figure 4 shows CIU tests results plotted in terms of stress path (p' x q) for SD test specimens with densities between 1.54 g/cm³ to 1.61 g/cm³ under 50 kPa and 300 kPa confining effective stress.

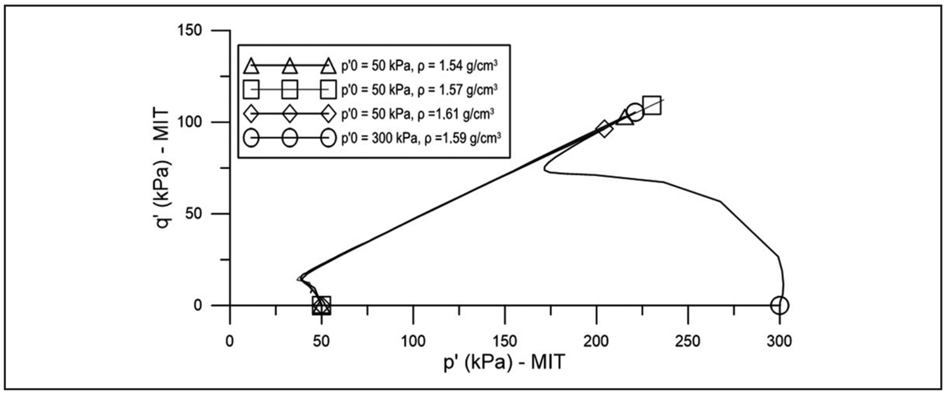

Figure 4
CIU triaxial test results stress path (MIT) for all SD test specimens.

The same behavior was observed in all four tests, regardless of the density difference or the confining stress. Firstly, stress paths rise, bending slightly to the left, generating low positive excess pore pressure, and then, as the deformation increases, the trajectory turns to the right, climbing the same slope, generating large values of negative excess pore pressure during shear, and revealing a dilating and hardening behavior. It is interesting to note that at large deformations, the stress paths of all tests overlap, characterizing a limit state of resistance (critical state strength parameters).

4.3 Triaxial result comparison between the two techniques

4.3.1 Comparison between low and medium densities

Observing Figure 5, there are apparently different and conflicting behaviors for the same soil element recreated according to different methods, MT and SD. First, it is possible to obtain specimens with liquefaction behavior by the MT method for low density (1.51 g/cm³). For intermediate densities (1.54 and 1.56 g cm³), the two methods produce very different patterns. The SD, with lower density (1.54 g/cm³) shows liquefaction resistance contrasting with the limited liquefaction behavior of a denser specimen (1.56 g/cm³) formed by MT.

4.3.2 Comparison between higher densities

In Figure 6, it can be seen that the two specimens show resistance to liquefaction, have hardening with deformation, and are dilating. These characteristics are more noticeable with the specimen prepared by MT. It can be concluded that regardless of the reconstituting technique, the same behavior is observed with increased density.

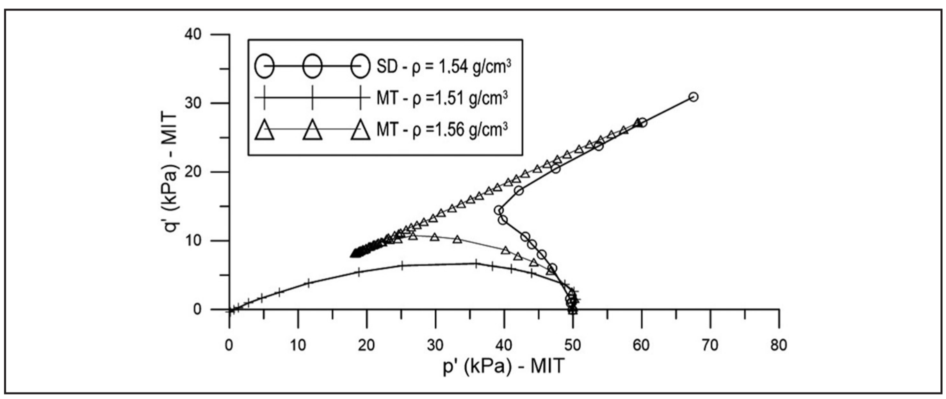

Figure 5
CIU triaxial test results stress path (MIT) for low and medium MT specimen densities and intermediate SD specimen density.

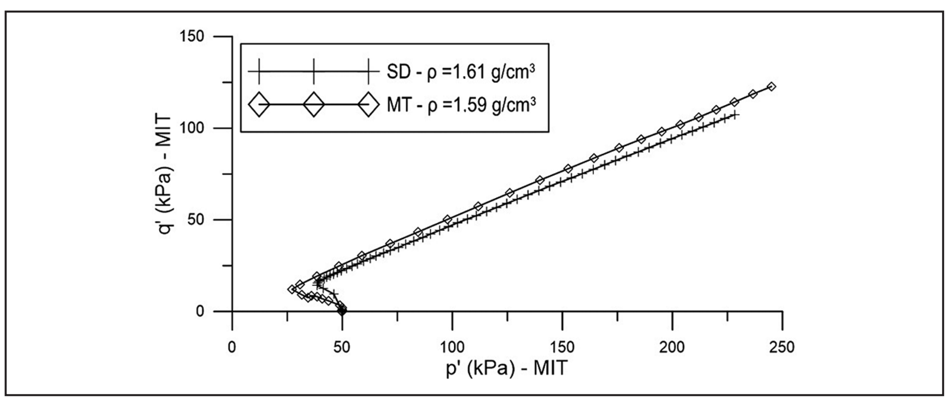

Figure 6
CIU triaxial test results stress path (MIT) for higher densities using MT and SD specimens.

5. Further discussions

Until the present, discussions on liquefaction susceptibility have focused on reconstitution techniques and specimen densities without referring the latter to material limits (item 3.1). Results in Figure 7 suggest several things, for example, that it is possible to achieve higher void ratios than the maximum considered. Another interesting matter is that all liquefaction, limited liquefaction or liquefaction resistance behaviors happened for specimens presenting relative densities in the range of loose, very loose and beyond. One can consider that sand soils with high fines content may need different limit standards in order to make comparisons with the copious literature on liquefaction susceptibility that relates it to relative density.

Even having resolved this issue, there still remains the question why SD specimens have not shown liquefaction. This research does not examine that aspect, but it endorses the previously mentioned idea that the static liquefaction condition may be achieved simply by bringing the material into a non-stable state (high pore pressure for example) in which its resistive force is reduced sufficiently to allow static conditions to produce static liquefaction. Such type of pre-triggering mechanism can be caused by, e.g., continuous vibrations generated by traffic equipment in the mining area setting (Penna and Oliveira-Filho, 2012).

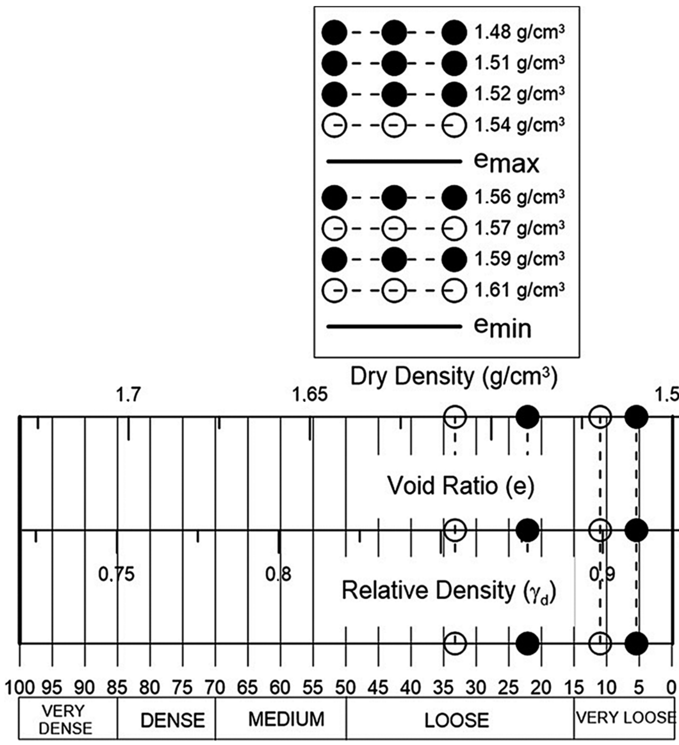

Figure 7
Voids ratio, dry density and relative density spectrum of all specimens data.

6. Conclusion

The present research established an experimental program to assess the mining tailings liquefaction potential through isotropically consolidated undrained triaxial tests. It was driven by the challenge of searching for the most adequate specimen reconstitution method that could make it possible to produce soil elements with a similar structure, as in tailings dam deposits, such as those found in mines in the Quadrilatero Ferrifero of Minas Gerais, Brazil.

The principal conclusions of the study are the following:

• The literature review carried out indicated that the Moisture Tamping (MT) specimen reconstitution method is not the appropriate way to replicate soil elements formed under an alluvial environment and hydraulic fills, as is the case of mining tailings deposits. In such conditions, the Slurry Deposition (SD) specimen method seems to render the best results.

• It has been observed that material density greatly influenced the results for very loose soil specimens, since a small difference in this index property was enough to manifest different behaviors in the MT campaign, as total liquefaction (lower density) and non-liquefaction (higher density). On the other hand, the SD technique showed dilating behavior, a characteristic that corresponds to liquefaction resistance, in all possible experimental densities, even in the overlapping range with the MT series.

• This research has shown how fabric, resulting from different specimen preparation, can affect liquefaction assessment. Unfortunately, scientific research based on laboratory tests cannot exactly replicate all possible and existing situations in the field; however, the SD technique may offer an appropriate method for studying fluvial or hydraulic fill deposits in the future.

• All specimens tested were prepared with relative densities in the range of loose and very loose and even beyond categories according to the Brazilian ABNT standards for dry densities limits. This finding generates several questions, for example, if the maximum and minimum void indexes found are true for this material, which does not seem to be the case. If they are not, what would actually be the range of relative density for the tested specimens. In addition, how logically and consistently the relative density (compactness) would relate to the mechanical response of these soils.

• It is fair to say that laboratory testing of representative samples is a valid resource. Research has been used to understand soil liquefaction susceptibility, although some intangible factors may limit its conclusiveness. This research has shown how fabric resulting from different specimen preparation can affect that phenomenon assessment.

Acknowledgments

We thank the Graduate Program on Mineral Engineering of UFOP (Federal University of Ouro Preto) for their general support. Also, many thanks to Mining Engineering Department undergraduate students Stephanie Oliveira Moura e Sá and Otávio Pataro for their help with sample characterization, CAPES, Brazilian federal government agency for higher education advanced training and FAPEMIG, Minas Gerais Research Support Foundation, for providing a scholarship to the first author.

References

ABNT. Solo – Determinação do índice de vazios mínimo de solos não-coesivos. MB 3384. São Paulo: Associação Brasileira de Normas Técnicas, 1991. 14 p.

ABNT. Solo – Determinação do índice de vazios máximo de solos não-coesivos. MB 3324. São Paulo: Associação Brasileira de Normas Técnicas, 1990. 6 p.

ABREU, I. C., OLIVEIRA, S., FILHO, W. L. O., FOURIE, A. ***Slurry deposition method for reconstituting specimens for triaxial and consolidation tests.*** COBRAMSEG, 2016.

CARRARO, J. A., PREZZI, M. A new slurry-based method of preparation of specimens of sand containing fines. ASTM. ***Geotechnical Testing Journal,*** v . 31, n. 1., 2007.

CASAGRANDE, A. Liquefaction and cyclic deformation of sands: a critical review. In: AMERICAN CONFERENCE ON SOIL MECHANICS AND FOUNDATION ENGINEERING, 5. ***Proceedings...*** Buenos Aires, v. 5, p. 79-133, 1979.

CASTRO, G. ***Liquefaction of Sands,*** Cambridge, MA: Harvard University, 1969. (Ph.D. Thesis).

KHALILI, A., WIJEWICKREME, D. New slurry displacement method for reconstitution of highly gap-graded specimens for laboratory element testing. ***Geotechnical Testing Journal,*** v. 31, n. 5, p. 424-432, 2008.

KUERBIS, R. ***The effect of gradation and fines content on the undrained loading response of sand.*** Vancouver, Canada: University of British Columbia, 1989. (Master of Applied Science).

LADD, R. S. Preparing test specimens using undercompaction. ***Geotech. Test. J.,*** v. 1, n. 1, p. 16–23, 1978.

MIURA, S., TOKI, S. A sample preparation method and its effect on static and cyclic deformation-strength properties of sand. ***Soils Found,*** v. 22, n. 1, 1982.

MONKUL, M. M., YAMAMURO, J. A. Influence of silt size and content on liquefaction behavior of sands. ***Canadian Geotechnical Journal,*** v. 48, n. 6, p. 931-942, 2011. SCI.

PENNA, L. R., OLIVEIRA FILHO, W. L. de. Monitoramento de poropressões construtivas. ***Revista Escola de Minas,*** v. 65, p. 443-448, 2012.

SUHINDRA, C., KUBERAN, R., KUMAR, B., AGGARWAL, P. K. Liquefaction of sand under cyclic triaxial condition. In: INDIAN GEOTECHNICAL CONFERENCE, GEOTECHNIQUES OF PROBLEMATIC SOILS AND ROCKS. ***Proceedings...*** Visakhapatnam, 14-16, v. 1, p. 249-253, 1989.

VAID, Y. P., NEGUSSEY, D. ***Preparation of reconstituted sand specimens, advanced triaxial testing of soil and rock,*** ASTM STP 977, 1988.

VAID, Y. P., SIVATHAYALAN, S. Fundamental factors affecting liquefaction susceptibility of sands. ***Can. Geotech. J.,*** v. 37, p. 592–606, 2000.

WANG, S., LUNA, R., STEPHENSON, R. W. A slurry consolidation approach to reconstitute low-plasticity silt specimens for laboratory triaxial testing. ***Geotechnical Testing Journal,*** v. 34, n. 4), p. 1-9, 2011.

YAMAMURO, J. A., LADE, P. V. Static liquefaction of very loose sands. ***Canadian Geotechnical Journal,*** v. 34, p. 905-917. 1997.

ZLATOVIC, S., ISHIHARA, K. Normalized behavior of very loose non-plastic soils: effects of fabric. ***Soils Found.,*** v. 37, n. 4, p. 47–56, 1997.

Received: 12 September 2018 - Accepted: 04 February 2019.