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Evaluation of the Static Liquefaction Behaviour of Silty Tailings in Unsaturated Conditions

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Abstract **-** Tailing wastes are the products resulting from mining processes, consisting of a mixture of silt, clay and sand with variable quantities of water, chemical reagents and unrecoverable metals. They are usually discharged into storage areas known as tailing dams or tailing storage facilities (TSF), characterized by a wide surface exposed to the atmosphere whose interaction governs the position of the water table within the basin, and so the extension of the unsaturated zone above the phreatic surface. A detailed knowledge of the hydro-mechanical response of the discharged tailings represents a fundamental tool to reliably assess the stability of tailing dams to minimize the high rate of recent failures in which static liquefaction has been widely recognized as one of the major causes of dam collapse. Moving from these reasons, this research presents the main overcomes of an experimental campaign to investigate the static liquefaction response of silty tailings collected after the collapse of the Stava dams. The mechanical response of Stava tailings was studied by performing monotonic triaxial tests. The dependency of the static liquefaction behaviour on the sample preparation technique and on the degree of saturation (B-Skempton parameter) was investigated. The sample preparation method and degree of saturation were shown to affect the static liquefaction strength of the Stava tailings. The experimental results were in accordance with data from literature, and the Critical State Line of the unsaturated Stava tailings was estimated.

Keywords**:** static liquefaction; tailings; unsaturated soil; degree of saturation; tailing dams; preparation technique; *B*-Skempton parameter.

1. Introduction

The static liquefaction is a temporary loss of the shear strength of saturated loose soils when the pore water pressure became the same of normal stress. Mainly induced by external monotonic loads in undrained conditions ([11], [2]), the occurrence of the static liquefaction is associated to 25% of the worldwide collapses of active or closed TSF, causing fatalities and raising up economic and environmental damages ([12]). Moving from these reasons, this research gives the main overcomes of an experimental campaign to study the static liquefaction response of unsaturated tailing wastes which, when modelled numerically will result in a more accurate evaluation of the tailing dam safety ([4], [6]). Within certain initial densities ([9]), the influence of the preparation method and the degree of saturation on the static liquefaction strength has been evaluated by means of monotonic triaxial tests.

2. Testing material and experimental apparatus

The experimental campaign was carried out at Politecnico di Torino (Italy) on silty samples passing through 0.074 mm sieve (mesh sieve n°200), collected from the Stava dams failed in 1985 due to the occurrence of the static liquefaction phenomena. According to [8] and [9], liquid limit, plastic limit, plasticity index, specific gravity and hydraulic conductivity are respectively w_L=27.4%, w_P=18.0%, PI=9.4, G_S=2.828, k=10^{-7}m/s confirming the Stava silty tailings as a medium-low permeable, heavy soil. X-ray diffraction analysis showed that it was predominantly made of quartz, with relevant amount of calcite and fluorite ([5]). The static liquefaction behaviour of silt specimens (initial sizes: 38mm diameter, 76mm height) was investigated by means of monotonic triaxial tests were carried out on samples having different initial void ratio, water content and preparation methods: *i)* an external compaction (E.C.) was the procedure adopted to prepare samples TEST-1 and TEST-2; *ii)* the moist tamping technique (M.T.) was the method used to compact samples TEST-3-TEST-8 in order to reproduce one of the most common deposition techniques of the tailings inside the basins ([3]). The list of performed triaxial tests is given in Table 1.

Table 1: Initial state of Stava samples: preparation method, void ratio (e_0), water content (w_0), dry density (γ_d), B-Skempton parameter (B). State of the Stava samples at the end of the consolidation phase: void ratio (e_C), degree of saturation (Sr_C).

Sample	Preparation technique	e_0 (-)	w_0 (-)	γ_d (kN/m^3)	B (-)	e_c (-)	Sr_c (%)	Comments
TEST-1	E.C.	1.00	21.2	13.90	0.87	0.94	95.8	Not liquefied
TEST-2	E.C.	1.06	21.2	13.80	0.99	1.02	100.0	Not liquefied
TEST-3	M.T.	1.22	5.0	12.75	0.99	0.82	98.1	Liquefied
TEST-4	M.T.	1.23	5.0	12.65	0.98	0.84	97.2	Liquefied
TEST-5	M.T.	1.20	5.0	12.85	0.97	0.71	98.5	Liquefied
TEST-6	M.T.	1.25	5.0	12.59	0.96	0.79	97.0	Liquefied
TEST-7	M.T.	1.34	5.0	12.07	0.91	0.78	88.9	Not liquefied
TEST-8	M.T.	1.20	5.0	12.85	0.89	0.75	97.3	Liquefied

All the tests were performed by using a conventional Bishop and Wesley's cell. After the saturation of the samples at different B-values, they were isotropically consolidated (p_c=80 kPa) in drained conditions. The shearing phase was carried at constant radial effective stress in strain-controlled conditions. The sample was extracted from the cell, weighted and oven dried for 24 hours at 105°C. Finally, it was weighted to obtain the water content at the end of the consolidation phase, assuming no variations of water content during the undrained shearing phase. Starting from the definition of -B Skempton parameter proposed by Bishop (Eq. (1)) and following the homogenization models proposed by [10]. The relationship between the theoretical -B parameter (lower bound) and the degree of saturation was obtained by assuming an isotropic, elastic behaviour of the soil skeleton (porosity Φ=0.5) made of interconnected pores, a pore fluid composed by water (K_w=2.2GPa) and air (K_a=1.42·10^{-4}GPa), as given in Eq. (2) where $\Delta p'$ is the variation of the mean effective stress, and $\Delta\varepsilon_v$ is the associated variation of the volumetric strain exhibited during the consolidation phase ($K=\Delta p'/\Delta\varepsilon_v$).

$$B = \frac{K_f}{K_f + \phi \cdot K} \tag{1}$$

$$B = \left[\frac{K_w K_a}{(1-S_r)K_w + S_r K_a}\right] / \left[\frac{K_w K_a}{(1-S_r)K_w + S_r K_a} + \phi \cdot \frac{\Delta p'}{\Delta \varepsilon_v}\right] \tag{2}$$

3. Experimental results

The evidence of the preparation method on the mechanical behaviour of the Stava silty tailings is given by the comparison of the stress-strain behaviour for test TEST-1 and TEST-4 (Fig. 1). The two samples were prepared, respectively, by means of the externally compaction procedure and the moist tamping method. At the end of consolidation phase the degree of saturation of the two samples was similar, but the stress strain response was significantly different. TEST-1 showed a stress-hardening behaviour, while test TEST-4, even if denser than TEST-1, approached the steady state by means of a stress-softening behaviour. Similar considerations can be done by analysing the experimental outcomes provided by [7] on gold tailings having comparable initial densities, but different preparation techniques as given in Fig. 2. The static liquefaction strength of samples having a degree of saturation lower than 90% seems to be greater than samples in nearly saturated conditions, as shown in Fig. 3 by comparing test TEST-6 and TEST-7, having the same initial density, in good agreement with outcome obtained from standard soils (Hostun sand) tested at different -B values, as shown in Fig. 4. As proved by the non-linear relationship between -B value and Sr (Fig. 5) for Stava tailings, when the degree of saturation slightly decreased below the unit due to changes in suction, the -B Skempton parameter (and so the excess pore pressure Δu) was proved to be much lower than that in saturated conditions, leading to an increase in the soil's shear strength, and so strongly influencing the occurrence of the static liquefaction.

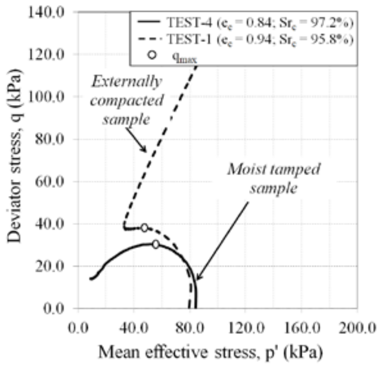


Fig. 1: Influence of the preparation method on the mechanical response of Stava tailings: effective stress paths.

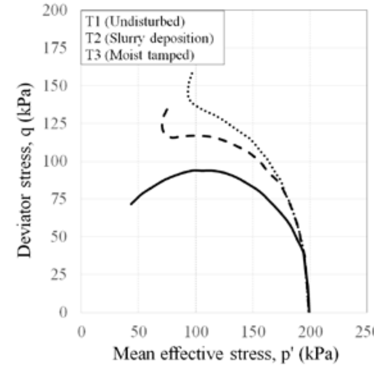


Fig. 2: Literature results - influence of the preparation method on the mechanical response of gold tailings ([7]).

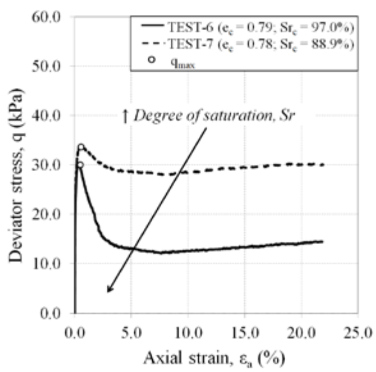


Fig. 3: Effect of the degree of saturation on the mechanical response of Stava tailings: stress-strain curves.

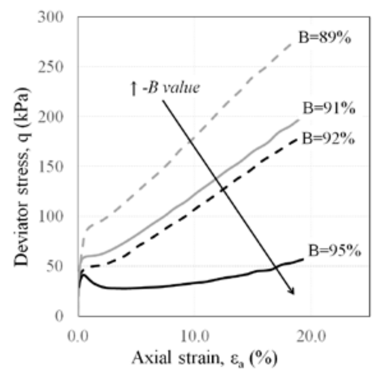
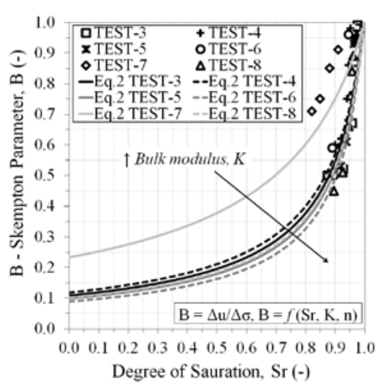


Fig. 4: Literature results - influence of the degree of sat. (-B value) on the mechanical response of Hostun sand ([1]).

The mechanical behaviour of Stava tailings was finally studied in the q-p' plane (Fig. 6) in which the transitional response of TEST-1 and TEST-2 was easily identified. M.T. samples exhibited a contractive behaviour, with the only exception of test TEST-7. The Critical Sate Line (CSL) was estimated (double solid line), giving M=1.3 in good accordance with those obtained by [9] on the same tailings under fully saturated conditions. The solid line passing through the peak deviator stresses of liquefied samples was the Instability Line (IL). According to [9], these outcomes suggested that samples showing a peak deviator stress between the CSL and the IL were not or less prone to liquefy.



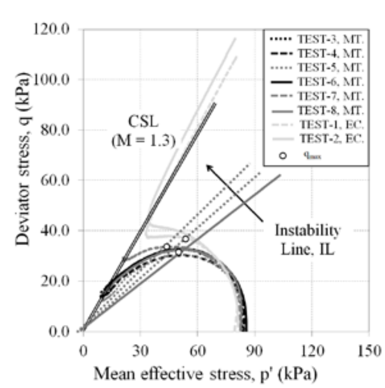


Fig. 5: Relationship between B-Skempton parameter - Sr, and experimental points (modified from [4]).

Fig. 6: Stress paths, CSL, IL and locus of q_{max} for unsaturated and nearly saturated Stava silty tailings.

4. Conclusion

This research has presented an insight of the mechanical response of the Stava silty tailings in unsaturated conditions, outlining the effects of the preparation technique and the degree of saturation on their static liquefaction behaviour:

- moist tamped silty samples showed a greater tendency to liquefy than those of the externally compacted samples. The experimental results were in a good agreement with literature data on gold tailings, deducting that the preparation technique affects the mechanical response of tailing wastes;
- an increase of the degree of saturation was proved to influence static liquefaction behaviour from a contractive response to a transitional behaviour. Degree of saturation equal to 90% seemed to represent a border value for Stava tailings: above this value, the strength was proved to strongly decrease. The experimental results were in a good agreement with literature data on more standard soils, and preliminary interpreted based on the correlation between B-Skempton parameter lower bound and the degree of saturation.
- outcomes of the current research were interpreted within the Critical State framework and, within the saturation states investigated, a unique CSL was found.

The outcome of this research finds their practical application as fundamental aspects for reliably assessing the stability of tailing dams, therefore improving their safety also after thier closure.

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