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Cyclic liquefaction behaviour of a moderately cemented grouted sand under repeated loading

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ABSTRACT

The aim of this paper is to provide an insight into the effects of a previous cyclic history "triggering" full liquefaction on the subsequent undrained cyclic behaviour of a moderately cemented grouted sand in terms of strength, deformability and pore pressure response. The research was conducted on sand specimens stabilized by a commercial mineral based chemical grout ("Silacsol"), capable of imparting unconfined compression strength (UCS) values ranging between 500 kPa and 700 kPa. Monotonic shear strength parameters of treated specimens were preliminary assessed through a series of isotropically consolidated drained triaxial tests (TX-CID). Afterwards, stress-controlled undrained cyclic simple shear (SS) tests were conducted on both treated and untreated sand specimens in order to evaluate the improvement provided by the grout on the liquefaction resistance of the sand. A significant beneficial effect of the grout was observed, regardless of the initial density of the pure sand. Finally the influence of a cyclic large preshearing on the undrained cyclic behaviour of the grouted sand was investigated by subjecting the specimens to a sequence of two cyclic loadings with the same stress ratio (CSR). After the first loading in which specimens were brought to full liquefaction, they were allowed to reconsolidate in approximately K_0 conditions and then subjected to the second loading. An increase in liquefaction resistance induced by cyclic history was clearly apparent on treated specimens.

Excess pore pressures build-up during the first cyclic loading on treated specimens followed a different trend compared to that observed on untreated ones. A significant difference was also observed on the excess pore pressure trends developed in the second loading compared to that developed in the primary loading. A simple model for the prediction of pore water pressure build-up of grouted sands during cyclic loading is proposed.

1. Introduction

Chemical grouting capable of inducing a moderate cementation is commonly used to improve mechanical and hydraulic properties of fine to medium sands. It also represents an efficient method for mitigating liquefaction risk of structures and lifeline systems that have been built on, or buried in liquefaction susceptible soils [1–6].

An extensive review of published laboratory tests carried out on grouted sands reveals that most previous research efforts have been focused on the following aspects: drained monotonic strength [7–9], shear modulus and damping [10–14], creep and fatigue behaviour [15,16], single event (first loading) liquefaction [17–21].

However, there have been few studies that deal with post-earthquake performance of treated sands [5,22,23]. One of the relevant issues concerning the performance of sand deposits improved by grouting technique during successive shocks, is the possible breakage of bonding between soil grains and ensuing microstructural changes of soil fabric that enhance excess pore pressure development. This topic is particularly relevant at sites where a number of high-magnitude aftershocks are likely to occur since it is feared that the main shock may be well resisted by bonding but cyclic stresses during subsequent shocks would not be.

Several studies on the influence of a previous seismic history ("cyclic preshearing"), involving small or large shear strains, have been conducted on uncemented/untreated sands [24–33]. The effect of specific factors influencing the undrained cyclic response of sands subjected to a previous cyclic preshearing, such as: void ratio and effective consolidation stresses, threshold axial strain or excess pore water pressure induced by cyclic loading, laboratory reconstitution method, direction of preshear (triaxial compression or extension), were investigated.

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Due to microstructural changes in soil fabric induced by cyclic preshearing, the liquefaction resistance of sand during the following aftershocks is expected to be different from that of "virgin" sand (i.e."without a previous seismic history") [34-36]. In particular, the above mentioned studies evidenced that in loose clean sands, a preshearing which induces large shear strains up to the onset of liquefaction, can increase the liquefaction susceptibility in subsequent earthquakes. Cases in which re-liquefaction phenomena were observed following severe repeated earthquakes have been reported in the literature (e.g. the 1983 Nihonkai Chubu earthquake [33], the 2011 Great East Japan Earthquake [37], the 2008 Wenchuan earthquake (China), the 2010-2011 earthquake sequence in Christchurch Earthquake (New Zealand)). Weakly or moderately cemented sands subjected to repeated cyclic loadings suffer bonding breakage and progressive decementation which could enhance the effects of preshearing compared to untreated sands.

Authors' previous work [20,21] have focused on undrained cyclic stress-strain-strength triaxial and simple shear response of weakly cemented sand samples treated by silicate-grout without taking into account the influence of a previous cyclic loading history.

The present paper reports an original experimental study concerning liquefaction and re-liquefaction cyclic undrained behaviour of a medium silica sand, moderately cemented by a commercial mineral-based (MB) chemical grout through a comprehensive laboratory investigation in an NGI type simple shear (SS) apparatus. This apparatus was adopted since it is capable of simulating more properly the stress conditions of in-situ soil both before and during a seismic event, even under repeated loading.

2. Tested materials

A natural medium sized silica sand dug out from Ticino river (TSM) was adopted. The grain size distribution of the sand is illustrated in Fig. 1.Other physical properties, such as particle specific gravity (G_s), maximum and minimum unit weight (γ_{max} and γ_{min}), uniformity coefficient (C_u), are summarized in Table 1.

The adopted grout consists of a commercial mineral-based (MB) chemical solution named "Silacsol", which is composed of an activated silica liquor with an inorganic calcium based reagent. This type of grout is a highly penetrating mix with two important advantages: it has no associated synaeresis and is less aggressive to the environment compared to the conventional silica gel. The reaction of the two components in the soil causes the precipitation of insoluble calcium silicate crystals with a structure very similar to hydrated cement. The treated soil is remarkably more stable and minimally subjected to creep. The adopted grout when used in sandy soils is capable of imparting a moderate cementation and drastically reducing their permeability. Actually a value of hydraulic conductivity coefficient $k \approx 10^{-11}$ m/s was obtained on treated specimens of loose TSM.

3. Test program

A preliminary series of unconfined compression strength tests (UCS) and isotropically consolidated monotonic drained triaxial tests (TX-CID) on grouted sand specimens, were performed to investigate the improvement of monotonic strength properties induced by the treatment. Some UCS tests were aimed at evaluating the effect of curing time on the strength properties of the treated soil. For the sake of brevity they have not been included in this paper. TX-CID tests on grouted specimens were carried out at the following effective confining stresses: 25 kPa, 50 kPa, 100 kPa and 150 kPa.

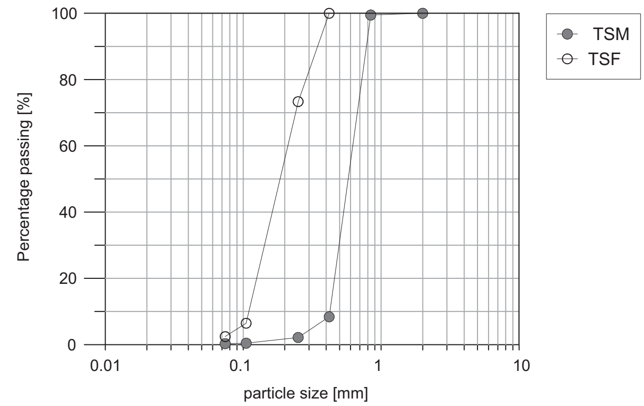

Fig. 1. Grain-size distribution curves of tested sands.

Table 1
Index properties of tested sands.

Sand	γ_{max} [kN/m^3]	γ_{min} [kN/m^3]	G_s	C_u	D_{50} [mm]
TSM	16.67	13.64	2.68	1.3	0.6
TSF	16.36	13.34	2.69	1.91	0.18

Subsequently, a series of undrained cyclic simple shear (SS) tests were carried out on treated specimens to determine cyclic stress-strain-strength response and excess pore pressure development of the grouted sand under repeated cyclic loadings.

Tests were conducted on specimens reconstituted at an initial density index (I_r) equal to 45% (loose state) and 60% (medium dense) and consolidated at an effective vertical consolidation stress (σ'_{vo}) equal to 100 kPa. The results obtained were compared with those gathered in companion tests conducted on untreated TSM consolidated at the same effective vertical stress.

In all SS tests performed in the present study, a cyclic shear strain in single amplitude $\gamma_{SA}=3.75\%$ was assumed as liquefaction criterion [38,39]. In order to better understand the influence of the initial vertical effective stress on the liquefaction resistance of treated specimens, some additional tests were also carried out with other values of σ'_{vo}, namely 50 kPa, and 150 kPa. A complete list of the tests is reported in Table 2.

4. Laboratory preparation of treated specimens

Grouted specimens were prepared by firstly pouring the sand into an aluminium split mould at the selected initial density index (I_r) using the dry deposition method, and then injecting the grout into the sample from the bottom of the mould. This procedure was adopted both for TX and SS tests with the only difference being in the size of the split mould that was 80 mm in diameter and 120 mm in height for SS tests, while it was 70 mm in diameter and 140 mm in height for TX tests. Fig. 2 shows a schematic picture of the adopted sample preparation system. Before grouting, in order to remove air-bubbles from sand, specimens were pre-saturated by first flushing with CO_2 and then forcing water to flow upward under low constant head. During flushing, a loading cap was mounted on the top of the sample and a small vertical load was maintained on it through a loading frame, monitoring the vertical displacement changes with a micrometre (Fig. 2). Afterwards, the grout was injected into the sample at low pressure (about 10 kPa).

The sample was left inside the mould for approximately 24 h, and then it was cured in moist conditions for a prefixed curing