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Effect of loading strain rate on creep and stress-relaxation characteristics of sandy silt

Amin Chegenizadeh [a,*], Mahdi Keramatikerman [b], Hamid Nikraz [a]

[a] Department of Civil Engineering, Curtin University of Technology, Kent Street, Bentley, Perth, Western Australia, 6102, Australia
[b] Arup Australia Services Pty Ltd, 61-73 Sturt Street, Townsville, Queensland, 4810, Australia

A R T I C L E I N F O

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A B S T R A C T

Silty soil is abundant in alluvium deposits within urban areas, and determination of its long-term settlement characteristics is a crucial issue. This study aims to investigate the effect of four different strain rates (i.e., 1, 0.1, 0.01, 0.001 mm/min) on the creep and stress-relaxation behaviour of a natural type of sandy silt by performing a series of triaxial compression tests. In monotonic (reference) tests, the peak deviatoric stress increased and the volumetric strain decreased by increasing the shearing rate. The results in greater shearing rates showed that the deviatoric stress curves have a greater quasi-elastic behaviour followed by a slight yield point. Also, an almost uniform behaviour was recorded in the deviatoric stress of the specimens tested at lower shearing rates. The creep testing showed that the specimens tested at greater initial shearing rates have a greater axial strain than those tested at lower shearing rates. Also, the stress-relaxation testing showed that the specimens tested at higher shearing rates have a greater relaxation than the specimens tested at lower initial shearing rates. A comparison between particle breakages that occurred in each testing condition showed that the particle breakage index (PBI) in a monotonic condition is 1.25 and 1.5 times (in average) greater than the creep and stress-relaxation tests respectively.

1. Introduction

Silt and sand are abundant geo-material throughout the world and many researchers tried to improve its mechanical behaviour [1–4]. Silt is categorised as a fine material similar to clay in geotechnical engineering, however the low-plasticity silt behaves the same as sand in many cases [5,6]. Boulanger and Idriss [7] categorised the fine-grained soil based on their plasticity index (PI) in a liquefaction study. They indicated that a fine-grained soil has a sand-like behaviour if its plasticity index (PI) is less than 7. Experimental investigation on the mechanical behaviour of silt started many years ago. For instance, Penman [8] performed a series of drained and undrained tests on silt and observed a dilative behaviour in both cases. To run the creep test triaxial testing was applied. Usage of traxial testing in geotechnical investigation has been also interest of researchers among them [9–12].

Investigation on the long-term settlement characteristics of soil has a great importance in ground improvement projects. These characteristics can be quantified through creep and stress-relaxation testing in the laboratory by conducting triaxial compression tests. This is an advanced method that considers the effect of confining pressure on soil.

Creep behaviour is a time-dependent process that is accompanied by soil deformation when subjected to a constant load over time. In general, the creep process causes a change in stress-strain characteristics of the soil over time [13]. Previous studies have reported the creep and stress-relaxation behaviour of different types of soil [14–16]. Sheahan [14] considered the creep behaviour of cohesive soils and they could correlate the time-dependent factor to use in constitutive modeling. Liu [15] considered the effect of confining pressure in creep modeling of gravelly soil and they reported that with increasing in confining pressure the creep strain increased. Enomoto [16] run a series of drained traixial to investigate creep and they found rate-dependant factors.

For instance, Sun et al. [17] investigated the creep behaviour of a slip zone consisting of clay and gravel by performing a series of drained triaxial compression tests. They recognised two creep stages of *decay* and *constant speed* for the tested soil. It was mentioned that the duration of the decay creep stage and the average creep rate at the secondary stage increased by increasing the stress level. In another example, Chen and Zhang [18] investigated the effect of stress continuity on dilative behaviour of the residual soil by a series of creep compression tests. They indicated that the PBI in creep compression tests have greater values in

* Corresponding author.
E-mail addresses: amin.chegenizadeh@curtin.edu.au (A. Chegenizadeh), mahdi.keramati@arup.com (M. Keramatikerman), h.nikraz@curtin.edu.au (H. Nikraz).

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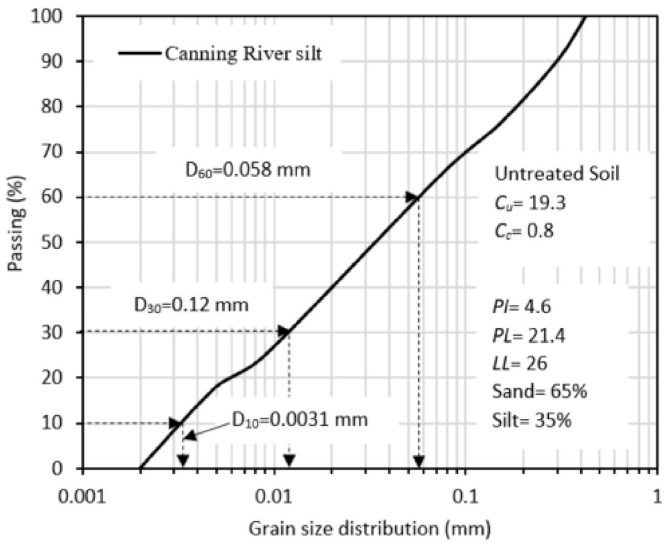

Fig. 1. PSD of the Canning sandy silt.

comparison with monotonic compression tests. They also mentioned that increasing the stress level and stress continuity caused particle damage by suppression of dilation. Karimpour and Lade [19] investigated the creep and stress-relaxation behaviour of sand and indicated that the changes in these characteristics happen due to the particle crushing and transformation of grain configurations and interlocking forces amongst soil particles. Hardin [20] introduced the PBI to quantify the occurred particle crushing in a particle size distribution (PSD) graph for granular soil.

In aforementioned literature, it has been determined that low plasticity sandy silt is an abundant and complicated geo-material that infrastructures are built on all around the globe and investigation of its long-term settlement characteristics has a crucial role in ground improvement projects. This study aims to investigate the creep and stress-relaxation behaviour of a natural type of low-plasticity sandy silt.

2. Soil used

The sandy silt was collected from the Canning river bank, located in Perth, Western Australia. Fig. 1 shows the particle size analysis conducted in accordance with ASTM C136 [21] and ASTM D4221 [22] on the soil used. The PSD analysis showed that this soil contains 65% silt and 35% sand. The relevant coefficient is presented in Fig. 1. The X-ray powder diffraction (XRD) analysis showed that the main constituent of the used soil is quartz and dolomite. The pycnometer specific gravity test conducted according to ASTM D854 [23] showed that the used soil has a specific gravity (Gs) of 2.72. Also, the results from soil index properties tests accomplished according to ASTM D4318 [24] showed that this soil has a liquid limit (LL) of 26, plastic limit (PL) of 21.4, and a plasticity index (PI) of 4.6. This soil is classified as ML [ASTM D2487 [25]]. Also, the measured maximum dry density and optimum moisture content (OMC) was 16.2 kN/m3 and 15.3% respectively [ASTM D1557, [26]. The analysis on scanning electron microscopic (SEM) images showed that the existing sand in the used soil has a sub-prismoidal and rounded geometry.

3. Methodology

In accordance with ASTM D7181 [27] an automated Bishop and Wesley triaxial apparatus [28] was used to model the creep behaviour. The tests were performed in a fully drained (CD) condition to avoid the generation of pore water pressure that causes changes in the effective confining pressure (σ'_3) during the test [13]. The tests were conducted in a temperature of 25 ± 1 °C to eliminate effect of the temperature on the specimens during the test. As the sandy silt is a fine soil and has a large bulking potential, the maximum and minimum void ratios (i.e., e_{max} and e_{min}) of specimens were determined using the slurry deposition technique proposed by Bradshaw and Baxter [29], which were equal to 1.08 and 0.44 respectively. Then, the specimens were prepared according to the under-compaction method by moist-tamping the soil [6]. The soil was compacted in mould in five layers until the maximum dry density ($\gamma_{d,\ max}$) was achieved [ASTM D1557 [26]]. After the completion of sample preparation (Diameter = 70-mm and height = 140-mm), specimens were saturated with the target value of 0.96. The specimens were consolidated at σ'_3 of 400 kPa. The amount of vertical deformation and volume changes were measured after the consolidation stage and the post-consolidation void ratio (e_f) values (i.e., 0.9% ± 0.05%). The tests conducted at four shearing rates of 1, 0.1, 0.01, and 0.001 mm/min and sieve analysis conducted at the end of each test to investigate PBI. Table 1 shows the experimental scheme used to perform the tests.

Table 1
Experimental program conducted on Canning River sandy silt.

No.	Test type	ID	σ'_3 (kPa)	Strain rate
1	Monotonic (Reference)	MS1	400	1
2		MS2	400	0.1
3		MS3	400	0.01
4		MS4	400	0.001
5	Creep	CS1	400	1
6		CS2	400	0.1
7		CS3	400	0.01
8		CS4	400	0.001
9	Stress-relaxation	RS1	400	1
10		RS2	400	0.1
11		RS3	400	0.01
12		RS4	400	0.001

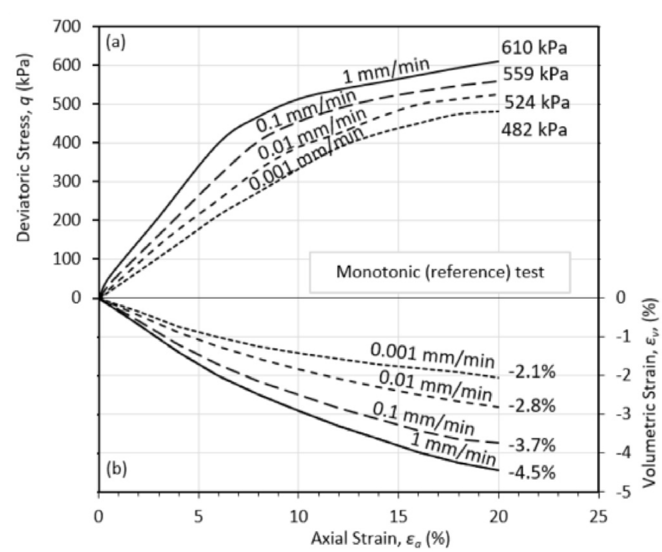

Fig. 2. Drained monotonic triaxial compression reference tests of the sandy silt specimens at loading strain rates of 1, 0.1, 0.01, and 0.001 mm/min under 400 kPa effective confining pressure (a) Deviatoric stress versus axial strain; (b) Volumetric strain versus axial strain.

4. Results and analysis

4.1. Monotonic triaxial compression test

To investigate the effect of shearing rate on the creep and stress-relaxation behaviour of sandy silt, it is necessary to investigate the behaviour of soil in a monotonic (reference) condition. Fig. 2 shows

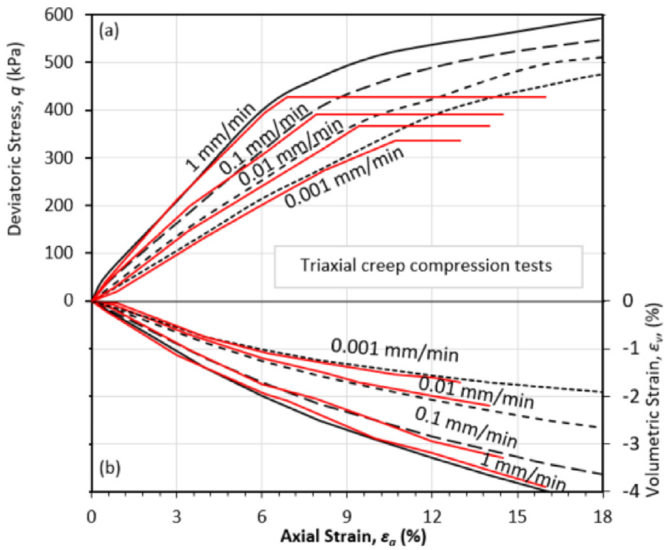

Fig. 3. Triaxial creep compression behaviour of the sandy silt specimens tested at 1, 0.1, 0.01 and 0.001 mm/min loading strain rate under 400 kPa effective confining pressure (a) Deviatoric stress versus axial strain; (b) Volumetric strain versus axial strain.

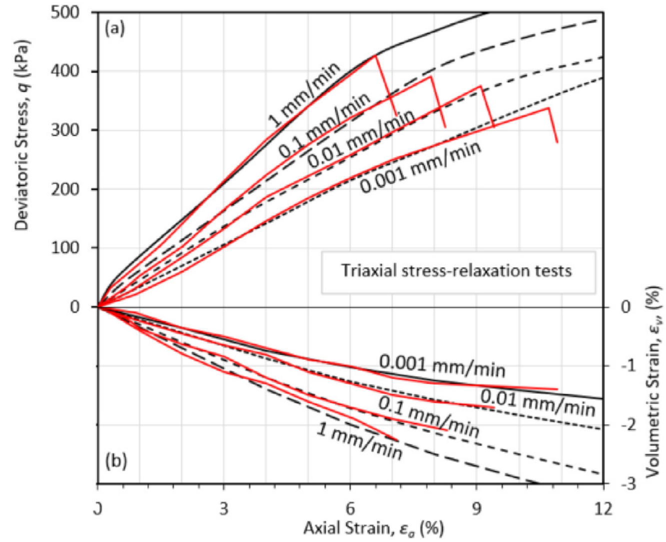

Fig. 4. Triaxial stress-relaxation behaviour of the sandy silt specimens tested at 1, 0.1, 0.01 and 0.001 mm/min loading strain rate under 400 kPa effective confining pressure (a) Deviatoric stress versus axial strain; (b) Volumetric strain versus axial strain.

variations in the deviatoric stress and volumetric strain with axial strain for monotonic compression tests at different strain rates under (σ'_3) of 400 kPa. It is seen from the figure that there is a slight yield point at the initial loading stage on stress-strain curves. This yield point is more apparent at higher shearing rates (i.e., 1 and 0.1 mm/min). The linear behaviour of the curves before the yield point is known as the quasi-elastic behaviour, and an increase in the strain rate incremented the quasi-elastic behaviour of the curves. After the yield points, the curves show a non-linear plastic deformation behaviour until the end of the tests, when its slope is slightly greater at higher strain rates. It is seen from Fig. 2(a) that the peak deviatoric strength of the specimens increased by increasing the shearing rate. For instance, when the tests were conducted at a shearing rate of 0.001 mm/min, a peak deviatoric strength of 482 was recorded at 20% axial strain. The peak deviatoric strength reached 524 kPa at 20% axial strain when the test was conducted at 0.01 mm/min. This value increased even more and reached 559 and 610 kPa when the tests were conducted at shearing rates of 0.1, and 1 mm/min respectively. Variations of the volumetric strains with axial strain were presented in Fig. 2(b). It is seen from the figure that increasing the shearing rate caused an increase in final volumetric strain of the specimens. For instance, when the sandy silt specimen was sheared at a strain rate of 0.001 mm/min, a final volumetric strain of −2.1% was recorded after 20% axial strain. Increasing the shearing rate to 0.01 mm/min caused an increase in final volumetric strain of the specimen to −2.8%. The final volumetric strains reached −3.7% and −4.5% when the specimens were sheared at strain rates of 0.1 and 1 mm/min respectively.

In general, the specimens tested at higher strain rates showed a more apparent yield point and plastic deformation behaviour, whereas, a more uniform deviatoric stress curve was recorded for the specimens tested at lower strain rate. This behaviour can be attributed to the longer periods of loading for the tests run at a lower strain rate that let a uniform deformation develop in the specimens. When the tests were conducted at high strain rates, the deformation of the specimens is not uniform and is localised in some parts of the specimens. This localised deformation provides stress in the parts of the specimens that carry the majority of the load. The yield limit increases due to limiting development of the plastic deformation by the mentioned localised deformations.

4.2. Effect of initial loading strain rate on subsequent creep

Triaxial creep compression tests were conducted on sandy silt specimens to investigate the effect of shearing rates on the creep behaviour of the soil. To conduct the creep tests, the specimens were initially sheared similarly to the monotonic condition until 70% of their peak deviator stresses. Then, the deviator stress was maintained for 50 h (i.e., 3000 min), and the axial and volumetric strains were recorded. Fig. 3 shows variations of the deviatoric stress and volumetric strain with axial strain for creep and superimposed reference tests at different shearing rates. A good coincidence for initial stages of the stress-strain and volumetric variation curves in the creep and reference tests highlights the repeatability of the test results. It can be seen that the tests with a greater initial loading strain rate show a greater amount of deviator stress and creep deformation (axial strain) during the constant loading duration. Also, the volumetric strain increased by increasing the initial shearing rate. For instance, when the tests were conducted at 0.001 mm/min a volumetric strain of −1.7% was recorded after around 13% axial strain. Increasing the shearing to 0.01 mm/min caused a greater volumetric strain of −2.2% after around 14% of axial strain. The specimens showed volumetric strains of −3.3% and −3.9% axial strain after around 14.5% and 16% when tested at shearing rates of 0.1 and 1 mm/min respectively.

Creep characteristics in soil are mainly due to the cumulative effects of the static fatigue of each particle [19]. When particles are located in the load transfer force chain developed through the contact point of particle break, sliding and rearrangement of broken particles result in change in the force chain. Over time, the number of particle to particle contacts is promoted. Since the applied deviatoric stress level is constant during creep, the stress level in individual particles is reduced and less particles break. Because of this, the rate of creep deformation is reduced with time in a creep test [30].

4.3. Effect of initial loading strain rate on subsequent relaxation stress

Triaxial compression stress-relaxation tests were conducted on the sandy silt specimens to investigate the effect of different shearing rates on the stress-relaxation of the sandy silt. The tests were conducted similarly to the monotonic condition of specimens tested at different shearing rates until 70% of the peak deviator stress. At this point the deviatoric stress was relaxed for 50 h. The variations of the deviatoric stress and

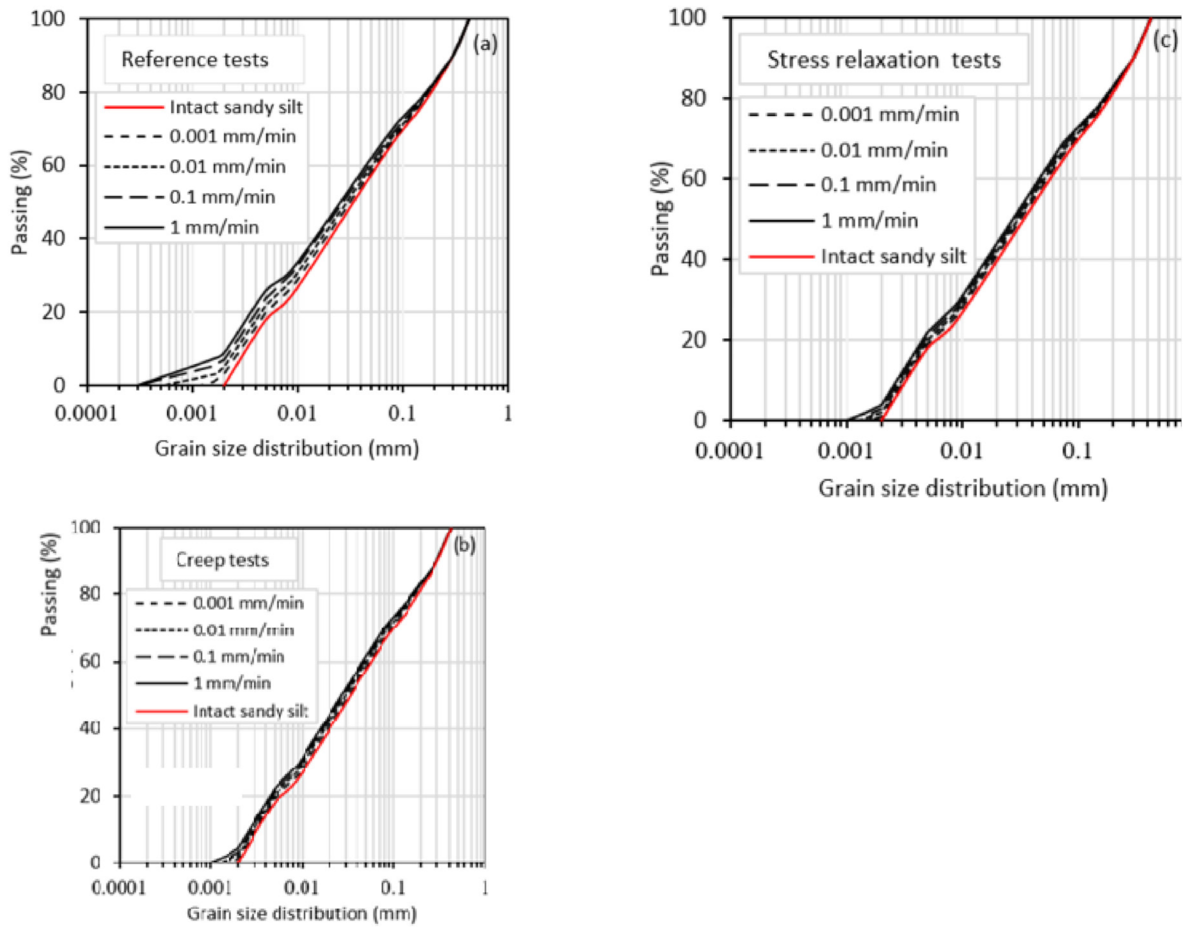

Fig. 5. Pre-test and post-test PSD of the sandy silt specimens; (a) Reference; (b) Creep; and (c) Stress-relaxation tests.

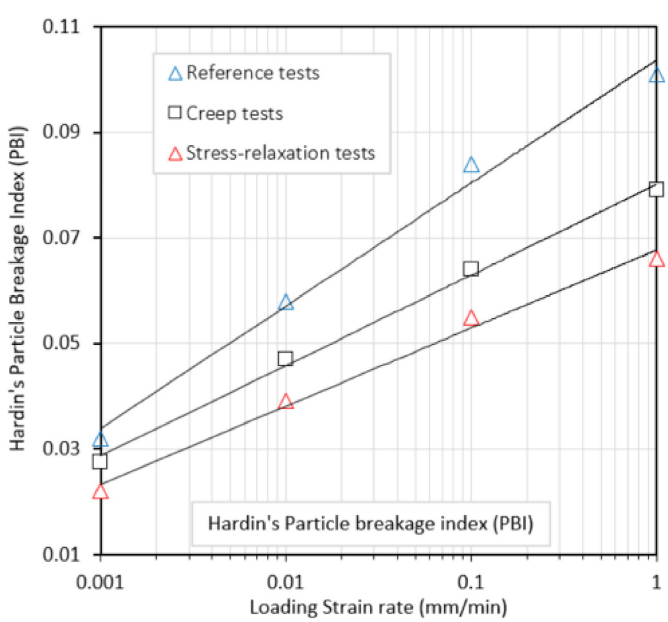

Fig. 6. Hardin's PBI after reference, creep, and stress relaxation tests.

volumetric strain with axial strain for stress relaxation and superimposed reference tests at different shearing rates were shown in Fig. 4. It is seen from the figure that there is good coincidence between acquired curves from reference tests and initial portions of the stress-relaxation tests, which highlights the repeatability of the results. Also, it is seen from the figure that the specimens tested at a greater strain rate have a greater value of stress-relaxation and volumetric strain after finishing stress-relaxation. For instance, the volumetric strain of the specimens is equal to −2.3%, −2.1%, −1.7% and −1.4% kPa after 1, 0.1, 0.01, and 0.001 mm/min initial loading strain rates and completion of the stress-relaxation stage respectively.

The particle breakage has a direct relation to static fatigue amongst soil particles in a stress-relaxation test. The specimens with a lower shearing rate have enough time to crush as required to be in an equilibrium state with its static fatigue state, therefore they showed a lower stress-relaxation [19].

4.4. Particle breakage analysis

To investigate the role of particle breakage on the creep and stress-relaxation behaviour of the tested soil, the PSD analysis was conducted on the soil after each reference, creep, and stress-relaxation test and the results were presented in Fig. 5. In all PSD graphs, the deviation of the curves is more pronounced at around 0.1 mm ≥ which highlights the cushioning behaviour of the larger particles [18]. Also, the deviations of the newly achieved PSD graphs were compared with the PSD graph of the original soil and were quantified based on the PBI introduced by Hardin [20]. Fig. 6 shows the results of these quantifications for monotonic, creep, and stress-relaxation tests at different shearing rates. It is seen from the figure that the particle breakage increased by increasing the shearing rate. Also, it can be seen that the computed PBI values in a monotonic condition are 1.25 times greater than the creep, and 1.5 times greater than the stress-relaxation condition.

5. Conclusions

This study investigated the effect of loading strain rate on the creep and stress-relaxation behaviour of sandy silt specimens by performing a series of triaxial compression tests. The results showed that increasing loading strain rate in a monotonic condition increased the peak deviatoric stress and decreased the volumetric strain of the specimens. Also, the results showed that the specimens tested at higher shearing rates have a greater quasi-elastic behaviour with a slight yield point in the deviatoric stress curves. In comparison, the specimens tested at lower shearing rates showed an almost uniform behaviour due to the longer period of the test. Identical trends and behaviour were recorded in the initial parts of the creep and stress-relaxation tests. Investigations on the effect of initial shearing rate in subsequent creep and stress-relaxation behaviour of the soil showed that the axial strain at higher shearing rates is greater than those in lower shearing rates due to static fatigue characteristics, and the stress-relaxations are more pronounced at higher shearing rates. A comparison between crushed particles in each testing condition showed that the PBI in a monotonic condition is 1.25 and 1.5 times (in average) greater than the creep and stress-relaxation tests respectively.

Declaration of competing interest

The authors confirm that there is no conflict of interests between the authors.

CRediT authorship contribution statement

Amin Chegenizadeh: Writing - original draft, Data curation, Visualization, Supervision, Project administration. **Mahdi Keramatikerman:** Writing - original draft, Data curation, Visualization. **Hamid Nikraz:** Writing - original draft, Data curation.

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