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Stress relaxation effect on uniaxial compressive strength values of a silt type soil

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Abstract. In this study, stress relaxation tests were carried out by keeping silt type soil specimens under different strain levels. Decreases in the stress values with time data was collected to better understand the effect of the strain level on the relaxation properties of soil specimens. In addition, the stress relaxation effect on the uniaxial compressive strength (UCS) values of the specimens was investigated with a series of tests. According to the results obtained from this study, the UCS values of the silt specimens significantly vary as a result of the stress relaxation effect. The UCS values were determined to increase with an increase of relaxation strain level to a threshold value. On the other hand, the UCS values were found to be affected adversely in case of high stress levels at the initiation of the relaxation, which are close to the peak level.

Keywords: compressive strength of silts; stress drop; stress relaxation; time-dependent effect

1. Introduction

Stress relaxation can be defined as the time-dependent reduction in stress values under a constant strain level. Time is an effective factor in terms of changing in the mechanical properties of soils. Sometimes stress relaxation is confused with the creep, which is another type of time-dependent event of deformation under a constant stress value condition. It is possible to find numerous studies about the effect of creep on strength values of soil materials in literature (Dob *et al.* 2016, Tran *et al.* 2018, Sabir *et al.* 2016, Wang *et al.* 2014, Kwok and Bolton 2013, Wang *et al*. 2021). However, stress relaxation of soils is a less studied topic compared to the creep. In case of being kept under a constant strain level, external stress values can significantly decrease because soils are granular materials and plastic deformations are induced at the grain contact surfaces by time (Lade *et al.* 2010, Yin *et al.* 2014, Staszewska and Cudny 2020). The stress relaxation is primarily resulted from gaining some amount of plasticity in case of keeping materials as strained for a time period.

Within previous studies, various parameters like grain size, grain shape, water content, confinement pressure from the second and third axes were studied and determined to have notable effect on the stress relaxation period and ratio (Sanchez-Giron *et al.* 2001, Lade and Karimpour 2015, Kutergin *et al.* 2013, Levin *et al.* 2019, Komurlu and Celik 2022). In this study, stress relaxation properties of silt type soils were investigated under various strain levels. Additionally, effect of different stress relaxation amounts on uniaxial compressive strength (unconfined compressive strength) values was tested with a series of experimental studies.

The stress relaxation occurs due to the start of plastic deformation and loss of the ability to revert previous length after loading. Even though a soil material is elastically deformed with a short-term loading condition, the plasticity is induced in case of keeping under a constant strain level by time. Depending on the stress relaxation amount, specimens can completely loose their elastic deformation property and the tendency to return to their lengths before loading.

Rate of the decrease in the stress values is high in the early stages of the stress relaxation. Then, the stress relaxation rate slows down in later stages. At the end of the stress relaxation, soil specimens with zeroed stress value fully keep its strain because of gaining plasticization and permanency in the strain (Kamao 2016, Liingaard *et al.* 2004, Wang and Xia 2021).

The particle size is another parameter which is effective on the relaxation properties of soils. Since the surface area and the contact number increase with a decrease in the particle size parameter, strain energies are relatively more in the fine grained soils in comparison with the soils with coarse particle sizes. Energy level is also a dependent of the time factor. As in the consolidation or creep deformations, the straining takes relatively long times for the fine soils like clays (Paul *et al*. 2021, Jun *et al*. 2021, Komurlu and Kesimal 2015a). As similar, an energy absorption process of relaxation due to the plasticization of the fine soils takes higher durations than those of the coarse particles (Komurlu 2021).

This study is aimed to be beneficial in terms of better understanding the effect of the strain relaxation event which is usually neglected in engineering designs and analyses on the strength values of soil materials. Additionally, time dependent changes in the stress values by the relaxation effect are determined in detail. Within this study, different strain levels and time periods were investigated to

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Fig. 1 Sieving for the specimen preparation

determine their effect on stress relaxation properties of a silt type soil specimens. The methodological details for the experimental study are given in the following title.

2. Materials and methods

All the soil specimen was sieved before tests to prepare them for passing the No. 50 (0.297 mm) sieve to use in the experimental study (Fig. 1). In addition, 65% of the soil specimen was determined to be under the No. 170 sieve aperture size of 0.090 mm, and 55% of the particles passed from the No. 200 sieve (0.075 mm). To classify the soil specimens from Giresun city of the Black Sea Region of Turkey, the Atterberg limits (Liquid limit and Plastic limit) were evaluated. The famous Casagrande test was carried out for determination of the liquid limit value. The methodology stated in the ASTM D4318-10 coded standard was followed in the Casagrande test. Soil and water mixtures were put in the Casagrande test cup and cut into two parts with the standard groove. The cup of the Casagrande test equipment was then dropped repeatedly by the motor until the groove is closed due to the flow of the soil and water mixture. The liquid limit was determined as the water content for closing the groove under the impact of 25 blows. In case of having a contact length of 13 mm, the test was stopped and the groove was considered to be closed (ASTM International 2010).

The water content was determined as the ratio of mass of water to mass of dry soil. To make dry soil, specimens were heated in the 105 °C stove for a day. The Plastic limit test is performed by repeated rollings of soil rods by hand on the standard glass plate. As stated in the ASTM D4318-10 coded test standard, the plastic limit was determined as the water content at which a thread of soil rods just crumbles when it is carefully rolled to a diameter of 3 mm (Fig. 2). To classify the soil specimen used in the experimental study, results obtained from sieve analysis and the Atterberg limit (liquid limit and plastic limit) tests were used in accordance with the unified soil classification system (USCS).

After the soil samples were brought from the field, they were put into the stove for a while to partly remove grain surface moisture. Then, they were crushed by impact using a straight surface mass block to separate the grains well before sieving. The separation of the grains is aimed to increase the amount of material passing under the No. 50 screen to use in tests. The sieved soil was kept in the laboratory at room temperature for two days and received some air humidity. Later on, the soil was mixed in a plastic basin after adding water with an amount of 9% of soil by mass and homogenized by hand. Then, soil specimens were filled in cylindrical moulds with the inner diameter of 46 mm. Some pictures from soil mixing and molding processes are given in Fig. 3. The purpose of adding some water before molding is to maintain the shape of the mould better. It was envisaged that a dry soil can spread while being removed from the mould. The specimens were filled into the moulds in three steps and 25 mallet drops were applied for the soil compaction after each filling steps.

The specimens with the ratio of height to diameter of 2 was kept at the room temperature for a day and removed from the moulds to use in the uniaxial compressive strength (unconfined compressive strength) test. The moulding and removing from the mould procedures were same for all the specimens tested within this study. Plastic pipes with the wall thickness of 2 mm and slit cuts along their lengths were used as moulds. The specimens were easily removed from their moulds by opening the slit. Roughness of the up-side end surfaces of the specimens was gently removed by using a snap blade knife to make a smooth contact with the loading platens. Additionally, the surface was flattened by mallet drops when the specimens are in the plastic moulds.

Totally, 16 specimens were used within this study. Some of the specimens were directly used in the uniaxial compressive strength (UCS) test without having a stress

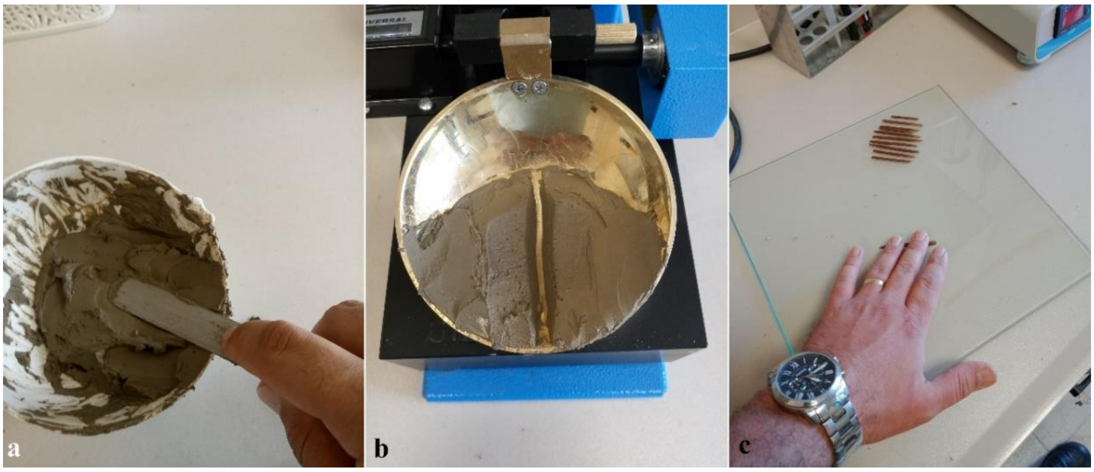

Fig. 2 Soil specimen homogenization for the Atterberg limits tests (a), liquid limit test (b) and plastic limit test (c)

Fig. 3 (a) Soil mixing, (b) soil moulding and (c) soil compaction in moulds

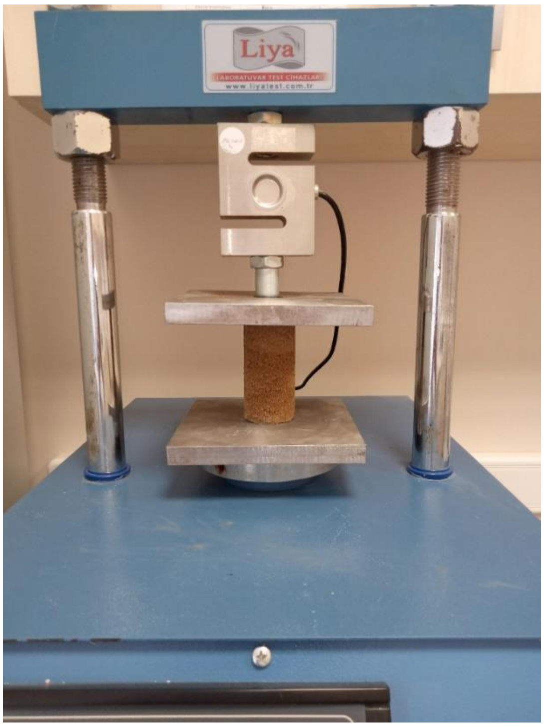

Fig. 4 Uniaxial compressive strength (UCS) test

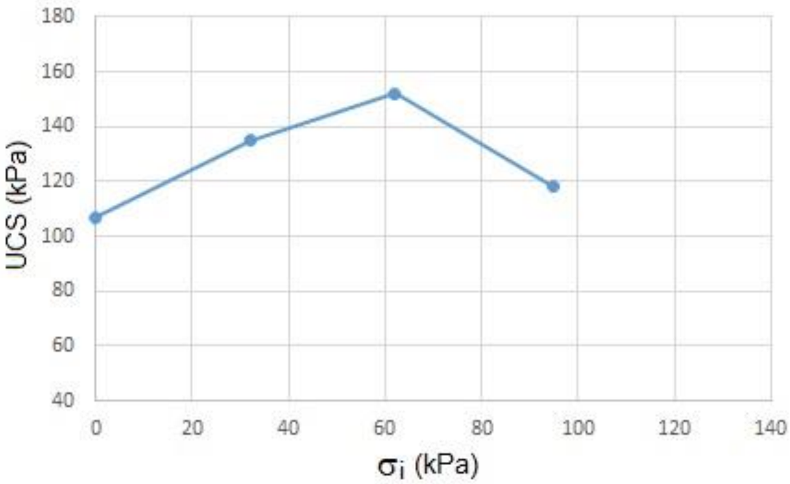

Fig. 5 UCS test results for various σ_i values

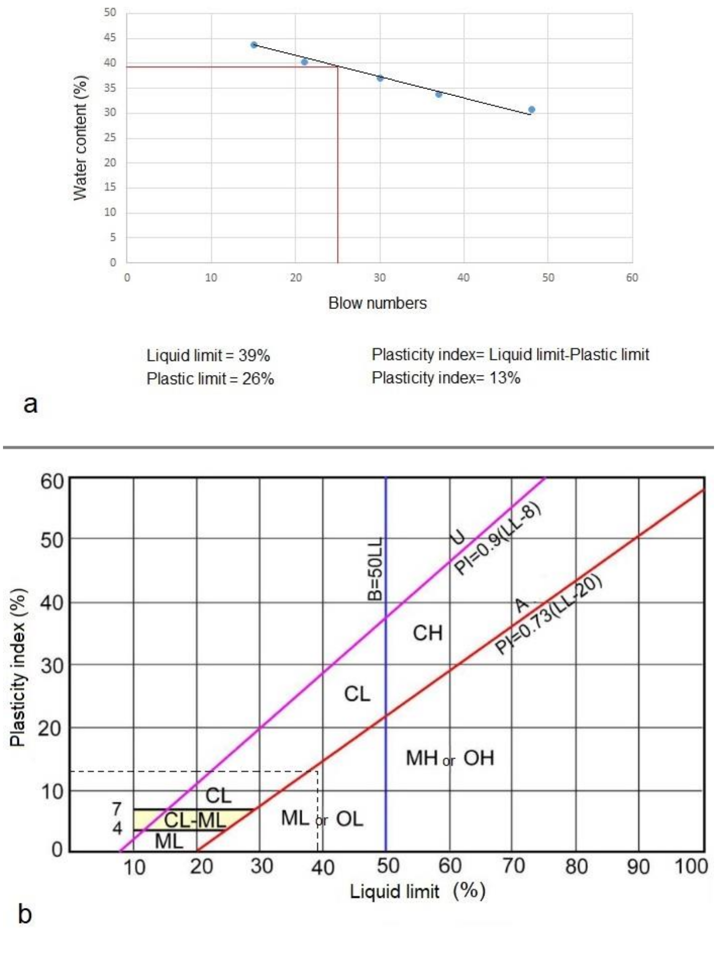

Fig. 6 (a) Liquid limit test results and (b) classification of the soil according to the Casagrande plasticity chart

relaxation, and the other ones were kept under various strain levels to investigate time-dependent variations in stress values due the relaxation. UCS tests of the specimens with the stress relaxation were performed after waiting until the load values dropped to zero. By this way, UCS values of specimens with and without the stress relaxation could be examined comparatively. The loading rate was chosen to be 0.5 mm/min in the UCS test. A sensitive electric motor press with the loading capacity of 50 kN was used to measure the load values during the uniaxial compressive strength test and the stress relaxation process (Fig. 4). To assess whether the soil specimens tested within this study

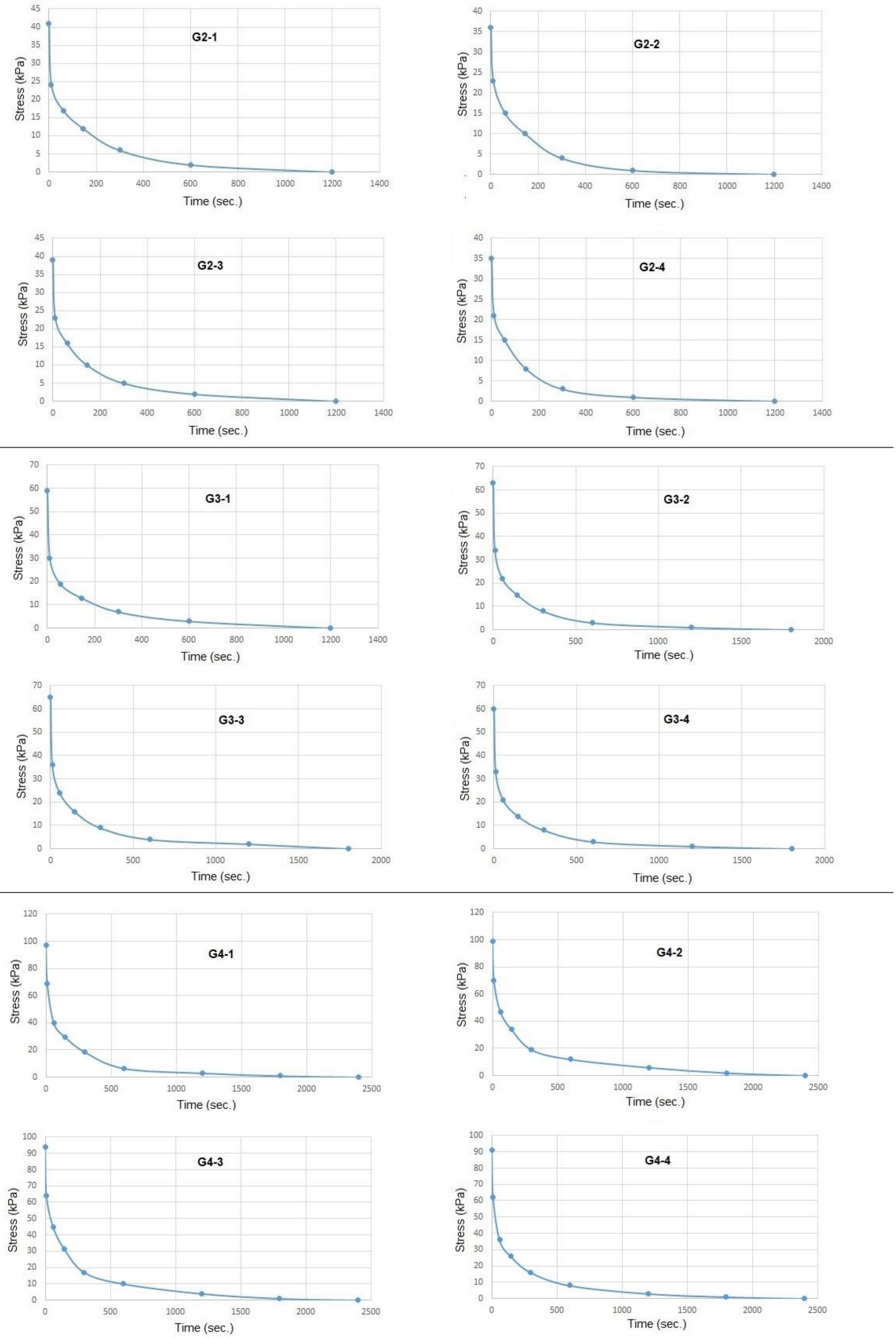

Fig. 7 Stress changes by the relaxation time

had similar void ratios, lengths of the samples were measured precisely and the density values were determined by weighing with 0.001 g sensitive electronic scales after the soil specimens were removed from the cylindrical plastic moulds.

3. Results

The liquid limit and plastic limit values were determined to be 39% and 26%, respectively. According to the unified soil classification system (USCS), the classification of the

Table 1 Stress level at the initiation of the relaxation (σ_i) values and densities of specimens (ρ) before the relaxation (SN: specimen number, SD: standard deviation)

Group	SN	σ_i (kPa)	SD for σ_i (kPa)	ρ (g/cm^3)	SD for ρ (g/cm^3)
G1	4	0	0	1.79	0.08
G2	4	38	3	1.77	0.10
G3	4	62	3	1.82	0.09
G4	4	95	4	1.76	0.07

Table 2 Stress (σ) variations for different relaxation periods

Replicate (Group)	σ_i (kPa)	σ after 10 sec (kPa)	σ after 60 sec (kPa)	σ after 150 sec (kPa)	σ after 5 min (kPa)	σ after 10 min (kPa)	σ after 20 min (kPa)	σ after 30 min (kPa)	σ after 40 min (kPa)
1 (G2)	41	24	17	12	6	2	0	-	-
2 (G2)	36	23	15	10	4	1	0	-	-
3 (G2)	39	23	16	10	5	2	0	-	-
4 (G2)	35	21	15	8	3	1	0	-	-
1 (G3)	59	30	19	13	7	3	0	-	-
2 (G3)	63	34	22	15	8	3	1	0	-
3 (G3)	65	36	24	16	9	4	2	0	-
4 (G3)	60	33	21	14	8	3	1	0	
1 (G4)	97	69	38	31	19	6	3	1	0
2 (G4)	99	70	47	35	18	12	6	2	0
3 (G4)	94	64	45	32	17	10	4	1	0
4 (G4)	91	62	36	27	16	8	3	1	0

Table 3 Uniaxial compressive strength (UCS) test results (SN: specimen number, SD: standard deviation)

σ_i (kPa)	Group	SN	UCS (kPa)	SD for UCS (kPa)
0	G1	4	107	6
38	G2	4	135	8
62	G3	4	152	9
95	G4	4	118	7

soil used in this study can be done in consideration of the Atterberg limits (Liquid and plastic limit) test results because more than 50% of the particles passed from the No. 200 sieve with the aperture size of 0.075 mm. The soil sample used in this study was classified to be a silt type cohesive soil. In more detail, it was found to be an ML coded inorganic silt type soil. Density values of the moulded specimens before the stress relaxation test are given in Table 1. The mean density value for all 16 specimens used in this study was determined to be 1.78 gr/cm^3, and the standard deviation of the density values did not exceed 6% of the mean value. Considering the similar density values, specimens were assessed to have close void ratios, which are proper for comparison of the results obtained from the laboratory study. Within the stress relaxation test, the data of stress variations with the change of time was measured as given in Table 2. According to the results, the stress relaxation rate was found to decrease with an increase in time. It was found that half of the decrease in the stress level was obtained within a minute, and the change in the stress levels was quite slow towards the end of the tests. All specimens completed their relaxation and had zeroed stress values in 40 minutes. The time for completion of variations in stress values was found to be lengthened as a result of increase in the stress level at the initiation of the relaxation (σ_i). As seen in Table 3, σ_i has also an important effect on the uniaxial compressive strength (UCS) test results. Even though UCS values were measured to increase with an increase in σ_i, the stress relaxation was found to have a negative effect on UCS values in case of having higher σ_i values than a threshold level (Fig. 5). According to the results obtained from the UCS test, the stress relaxation was assessed to have a nonignorable effect. The results obtained from the Casagrande liquid limit test are given in Fig. 6. Stress changes by the relaxation time are given in Fig. 7.

4. Discussions

The stress relaxation values for various σ_i levels were measured till the completion of the decrease in the load values. One of the main outcomes of this study is observing an increase in the time period for completion of the relaxation with an increase in the σ_i values. In other words, completion of the decrease in the stress values takes longer time with increasing strain level during the relaxation. The stress relaxation event occurs due to gaining the plasticity resulting from the energy supplied by an external load on the strained material. As the energy level increases with an increase in the strain level, it is expected to also have increase in gaining plasticization in deformation and time for completion of it. As confirmed by the results obtained from this study, the relaxation takes longer time under an increased energy level (Lade and Karimpour 2016, Li *et al.* 2013).

The stress relaxation was assessed to be quite rapid especially in early times that significant amount of decrease in the stress values occurred within several seconds, and a period of fourty minutes was enough for having completely dropped stress values of investigated specimens (Fig. 7). Results of other relevant studies are parallel to those obtained from this study that the stress relaxation rate decreases with an increase in time (Bagheri *et al.* 2019, Augustesen *et al.* 2004, Tong and Yin 2013).

Due to loading specimens to a strain level, void ratios of samples decrease and a compaction happens in the soil materials exposed to the stress relaxation. Therefore, it is assessed to be a well-estimated outcome to obtain an increase in the strength values after the stress relaxation. On the other hand, very high σ_i values were found to make a decrease in the UCS values. It is inferred that excessive stresses, which are close to the strength level can make an initiation of damage in soil specimens kept under a high strain case. Because high load levels cause initiation of micro-damaging or macro-damaging, the strength values of samples can be affected by excessive increases in the σ_i values (Dijkstra *et al.* 2019, Komurlu and Kesimal 2015, Hanley *et al.* 2015).

The compaction by being strained is also effective for variations in deformability properties such as the modulus of elasticity of soil materials. Contact conditions of grains and the void ratio can significantly change depending on the strain level. According to the results of some relevant studies, the modulus of elasticity and the stiffness of soil materials increase owing to the relaxation of the soil samples strained (Miksic and Alava 2013, Sheahan *et al.* 1994, Chegenizadeh *et al.* 2020).

The soil layer size effect is essential to consider for differences in time-wise properties. It is known that the stress relaxation takes longer time with an increase in the specimen size (Bock *et al.* 1991, Xu *et al.* 2018). Therefore, completion of the stress relaxation in the field is estimated to take much longer time in comparison with those of the laboratory specimens.

The particle size property and grading are important parameters in various mechanical aspects of soils (Azarafza *et al.* 2021, Zhou *et al.* 2018, Xin *et al.* 2019, Thomas and Rangaswamy 2020). In this study, it was aimed to investigate the effect of the stress relaxation on the UCS values of a silt type soil with a series of laboratory tests. Although the stress relaxation effect was found to significantly influence the change in the UCS values, it is neglected in engineering designs and analyses in many times. This study has an outcome to note that the effect of the stress relaxation on the UCS values is unneglectable. Depending on the strain level of the stress relaxation, UCS values can be improved. This study is aimed to contribute to better understanding the strength changes due to the stress relaxation effect. Because there are a limited number of studies on the topic of stress relaxation of soils in the current situation, new investigations will be beneficial for further analyses on its effect on various parameters of soil materials.

5. Conclusions

Following matters can be listed as the conclusion of this study:

- Stress change rate decreases with an increase in the stress relaxation duration.
- The stress relaxation has a notable effect on the UCS values of soil materials.
- The UCS values can significantly increase as a result of the stress relaxation effect depending on the stress level at the initiation of the relaxation (σ_i).
- In case of quite high σ_i values which are over a threshold level, the UCS values are inversely varied due to the relaxation effect.

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References

ASTM International (2010), "ASTM D4318-10: Standard test methods for liquid limit, plastic limit, and plasticity index of soils", *2010 Annual Book of ASTM Standards*, ASTM International, West Conshohocken, PA.

Augustesen, A., Liingaard, M. and Lade, P.V. (2004), "Evaluation of time-dependent behavior of soils", *Int. J. Geomech.*, **4**(3), 137-156. https://doi.org/10.1061/(ASCE)1532-3641(2004)4:3(137).

Azarafza, M., Nanehkaran, Y.A., Akgun, H. and Mao, Y. (2021), "Application of an image processing-based algorithm for river-side granular sediment gradation distribution analysis", *Adv. Mater. Res.*, **10**(3), 229-244. https://doi.org/10.12989/amr.2021.10.3.229.

Bagheri, M., Rezania, M. and Nezhad, M.M. (2019), "Rate dependency and stress relaxation of unsaturated clays", *Int. J. Geomech.*, **19**(12), 04019128. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001507.

Bock, R.G., Puri, V.M. and Manbeck, H.B. (1991), "Triaxial test sample size effect on stress relaxation of wheat en masse", *Trans. ASAE*, **34**(3), 0966-0971. https://doi.org/10.13031/2013.31757.

Chegenizadeh, A., Keramatikerman, M. and Nikraz, H. (2020), "Effect of loading strain rate on creep and stress-relaxation characteristics of sandy silt", *Result. Eng.*, **7**, 100143. https://doi.org/10.1016/j.rineng.2020.100143.

Dijkstra, J., Andò, E. and Dano, C. (2019), "Grain kinematics during stress relaxation in sand: not a problem for X-ray imaging", *E3S Web of Conferences*, **92**, 01001. https://doi.org/10.1051/e3sconf/20199201001.

Dob, H., Messast, S., Boulon, M. and Flavigny, E. (2016), "Treatment of the high number of cycles as a pseudo-cyclic creep by analogy with the soft soil creep model", *Geotech. Geol. Eng.*, **34**, 1985-1993. https://doi.org/10.1007/s10706-016-0078-7.

Hanley, K.J., O'Sullivan, C., Wadee, M.A. and Huang, X. (2015), "Use of elastic stability analysis to explain the stress-dependent nature of soil strength", *R. Soc. Open Sci*., **2**(4), 150038. https://doi.org/10.1098/rsos.150038.

Jun, S.H., Lee, J.H., Park, B.S. and Kwon, H.J. (2021), "Design charts for consolidation settlement of marine clays using finite strain consolidation theory", *Geomech. Eng.*, **24**(3), 295-305. https://doi.org/10.12989/gae.2021.24.3.295.

Kamao, S. (2016), "Creep And Relaxation Behavior of Highly Organic Soil", *Int. J. Geomate*, **11**(25), 2506-2511. https://doi.org/10.21660/2016.25.5301.

Komurlu, E. (2021). "An experimental study on stress relaxation of a silt type soil", *Yerbilimleri*, **42**, 70-84. https://doi.org/10.17824/yerbilimleri.774533.

Komurlu, E. and Celik, A.G. (2022). "An experimental study on stress relaxation behaviour of cement stabilized sands", *J. Geoeng*., **17,** 189-194. https://doi.org/10.6310/jog.202212_17(4).2.

Komurlu, E. and Kesimal, A. (2015a). "Experimental study on sulfide-rich mine tailings usage for short-term support purpose", *Geomech. Eng.*, **9**(2), 195-205. https://doi.org/10.12989/gae.2015.9.2.195.

Komurlu, E. and Kesimal, A. (2015b). "Experimental study of polyurethane foam reinforced soil used as a rock-like material", *J. Rock. Mech. Geotech. Eng.*, **7**(5), 566-572. https://doi.org/10.1016/j.jrmge.2015.05.004.

Kutergin, V.N., Kal'bergenov, R.G., Karpenko, F.S., Leonov, A.R. and Merzlyakov, V.P. (2013), "Determination of rheological properties of clayey soils by the relaxation method", *Soil. Mech. Found. Eng.*, **50**, 1-6. https://doi.org/10.1007/s11204-013-9201-4.

Kwok, C.Y. and Bolton, M.D. (2013), "DEM simulations of soil creep due to particle crushing", *Géotechnique*, **63**(16), 1365-1376. https://doi.org/10.1680/geot.11.P.089.

Lade, P.V. and Karimpour, H. (2016), "Stress drop effects in time dependent behavior of quartz sand", *Int. J. Solids Struct.*, **87**(1), 167-182. https://doi.org/10.1016/j.ijsolstr.2016.02.015.

Lade, P.V. and Karimpour, H., (2015), "Stress relaxation behavior in Virginia Beach sand", *Can. Geotech. J.*, **52**(7), 813-835. https://doi.org/10.1139/cgj-2013-0463.

Lade, P.V., Nam, J. and Liggio, C.D.J. (2010), "Effects of particle crushing in stress drop-relaxation experiments on crushed coral sand", *J. Geotech. Geoenviron.*, **136**(3), 500-509. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000212.

Levin, F., Vogt, S. and Cudmani, R. (2019), "Time-dependent behaviour of sand with different fine contents under oedometric loading", *Can. Geotech. J.*, **56**(1), 102-115. https://doi.org/10.1139/cgj-2017-0565.

Li, G., Ni, C., Pei, H., Wan-ming, G. and Ng, C.W.W. (2013), "Stress relaxation of grouted entirely large diameter B-GFRP soil nail", *China Ocean Eng.*, **27**, 495-508. https://doi.org/10.1007/s13344-013-0042-8.

Liingaard, M., Augustesen, A. and Lade, P.V. (2004), "Characterization of Models for Time-Dependent Behavior of Soils", *Int. J. Geomech*., **4**(3), 157-177. https://doi.org/10.1061/(ASCE)1532-3641(2004)4:3(157).

Miksic, A. and Alava, M.C. (2013), "Evolution of grain contacts in a granular sample under creep and stress relaxation", *Phys. Rev. E*., **88**, 032207. https://doi.org/10.1103/PhysRevE.88.032207.

Paul, M., Bakshi, K. and Sahu, R.B. (2021), "An analytical model for radial consolidation prediction under cyclic loading", *Geomech. Eng.*, **26**(4), 333-343. https://doi.org/10.12989/gae.2021.26.4.333.

Sabir, M.A., Umar, M., Farooq, M. and Faridullah, F. (2016), "Computing soil creep velocity using dendrochronology", *Bull. Eng. Geol. Environ.*, **75**, 1761-1768. https://doi.org/10.1007/s10064-015-0838-2.

Sanchez-Giron, V., Andreu, E. and Hernanz, J.L. (2001), "Stress relaxation of five different soil samples when uniaxially compacted at different water contents", *Soil Till. Res.*, **62**(3-4), 85-99. https://doi.org/10.1016/S0167-1987(01)00213-6.

Sheahan, T., Ladd, C. and Germaine, J. (1994), "Time-dependent triaxial relaxation behavior of a resedimented clay", *Geotech. Test. J.*, **17**(4), 444-452. https://doi.org/10.1520/GTJ10305J.

Staszewska, K. and Cudny, M. (2020), "Modelling the time-dependent behaviour of soft soils", *Stud. Geotech. Mech.*, **42**(2), 97-110. https://doi.org/10.2478/sgem-2019-0034.

Thomas, G. and Rangaswamy, K. (2020) "Strengthening of cement blended soft clay with nano-silica particles", *Geomech. Eng.*, **20**(6), 505-516. https://doi.org/10.12989/gae.2020.20.6.505.

Tong, F. and Yin, J.H. (2013), "Experimental and constitutive modeling of relaxation behaviors of three clayey soils", *J. Geotech. Geoenviron.*, **139**(11), 1973-1981. https://doi.org/10.1061/(ASCE)GT.1943-5606.0000926.

Tran, T.T.T., Hazarika. H., Indrawan, I.G.B. and Karnawati, D. (2018), "Prediction of time to soil failure based on creep strength reduction approach", *Geotech. Geol. Eng.*, **36**, 2749-2760. https://doi.org/10.1007/s10706-018-0496-9.

Wang, J. and Xia, Z. (2021) "DEM study of creep and stress relaxation behaviors of dense sand", *Comput. Geotech*., **134**, 104142. https://doi.org/10.1016/j.compgeo.2021.104142.

Wang, S., Zhan, Q., Wang, L., Guo, F., Liu, T. and Pan, Y. (2021), "Unsaturated creep behaviors and creep model of slip-surface soil of a landslide in Three Gorges Reservoir area, China", *Bull. Eng. Geol. Environ.,* **80**, 5423-5435. https://doi.org/10.1007/s10064-021-02303-5.

Wang, Y.F., Zhou, Z.G. and Cai, Z.Y. (2014), "Studies about creep characteristic of silty clay on triaxial drained creep test", *Appl. Mech. Mater*., **580-583**, 355-358. https://doi.org/10.4028/www.scientific.net/amm.580-583.355.

Xin, Z.H., Moon, J.H., Kim, L.S., Kim K.B. and Kim, Y.U. (2019), "Effect of arbitrarily manipulated gap-graded granular particles on reinforcing foundation soil", *Geomech. Eng.*, **17**(5), 439-444. https://doi.org/10.12989/gae.2019.17.5.439.

Xu, M., Hong, J. and Song, E. (2018), "DEM study on the macro- and micro-responses of granular materials subjected to creep and stress relaxation", *Comput. Geotech.,* **102**, 111-124. https://doi.org/10.1016/j.compgeo.2018.06.009

Yin, Z.Y., Zhu, Q.Y., Yin, J.H. and Ni, Q. (2014), "Stress relaxation coefficient and formulation for soft soils", *Geotech. Lett.*, **4**(1), 45-51. https://doi.org/10.1680/geolett.13.00070.

Zhou, C., Xu, C., Karakus, M. and Shen, J. (2018), "A systematic approach to the calibration of micro-parameters for the flat-jointed bonded particle model", *Geomech. Eng.*, **16**(5), 471-482. https://doi.org/10.12989/gae.2018.16.5.471.

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