Investigation of the Brittleness and Sensitivity of the Gypseous Sand Improved by Nano-clay

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ABSTRACT

This study examines the brittleness index and sensitivity ratio of two gypseous sand soils under saturation conditions improved by nano-clay. The soil samples were obtained from the cities of Al-Najaf and Tikrit containing 29% and 55% gypsum, respectively. The tests were performed on remolded specimens in a direct shear box. The soil specimens were examined mainly under saturated conditions for both different soil and nano-clay contents (0, 2, 5, and 7 %) under three normal stress levels: 25, 50, and 100 kPa. Additional tests were performed under dry soil conditions for comparison. The calculations of the brittleness index and sensitivity ratio of the saturated soil specimens were dependent on the newly suggested definitions of the peak values of the shear stress. The τ_P is the peak value in the dry condition, whereas the τ_R is the peak value in the saturation condition. The results emphasize that the values of the brittleness index and sensitivity ratio require more attention to the possibility that the soil is brittle owing to increased gypsum dissolution and the demolition of the soil structure. The brittleness index and sensitivity ratio increased with increasing gypsum content and decreased with increasing nano-clay content and average stress levels. The optimum percentage of nano-clay for both soil specimens was found to be 5%.

Keywords-brittleness index; direct shear test; gypseous sand; nanoclay; shear strength; sensitivity ratio

I. INTRODUCTION

Estimating the Brittleness Index (BI) is a prominent method for assessing soil-strain-softening tendency. When brittle materials fail for the first time, they frequently exhibit significant strength loss [1]. Brittleness indicates a decrease in the shear resistance of the soil after achieving its maximal strength [2]. The values of shear strength reduce throughout the first two weeks of the soaking process and then rise when the grains come back into contact after a month of soaking [3]. In a saturation process, the values of the angle of internal friction for soils with gypsum content of 29 and 55% decrease by approximately 25% [4]. Long-term water-soaking durations have a more complicated influence on settlement behavior than the parameters of shear strength [5]. Many variables, such as the permeability, wetting procedure, void ratio, gypsum content, soil wetting interval before loading, and initial saturation degree, affect the collapse potential [6-11]. More significantly, the mean net stress during the soaking process causes the unsaturated state of gypseous sand soil to collapse more severely [12-15]. Due to the re-bonding of the gypseous sand grains during the initial reduction of the matric suction (wetting), settlement dropped barely one week after the remolding [16]. The shear strength parameters were reduced by increasing the matric suction (dry condition) [17]. During the pre-loading curing process, in the oedometer collapse test, the gypsum did not cause fake re-bonding of the particles owing to the nano-clay [18]. It has been shown that 6% of nano-clay is the ideal percentage for decreasing gypsum dissolving [19].

According to previous test results, BI increases as the fine content increases and decreases when the effective normal stress increases [1]. Bishop [20] developed the concept of soil brittleness and defined the BI as the difference between the soil's peak (τ_P) and residual shear strength (τ_R), normalized by τ_P, as indicated in (1) [2]. The authors of [21] developed the BI connected to the soil Sensitivity Ratio (SR), as described in (2) [2]:

$$Brittleness\ Index\ (IB) = \frac{\tau_P - \tau_R}{\tau_P} \quad (1)$$

$$Sensitivity\ Ratio\ (SR) = \frac{\tau_P}{\tau_R} \quad (2)$$

BI ranges from 0 to 1. When BI is 0, the peak stress is equal to the residual stress, implying a ductile regime. When BI is 1, the residual stress is 0, an absolute brittleness regime.

Recent studies have used a strain control direct shear device on remolded specimens with a precise initial density to investigate the brittleness and sensitivity of gypseous sand, which is then improved with nano-clay and subjected to a soaking process.

II. RESEARCH MATERIALS AND METHODOLOGY

A. Soil

Two soil samples were collected from two locations: the northern district of Al-Najaf city, south of Iraq, named "GS-29," and Tikrit city, central Iraq, named "GS-55." Figure 1(a) and b show the grain size distribution and standard Proctor test results of the samples. Table I details the experimental results for identifying and classifying the soil samples. A non-toxic nano-clay, "Montmorillonite K10," with a particle size of 100 nm, density of 2.3-2.5 g/cm³, pH of 3-4, and a surface area of 220-270 m²/g, was added to the soil specimens [21].

TABLE I. RESULTS FROM THE SOIL SAMPLES TESTS

Test parameter	Values	
	GS-29	**GS-55**
Sand (%)	96.7	94.4
Fine (%)	2.65	5.6
Soil classification (USCS)	SP	SP-SM
Specific gravity (Gs)	2.38	2.54
Gypsum content (%)	29	55
Maximum dry density (gm/cm^3)	1.825	1.77
Optimum moisture content (%)	15	11.8

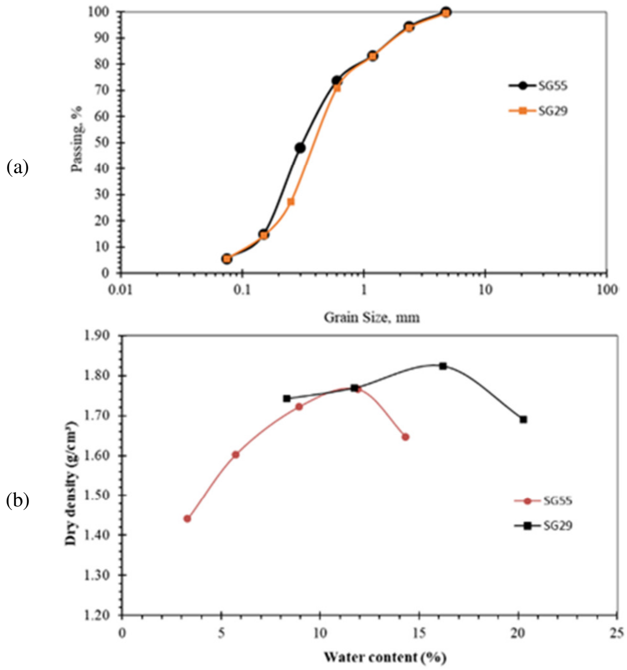


Fig. 1. Soil properties of GS-29 and GS-55. (a) grain size distribution of GS-29 and GS-55, (b) results of the standard Proctor test for GS-29 and GS-55.

B. Devices and Tools

A direct shear apparatus, which has a box area of 6×6 cm^2 and height of 2 cm was used for the tests. The device is shown in Figure 2. The tests were conducted at the Andera Engineering Tests Laboratory in Baghdad, Iraq. During testing, the strain was set to 1 mm/min and a constant strain method was used.

Fig. 2. Direct shear device.

C. Materials and Methods

The test was performed using a strain-controlled direct-shear instrument. The distributed soil specimens were remolded with a constant initial density of 1.643 gm/cm^3 for both soil samples (GS-29 and GS-55). The soil specimens were examined mainly under saturated conditions for both soils and different nano-clay contents (0, 2, 5, and 7 %) under three normal stress levels: 25, 50, and 100 kPa. Additional tests were performed under dry soil conditions for comparison. The calculations of BI and SR of the saturated soil specimens were based on the newly suggested definitions of the shear stress peak values. τ_P is the peak value under dry conditions and τ_R is the peak value under saturation conditions. The peak value of shear stress was controlled with a maximum strain of 10% of the sample length (6 mm). Table II illustrates the testing protocol.

TABLE II. SUMMARY OF THE TESTING PROTOCOL

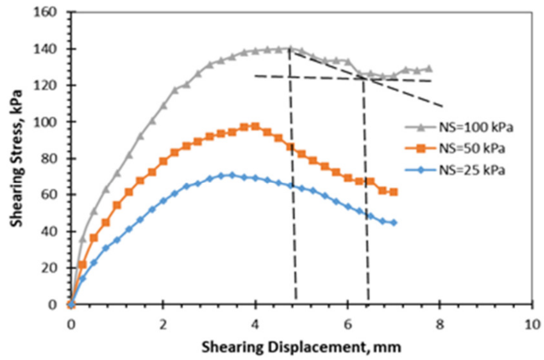
Test No.	Soil specimen	Saturation state	Nano-clay (%)	Normal stress (kPa)
1	GS-29	Dry	0	25
2				50
3				100
4		Saturated	0	25
5				50
6				100
7			2	25
8				50
9				100
10			5	25
11				50
12				100
13			7	25
14				50
15				100
16	GS-55	Dry	0	25
17				50
18				100
19		Saturated	0	25
20				50
21				100
22			2	25
23				50
24				100
25			5	25
26				50
27				100
28			7	25
29				50
30				100

III. RESULTS OF DIRECT SHEAR TESTS

A. Dry Specimens

Figure 3(a) presents the results of the shear stress versus shearing displacement under Normal Stress (NS) of 25, 50, and 100 kPa for GS-29 under dry conditions. The initial shear stress of the soil increased rapidly, i.e., the shear modulus of the soil apparently increased. The peak values were within ≤ 6 mm of the shearing displacement according to the failure criteria (10% strain). The shear stress then gradually decreased after the peak value, exhibiting strain-softening characteristics. This state may be attributed to the crushing process of the apparent cementing by gypsum under the peak value of the shearing stress. The peak-residual shearing stresses were 71-46, 98-67, and 140-127 kPa under normal stresses of 25, 50, and 100 kPa, respectively. Figure 3(b) shows the BI and SR calculated according to (1) and (2), respectively. These indices and ratios are related to the τ_P and τ_R from Figure 3(a) for each average stress level. The values of BI decreased with an increase in the normal stress (0.36-0.095), as also observed in the literature. The soil was in a medium to ductile state under a normal stress of 100 kPa, according to the values of BI (< 0.5), as shown in Figure 3(b). The values of the SR were less than 2 (1.6-1.1), indicating low sensitivity according to the literature [22]. With a higher gypsum material content (55%), GS-55 exhibited a different stress-strain behavior with a lower peak shearing stress than GS-29. However, the values of the peak stress were still within the failure strain range (≤6 mm or ≤10%), as shown in Figure 4(a). After reaching the peak value of shear stress, the shear stress did not decrease. The GS-55 sample exhibited strain hardening characteristics. The peak residual shearing stresses were 61-54, 93-91, and 136-135 kPa under normal stresses of 25, 50, and 100 kPa, respectively. The values of BI and sensitivity ratios were lower than those for specimen GS-29 as a result of the shear-strain behavior, i.e., ductile behavior. The values of BI were between 0.11 and 0.006, whereas the values of SR ranged from 1.12 to 1.

(a)



(b)

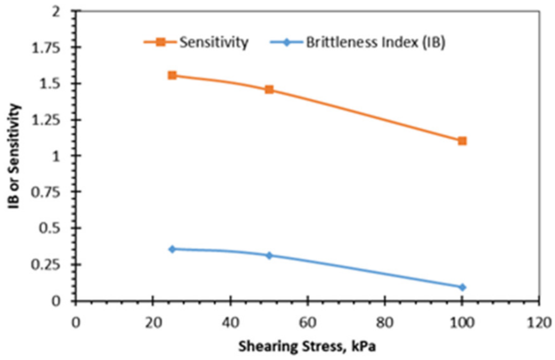


Fig. 3. (a) Shear stress vs. shearing displacement curves and (b) BI and SR curves for dry GS-29 samples.

B. Saturated Specimens

With the saturation process, there was a significant decrease in the peak values of the shearing stress within the greater shearing displacement for both soil specimens, GS-29 and GS-55, as shown in Figure 5. However, the specimen with a higher gypsum content (55%) exhibited a larger decrease in the shearing stress, which may have contributed to the larger dissolution of gypsum owing to the saturation process. Both soil specimens were in the hardening state after reaching failure, according to the criteria of 10% strain (6 mm). The peak shearing stresses were 33, 58, and 82 kPa for GS-29, and 26, 46, and 71 kPa for GS-55 under normal stress of 25, 50, and 100 kPa, respectively.

(a)

(b)

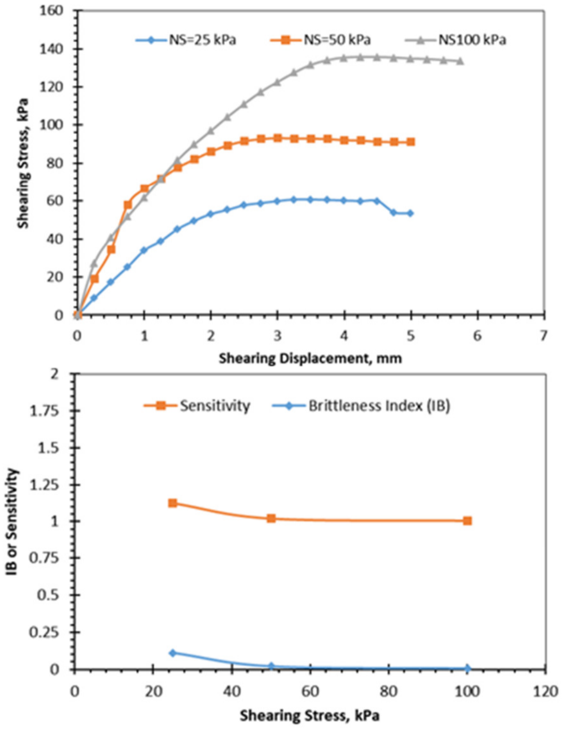


Fig. 4. (a) Shear stress vs. shearing displacement curves and (b) BI and SR curves for dry GS-55 samples.

(a)

(b)

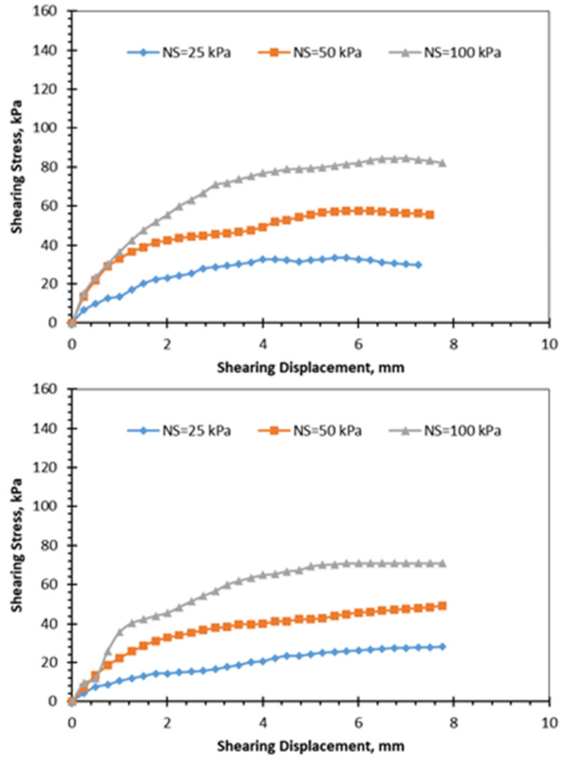


Fig. 5. a) Shear stress vs. shearing displacement curves after the saturation process for (a) GS-29 and (b) GS-55.

C. Nano-Clay Treated Specimens

For the improvement process, nano-clay was added to the soil, where it was supposed to cover the gypsum and decrease its solution in a saturated state. Figure 6 presents the shearing stress versus shearing displacement for both soil specimens with 2% nano-clay. There was a recovery in the peak shearing stress, and this recovery decreased with increasing gypsum content. The peak shearing stresses were 37, 72, and 94 kPa for GS-29, and 30, 49, and 91 kPa for GS-55 under normal stress of 25, 50, and 100 kPa, respectively.

(a)

(b)

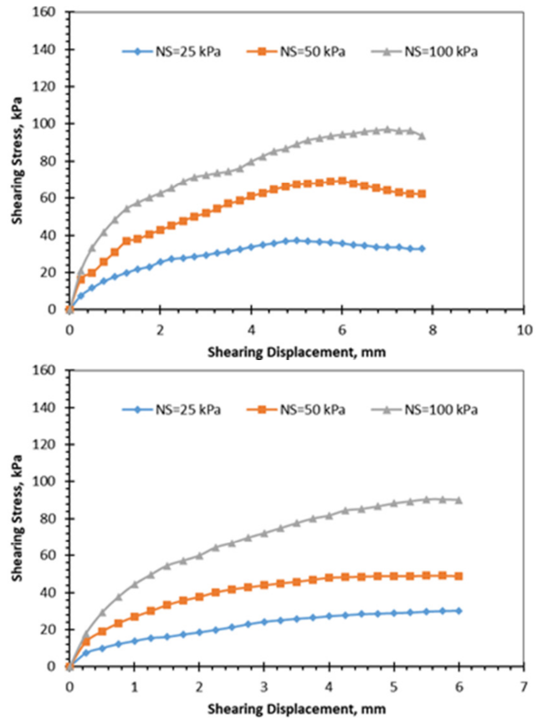


Fig. 6. Shear stress vs. shearing displacement curves with 2% nano-clay after saturation.

A slight change, or increase, in the values of the peak shearing stress was observed with the addition of 5% nano-clay, especially at the higher normal stress level (100 kPa), as shown in Figure 7. At the same time, these peak shearing stresses demonstrate a shearing displacement lower than that of the 2% nano-clay sample. The peak shearing stresses were 37, 72, and 100 kPa for GS-29, and 29, 50, and 93 kPa for GS-55 under normal stress of 25, 50, and 100 kPa, respectively. It is not worth increasing the nano-clay content to more than 5%. Figure 8 illustrates that there was no significant improvement in the shearing stress with the addition of 7% nano-clay. The peak shearing stresses were 35, 58, and 94 kPa for GS-29 and 29, 48, and 90 kPa for GS-55 under normal stress of 25, 50, and 100 kPa, respectively.

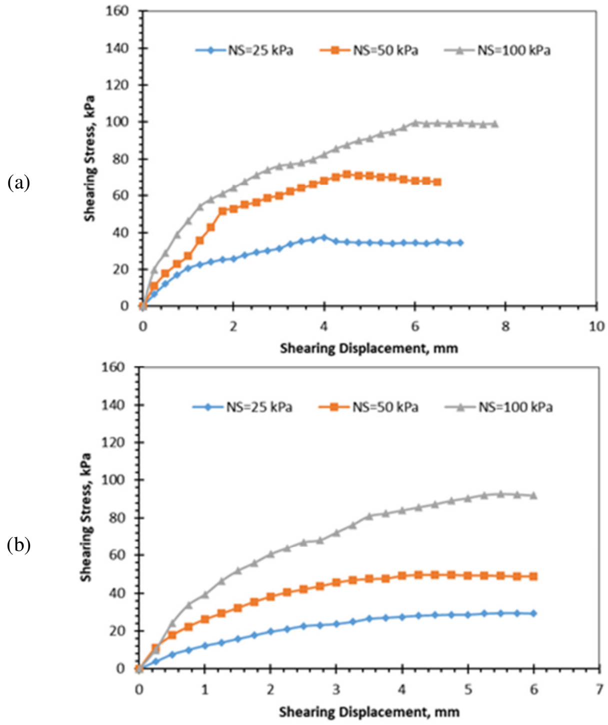


Fig. 7. Shear stress vs. shearing displacement curves with 5% nanoclay after saturation.

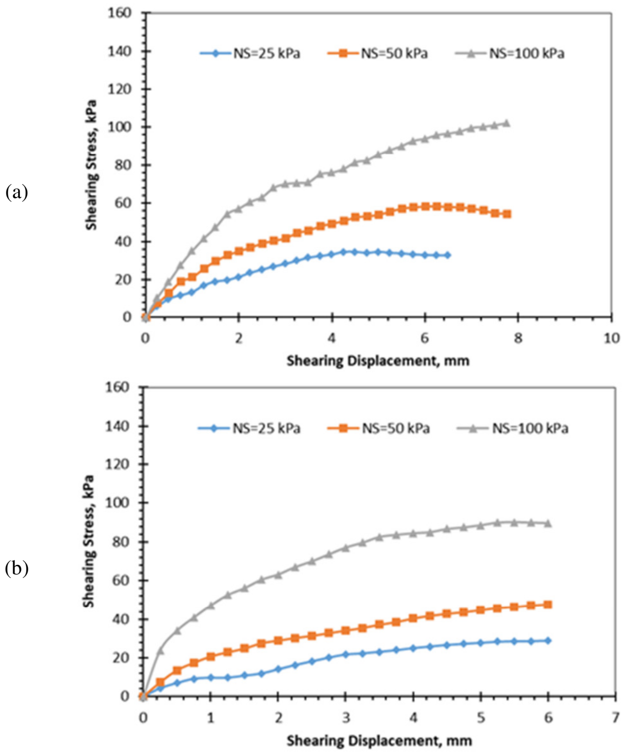


Fig. 8. Shear stress vs. shearing displacement curves with 7% nanoclay after saturation.

IV. BRITTLENESS AND SENSITIVITY FOR SATURATION CONDITIONS

To investigate the effect of saturation on the brittleness and sensitivity of the soil, modifications of (1) and (2) were made. The modifications are presented as new definitions for the peak and residual shear stress. The τ_P is the peak value in the dry condition, whereas the τ_R is the peak value in the saturation condition.

A. Brittleness Index

Figure 9 shows the values of the BI (see (1)), and the sensitivity ratio in (2), related to the new definitions of the peak values for both soils (GS-29 and GS-55). These values start from 0.5 and generally decrease with an increase in the normal stress and nano-clay content. The specimen with a higher gypsum content (55%) exhibited less effect when the nano-clay content was increased. In general, 5% was the optimum percentage of nano-clay for both soil specimens. The resulting values attract more attention to the possibility of soil brittleness due to increased gypsum dissolution and the demolition of the soil structure.

B. Sensitivity Ratio

Figure 10 presents the results of sensitivity ratios for the saturated soil specimens (GS-29 and GS-55) related to the new definitions of peak shearing stresses—similar trends to those in the brittleness index. The values of SR started to be larger than two and then decreased with an increase in the normal stress and nano-clay content. The SR of the saturation is more distinguishable, as for the BI, which increases with an increase in gypsum content. The nano-clay was effective for gypsum contents of less than 55%.

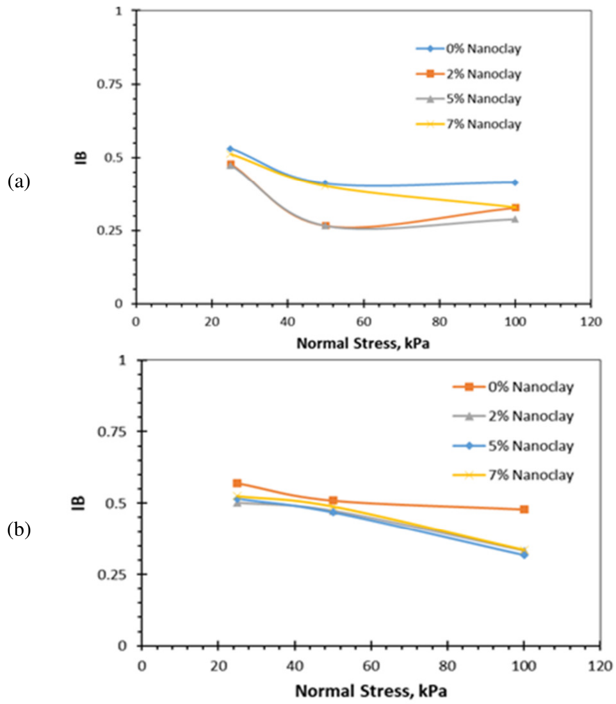


Fig. 9. IB values for saturated gypseous soil (a) GS-29 and (b) GS-55 with different nanoclay percentages and normal stress levels.

(a)

(b)

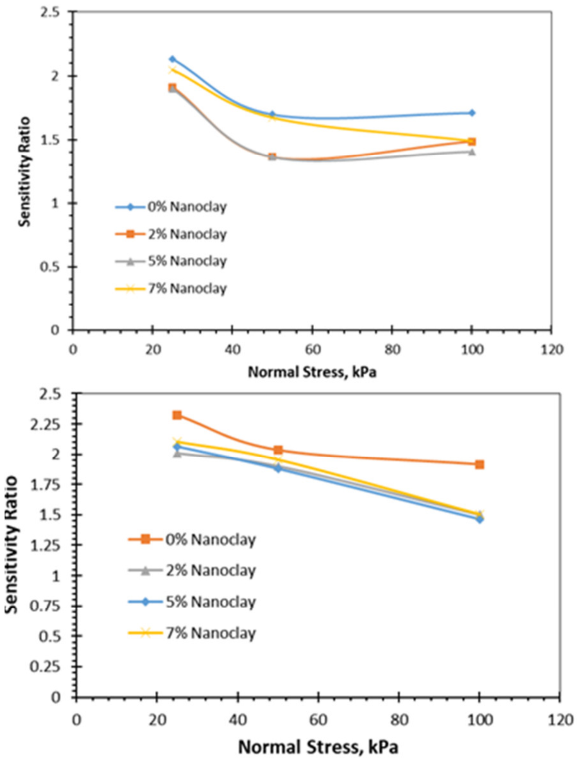


Fig. 10. The SR values for saturated gypseous soil (a) GS-29 and (b) GS-55 with different nano-clay percentages and normal stress levels.

C. Fitting Equation

Equations (3) and (4) were used as fitting models to predict the BI and SR with R^2 of 0.72 and 0.98, respectively:

$$BI = 0.53 + 0.25 * log_{10}(GC) - 0.025 * \sqrt{Nc} - 0.27 * log_{10}(NS) \quad (3)$$

$$SR = IB * 4.2 \quad (4)$$

where *GC* is the gypsum content (%) in the soil specimen, *Nc* is the added nano-clay (%), and *NS* is the normal stress (kPa).

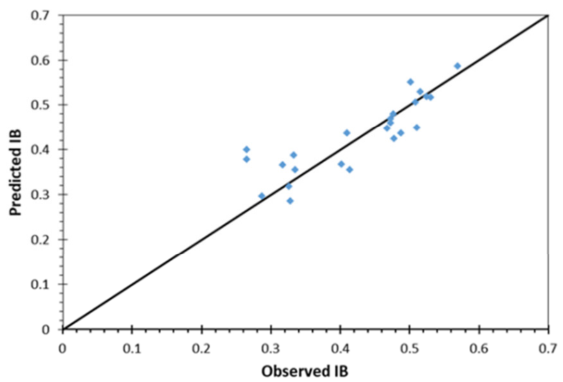


Fig. 11. Relationship between predicted and observed BI.

Equation (3) emphasizes that the BI increases with increasing gypsum content and decreases with increasing nano-clay and normal stress levels. Within the ranges of gypsum and nano-clay content, nano-clay was less significant among the studied factors. A direct relationship exists between BI and SR, as shown in (4). Figures 11 and 12 illustrate the correlation between the observed and predicted values of BI and SR.

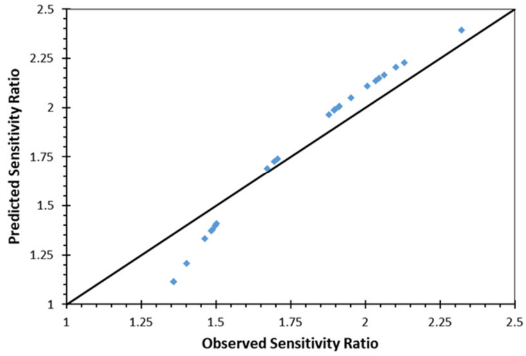


Fig. 12. Relationship between predicted and observed SR.

V. CONCLUSIONS

This study assessed the Brittle Index (IB) and Sensitivity Ratio (SR) for two gypseous sand soils, containing 29% and 55% gypsum, under dry and saturated conditions. The BI and SR of the soil were calculated using standard formulas. However, a new suggested definition of the peak and residual shear stress, where the τ_P is the peak value in the dry condition and the τ_R is the peak value in the saturation condition. The resulting values of BI and SR require more attention to the possibility of soil brittleness due to increased gypsum dissolution and the demolition of the soil structure. BI started at 0.5, and generally decreased with an increase in the normal stress and nano-clay content, which matches the literature observations. The values of the SR started to be larger than two and then decreased with an increase in the normal stress and nano-clay content. 5% was found to be the optimum amount of nano-clay addition for both soil specimens according to the improvement level. A fitting model was proposed, which can predict the BI with an R^2 of 0.72 by using the gypsum and nano-clay content (%), and average stress (kPa). A direct relationship was observed between BI and SR, with an R^2 value of 0.98.

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REFERENCES

[1] N. P. G. Amali, H. R. Maduranga, and A. R. P. Weerasinghe, "Experimental Study on Residual Shear Strength of Soil Using Undrained Ring Shear Apparatus," in *Progress in Landslide Research and Technology*, vol. 3, B. Abolmasov, I. Alcántara-Ayala, Ž. Arbanas, D. Huntley, K. Konagai, S. Mihalić Arbanas, M. Mikoš, M. V. Ramesh, K. Sassa, S. Sassa, H. Tang, and B. Tiwari, Eds. Cham: Springer Nature Switzerland, 2024, pp. 387–395.

[2] J. Herza, K. Smith, and R. Singh, "Accounting for brittleness in tailings storage facilities," presented at the Australian National Committee on Large Dams, Hobart, Australia, 2021.

[3] M. S. Mahmood, W. H. Al-Baghdadi, A. M. Rabee, and S. A. Almahbobi, "Reliability of Shear-Box Tests Upon Soaking Process on

the Sand Soil in Al-Najaf City," *Key Engineering Materials*, vol. 857, pp. 212–220, 2020, https://doi.org/10.4028/www.scientific.net/KEM.857.212.

[4] M. S. Bilal Muiassar, H. N. Salami, M. J. Abrahim, M. Sh. Mahmood, and S. A. H. Aldarraji, "Nanoclay-Depended Treatment on the Mechanical Behavior of a Collapsable Soil." To be published.

[5] M. Mahmood, "Effect of Soaking on the Compaction Characteristics of Al-Najaf Sand Soil," *Kufa Journal of Engineering*, vol. 9, no. 2, pp. 1–12, Apr. 2018, https://doi.org/10.30572/2018/KJE/090201.

[6] M. M. Abdalhusein, A. Akhtarpour, and M. S. Mahmood, "Effect of Soaking on Unsaturated Gypseous Sand Soils," *International Journal of Civil Engineering and Technology*, vol. 10, no. 5, pp. 550–558, May 2019.

[7] M. S. Mahmood, A. Akhtarpour, R. Almahmodi, and M. M. A. Husain, "Settlement assessment of gypseous sand after time-based soaking," *IOP Conference Series: Materials Science and Engineering*, vol. 737, no. 1, Feb. 2020, Art. no. 012080, https://doi.org/10.1088/1757-899X/737/1/012080.

[8] M. S. Mahmood, L. J. Aziz, and A. M. B. Al-Gharrawi, "Settlement Behavior of Sand Soil Upon Soaking Process," *International Journal of Civil Engineering and Technology*, vol. 9, no. 11, pp. 860–869, Nov. 2018.

[9] A. H. Rasheed and B. A. Ahmed, "Study the Behaviour of the Natural Clay Soil Shallow Foundation System Subjected to Impact Loads," *Journal of Engineering*, vol. 30, no. 03, pp. 110–128, Mar. 2024, https://doi.org/10.31026/j.eng.2024.03.08.

[10] A. H. Rasheed and B. A. Ahmed, "Dynamic monitoring of saturated stiff clay soil foundation structure by falling weight deflectometer system under impact loads sensors effect," *Measurement: Sensors*, vol. 25, Feb. 2023, Art. no. 100673, https://doi.org/10.1016/j.measen.2023.100673.

[11] B. A. Ahmed and A. H. Rasheed, "Experimental Analysis of the Dynamic Response of Saturated Clayey Soil Under Impact Loading," *Engineering, Technology & Applied Science Research*, vol. 12, no. 6, pp. 9787–9794, Dec. 2022, https://doi.org/10.48084/etasr.5388.

[12] A. L. Hayal, A. M. B. Al-Gharrawi, and M. Y. Fattah, "Collapse Problem Treatment of Gypseous Soil by Nanomaterials," *International Journal of Engineering*, vol. 33, no. 9, pp. 1737–1742, Sep. 2020, https://doi.org/10.5829/ije.2020.33.09c.06.

[13] M. S. Mahmood and M. J. Abrahim, "Effect of Matric Suction on Deformation of Gypseous Sand Using Modified Oedometer," *International Journal of Engineering*, vol. 34, no. 12, pp. 2636–2641, Dec. 2021, https://doi.org/10.5829/ije.2021.34.12C.08.

[14] M. J. Abrahim and M. S. Mahmood, "Water Volume Change Due to Wetting of Unsaturated Gypseous Sand Using Modified Oedometer," *IOP Conference Series: Earth and Environmental Science*, vol. 856, no. 1, Sep. 2021, Art. no. 012048, https://doi.org/10.1088/1755-1315/856/1/012048.

[15] S. M. Saleh and M. S. Mahmood, "Behavior of load-settlement-time for short-term wetting in unsaturated test of Al-Najaf gypseous soil," *AIP Conference Proceedings*, vol. 2787, no. 1, Jul. 2023, Art. no. 080023, https://doi.org/10.1063/5.0148016.

[16] M. S. Mahmood and M. J. Abrahim, "Sensitivity of unsaturated tests results for time-based remolded gypseous sand specimens," *AIP Conference Proceedings*, vol. 2864, no. 1, Jan. 2024, Art. no. 030004, https://doi.org/10.1063/5.0186102.

[17] M. M. Abdalhusein, A. Akhtarpour, R. Almahmodi, and M. Sh. Mahmood, "Investigation of Shear Strength Parameters for Gypseous Soils Using a Modified Apparatus of Triaxial Test," in *Current Trends in Geotechnical Engineering and Construction*, Singapore, 2023, pp. 317–330, https://doi.org/10.1007/978-981-19-7358-1_27.

[18] S. A. Aldarraji, N. Ganjian, and M. S. Mahmood, "Mechanical Behavior of Pre-Test-Curing Nanoclay-Treated Gypseous Sand," in *BIO Web of Conferences*, vol. 97, 2024, Art. no. 00040, https://doi.org/10.1051/bioconf/20249700040.

[19] S. Aldarraji and N. Ganjian, "Interaction of Curing and Soaking on Collapse Potential of Nanoclay-Treated Soil," *Journal of Engineering and Sustainable Development*, vol. 28, no. 4, pp. 480–485, Jul. 2024, https://doi.org/10.31272/jeasd.28.4.7.

[20] E. Bishop, *Foundations of Constructive Analysis*. New York: McGraw-Hill, 1967.

[21] K. Terzaghi, B. R. Peck, and G. Mesri, *Soil Mechanics in Engineering Practice*. New York: Wiley, 1996.

[22] C. A. Bareither, C. H. Benson, and T. B. Edil, "Reproducibility of Direct Shear Tests Conducted on Granular Backfill Materials," *Geotechnical Testing Journal*, vol. 31, no. 1, pp. 84–94, Jan. 2008, https://doi.org/10.1520/GTJ100878.