Geomechanics and Engineering, *Vol. 25, No. 2 (2021) 89-98*
DOI: https://doi.org/10.12989/gae.2021.25.2.089

Shear strength behaviour of coral gravelly sand subjected to monotonic and cyclic loading

Anh-Tuan Vu*

Le Quy Don Technical University, Hanoi, Vietnam

(Received October 8, 2020, Revised February 17, 2021, Accepted March 27, 2021)

Abstract. The paper presents an experimental study on the strength behaviour of a coral gravelly sand from Vietnam subjected to monotonic and cyclic loading. A series of direct shear tests were carried out to investigate the shear strength behaviour and the factors affecting the shear strength of the sand such as relative density, cyclic load, amplitude of the cyclic load and loading rate. The study results indicate that the shear strength parameters of the coral gravelly sand include not only internal friction angle but also apparent cohesion. These parameters vary with the relative density, cyclic load, the amplitude of the cyclic load and loading rate. The shear strength increases with the increase of the relative density. The shear strength increases after subjecting to cyclic loading. The amplitude of the cyclic load affects the shear strength of coral gravelly sand, the shear strength increases as the amplitude of the cyclic load increases. The loading rate has insignificantly effect on the shear strength of the coral gravelly sand.

Keywords: coral gravelly sand; shear strength; direct shear test; cyclic load

1. Introduction

Coral soil, which is also called as calcareous soil due to the main chemical component as calcium carbonate, is widely distributed in South East Asia sea area, especially in Truong Sa island of Vietnam (Fig. 1). Recently, construction activities in coral ground have been carried out more and more popular. However, calcareous soil are still considered as a problematic soil due to high crushability and high void ratio, leading to high compressibility (Coop *et al.* 2004, Wei *et al.* 2018). Physical properties of coral sands have been reported in Murff (1987), Chengjie *et al.* (2013) and Wang *et al.* (2017).

Recently, studies on the mechnical behaviours of calcareous sands have been conducted more common. Hassanlourad *et al.* (2008) investigated shear behaviour of two calcareous sands from two different zones located in Persian Gulf using drained and undrained triaxial tests. It is derived from the research that the calcareous sands had substantial interlocking that resulted in dilative behaviour of them in both loose and dense states and the increase of confining pressure reduced the dilation component. Dehnavi *et al.* (2010) carried out an experimental study on compressibility and undrained behaviour of Hormuz calcareous sand from Persian Gulf. Brandes (2011) investigated shear behaviour of calcareous and quartz sands through monotonic and cyclic simple shear tests. It is derived from the study that differences in the behaviour between the calcareous and quartz sands are due to contrasts in grain geometry, hardness, gradation and the amount of intraparticle voids. Wang *et al.* (2016) studied on shear characteristics of calcareous gravelly soil through large-scale direct shear tests. The results revealed that the calcareous gravelly soil has greater apparent cohesion, larger friction angle, and lower softening value than quartz sand. Rezvani (2019) carried out a study on shearing response of geotextile-reinforced calcareous soil through triaxial tests. The results indicate that geotextile reinforcements increased the shear strength of the calcareous soil and higher confining pressures reduce the dilative behavior and efficiency of geotextile reinforcement. Shahnazari and Rezvani (2013) studied on effective parameters for the partical breakage of calcareous sands. The results from the research showed that the input energy played an important role in the particle breakage behaviour of the soils. Vu and Matsumoto (2019) carried out an investigation on behaviour of monopile subjected to cyclic loading in a calareous ground, in which the results of the triaxial tests and numerical simulation on mechanical behaviour of a calcareous sand of Vietnam were reported. The studied results indicated that the coral sand had post-peak softening behaviour and it is better to use the Hypoplastic model to simulate the mechnical behaviour of the sand compared to the Mohr-Coulomb and Harderning soil models. Several other studies on mechanical behaviours focussing on shear strength of soils subjected to static and dynamic loading have been conducted as Hyodo *et al.* (1996), Ismail (2002), Goual *et al.* (2011), Salem *et al.* (2013), Morsy *et al.* (2019), Park *et al.* (2018), Shanazari *et al.* (2019) and Shi *et al.* (2020).

Generally, there are studies on mechanical properties of coral or calareous sands with particle size smaller than 2 mm, but few study on coral gravel sand with particle size larger than 2 mm. Hence, in this study, the shear strength behaviours of a coral gravelly soil sampled from Truong Sa

*Corresponding author, Ph.D.
E-mail: vuanhtuan@mta.edu.vn

Copyright © 2021 Techno-Press, Ltd.
http://www.techno-press.org/?journal=gae&subpage=7
ISSN: 2005-307X (Print), 2092-6219 (Online)

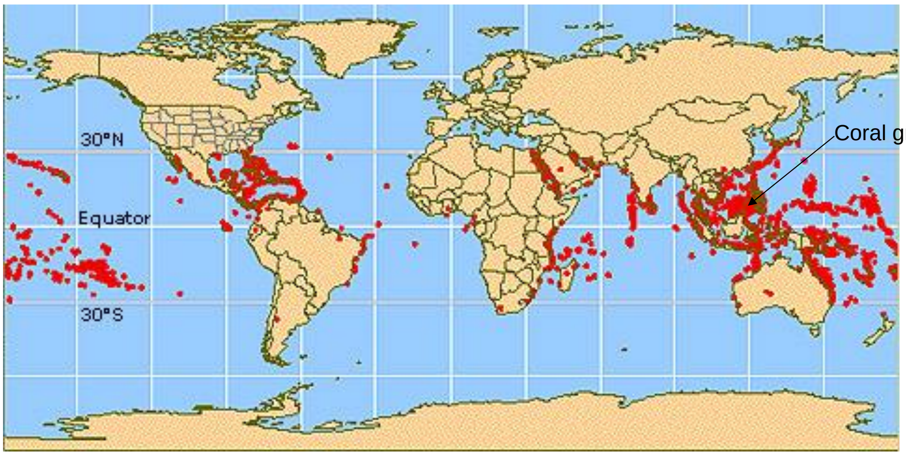

Fig. 1 Distribution of coral ground (Yap 2012)

Fig. 2 Stratum profile of coral ground

Table 1 Physical properties of the coral gravelly sand

Properties	Value
Soil particle density, ρ_s (t/m^3)	2.820
Maximum dry density, ρ_{dmax} (t/m^3)	1.801
Minimum dry density, ρ_{dmin} (t/m^3)	1.450
Dry density at relative density D_r= 0.3; $\rho_{d0.3}$ (t/m^3)	1.555
Dry density at relative density D_r= 0.6; $\rho_{d0.6}$ (t/m^3)	1.661
Dry density at relative density D_r= 0.9; $\rho_{d0.9}$ (t/m^3)	1.766
Minimum void ratio, e_{min}	0.566
Maximum void ratio, e_{max}	0.945
Void ratio at relative density D_r= 0.3	0.813
Void ratio at relative density D_r= 0.6	0.698
Void ratio at relative density D_r= 0.9	0.597

island of Vietnam are investigated through direct shear tests. Influecing factors as relative density, cyclic load, amplitude of cyclic load and loading rate are considered in the study.

2. Physical properties

Coral soil from Truong Sa island of Vietnam was used in this study. Fig. 2 shows the stratum profile of the site where the samples were collected. The coral ground here contains stones, branches, gravels and sands. In this research, however, only coral gravelly sand having particle diamater smaller than 10 mm is focussed to investigate the shear strength behaviour. Soil particles having a diameter larger than 10 mm were removed through sieving. Fig. 3 shows the picture of the coral gravel sand used in the

Fig. 3 Coral gravelly sand

Table 2 Grain size characteristics of the coral gravelly sand

Sieve size	Initial	After monotonic test			After cyclic test		
(1)	(2)	(3)	(4)=(3)-(2)	(5)=(4)/(2) (%)	(6)	(7)=(6)-(2)	(8)=(7)/(2) (%)
D_{30} (mm)	0.237	0.232	-0.005	-2.221	0.209	-0.028	-11.809
D_{50} (mm)	1.051	1.019	-0.032	-3.032	0.821	-0.230	-21.846
D_{60} (mm)	2.409	2.404	-0.004	-0.177	1.639	-0.770	-31.973

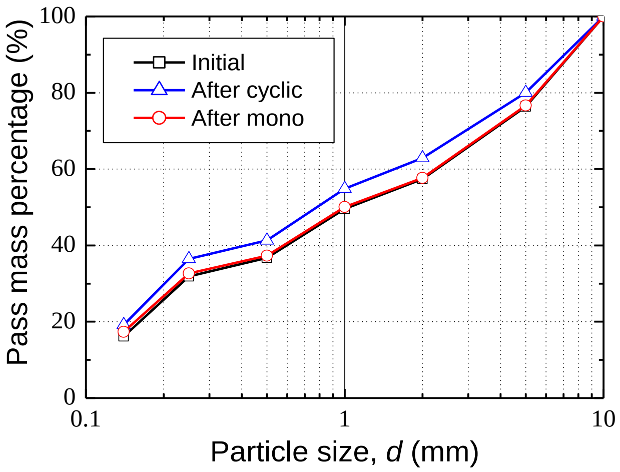

Fig. 4 Grain size distribution curves before and after the tests

experiments. The physical properties of the sand are presented in Table 1.

Sieve tests were conducted using the sieves set having the sizes of 10 mm, 5 mm, 2 mm, 1 mm, 0.5 mm, 0.25 mm, 0.14 mm, and less than 0.14 mm to obtain the grain size distribution and evaluate crushability of the sand. Dry sieving tests were carried out consistently before and after the direct shear tests. Wet sieve tests were not conducted. Fig. 4 shows the grain size distribution curves of the sand before (at the initial stage) and after the direct shear tests. The curve of after cyclic test is clearly higher than the curves of the initial stage and after the monotonic test, indicating higher percentage of small-size particles. The soil is composed mainly of sand and gravel, classified as poorly graded sand (SP) based on particle size characteristics according to Unified Soil Classification System (ASTM D 2487-00 2016). The grain size characteristics are presented in Table 2, indicating that the soil particles were crushed considerably by cyclic loading.

3. Shear strength behaviour

Direct shear tests were used to investigate the shear strength behaviour of the coral gravelly sand subjected to monotonic and cyclic loads. The testing machine is an automatic device controlled by a microprocessor system which reads and processes horizontal force and displacement readings (Fig. 5). Technical specifications of the machine are summarised in Table 3.

Fig. 5 Direct shear test machine

Table 3 Technical specifications of the direct shear testing machine

Items	Value
Speed range (mm/min)	0.0001 – 15.000
Maximum shear force (N)	5000
Maximum vertical load using 10:1 lever-arm (N)	5000
Maximum horizontal displacement (mm)	20
Maximum vertical displacement (mm)	10
Maximum shear cycles (cycles)	100
Precision in force (N)	0.001
Precision in displacement (mm)	0.001
Specimen diameter (mm)	63.5

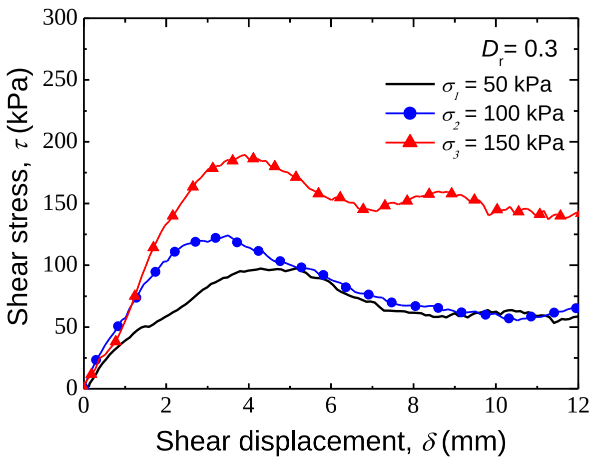

Fig. 6 Shear stress vs. shear displacement, D_r= 0.3

3.1 Influence of relative density

To investigate the influence of relative density on the shear strength behaviour of the coral gravelly sand, direct shear tests on the sand having the relative densities D_r= 0.3, 0.6 and 0.9 were carried out. Note that the relative densities are identified at the initial stage (prior to application of normal stress). As for each relative density, three levels of

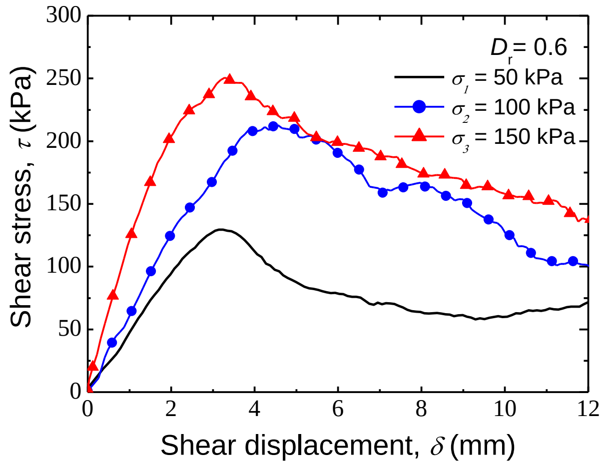

Fig. 7 Shear stress vs. shear displacement, D_r= 0.6

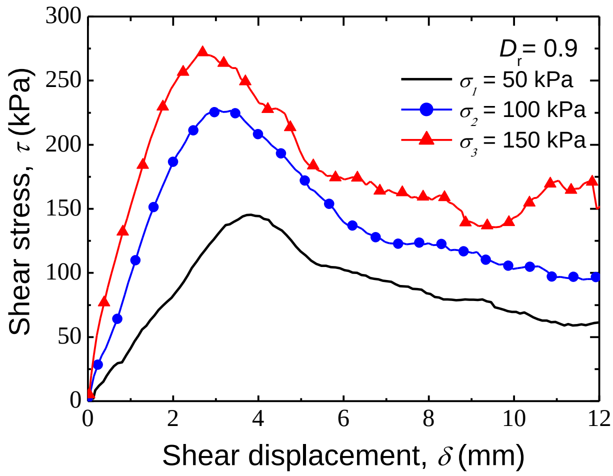

Fig. 8 Shear stress vs. shear displacement, D_r= 0.9

normal stress were applied in the tests as 50, 100 and 150 kPa. After application of normal stress, the void ratio of the samples has minor change comparing to that at the initial stage. The void ratios before shearing are 0.810, 0.696 and 0.595 corresponding to the relative densities D_r= 0.3, 0.6 and 0.9.

Figs. 6-8 show the relationship between shear force and shear displacement of the samples having a relative density of 0.3, 0.6 and 0.9, respectively. It is indicated from the figures that the nonlinear post-peak softening behaviour of the coral sand are obtained, in which the peak appears more obviously in the cases of densed samples (D_r= 0.6 and 0.9) than that of the loosed sample (D_r= 0.3). The results indicate that the position of the peaks varies in the range from 3 mm to 5 mm of the shear displacement corresponding to the shear strain from 4.7% to 7.9% (the diameter of the sample is 63.5 mm). The range of the peak appearance in this study is similar to that of a calcareous gravelly soil investigated by Wang *et al.* (2016) and larger than that of Toyoura sand presented in Wu *et al.* (2008).

Table 4 shows the shear strength parameters of the coral gravelly sand with different relative densities. The results indicate that the shear strength parameters of the sand include not only internal friction angle, φ, as other granular

Table 4 Shear strength parameters of coral gravelly sand with different relative densities

Relative density, D_r	Internal friction angle, φ (°)	Unit cohesion, c (kPa)	Relative internal friction angle (%)	Relative unit cohesion (%)
0.3	42.55	45.23	100	100
0.6	50.47	76.49	119	169
0.9	51.65	88.36	121	195

Table 5 Comparison of shear strength parameters of silica sand and coral gravelly sand

Relative density, D_r	Silica sand		Coral gravelly sand		Increment	
	Internal friction angle, φ (°)	Unit cohesion, c (kPa)	Internal friction angle, φ (°)	Unit cohesion, c (kPa)	Internal friction angle, φ (°)	Unit cohesion, c (kPa)
(1)	(2)	(3)	(4)	(5)	(6)=(4)-(2)	(7)=(5)-(3)
0.3	39.00	0.57	42.55	45.23	3.55	44.66
0.6	42.95	3.75	50.47	76.49	7.52	72.74
0.9	44.66	10.25	51.65	88.36	6.99	78.11

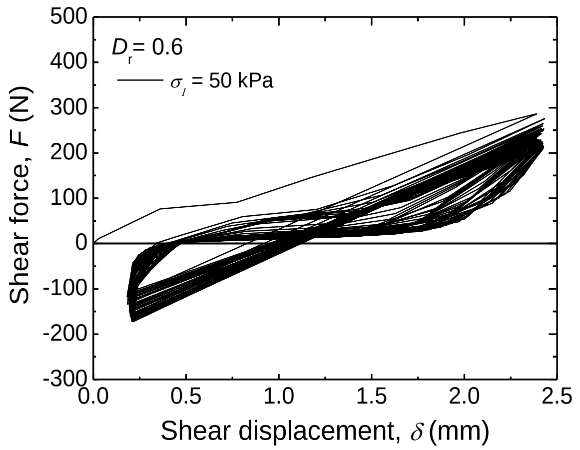

Fig. 9 Shear force vs. shear displacement in cyclic load test under normal stress of 50 kPa

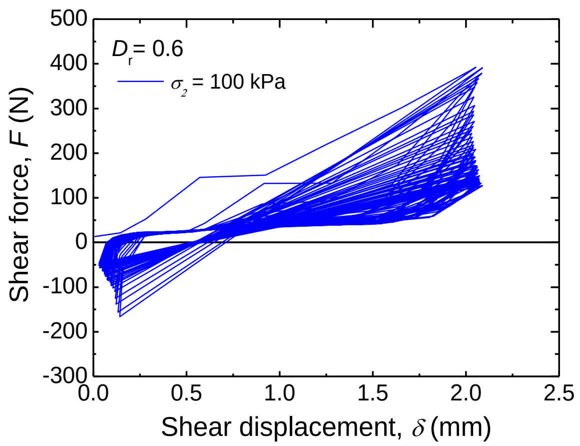

Fig. 10 Shear force vs. shear displacement in cyclic load test under normal stress of 100 kPa

soils but also unit cohesion, c, called as apparent unit cohesion. It is in agreement with the research of Wang *et al.* (2017). As shown in Wang *et al.* (2016), the corals have an intestinal lumen structure, the shapes of coral soil particles originated from the breakage of dead corals are extremely irregular. The results from the scanning electron microscopy (SEM) and computed tomography (CT) scan photographs showed that the coral soil particles are angular and contain plentiful inner voids. Hence, it is possible that the cohesion in the coral sand was generated by the grain interlocking between coarse soil particles. The internal friction angle, φ, of the coral gravelly sand used in this study is in the range of 42.5 to 51.65 degrees. The apparent unit cohesion, c, is in the range of 45.23 to 88.36 kPa. These shear strength parameters increase with the increase of the relative density, D_r, of the soil. When D_r increases from 0.3 to 0.6, the internal friction angle increases by 19%, unit cohesion increases by 69%. When D_r increases from 0.3 to 0.9, the internal friction angle increases by 21%, unit cohesion increases by 95%.

For the comparison purpose, similar direct shear tests were conducted on a silica sand having properties presented in Vu *et al.* (2017). Table 5 shows a comparison of shear strength parameters of a silica sand and the coral gravelly sand. The results obviously show that shear strength parameters of the coral gravelly sand are larger than those of the silica sand. Particularly, the apparent cohesion values of the coral sand are significantly larger than those of the silica sand. Cerato *et al.* (2011) carried out a series of direct shear tests on five sands at three relative densities (loose, medium and dense). It is indicated from the study that the internal friction angle of the sands was in the range of 30.7 to 43.5 degrees for the loose state, in the range of 35 to 44.5 degrees for the medium state, and in the range of 36 to 45.5 degrees for the dense state. Qureshi *et al.* (2014) presented that the internal friction angles Muscat and silica sands at loose state were 38.7 and 39.9 degrees, respectively. The cohesion was neglected due to small value in both studies of Cerato *et al.* (2011) and Qureshi *et al.* (2014).

3.2 Influence of cyclic load

To investigate the influence of cyclic load on variation of the shear strength characteristics of the coral gravelly sand, cyclic direct shear tests were carried out on the

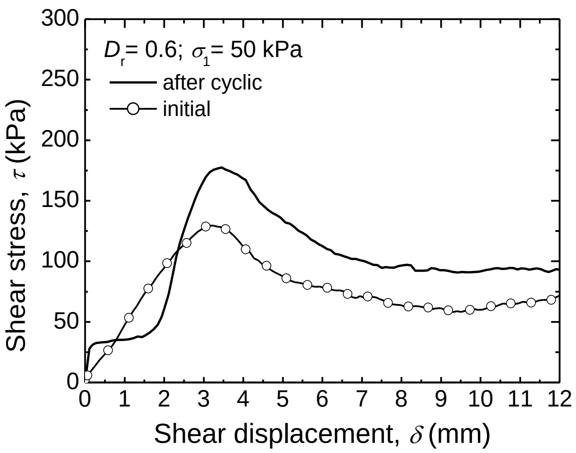

Fig. 11 Shear stress vs. shear displacement in monotonic load test under normal stress of 50 kPa

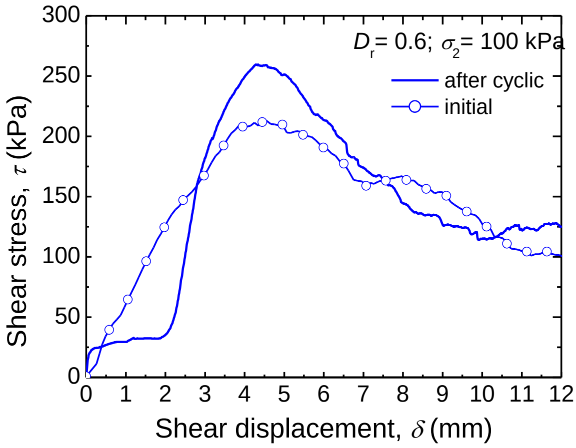

Fig. 12 Shear stress vs. shear displacement in monotonic load test under normal stress of 100 kPa

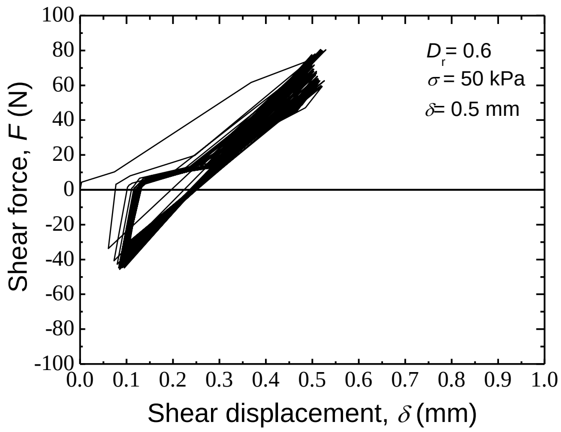

Fig. 13 Shear force vs. shear displacement in cyclic loading with δ = 0.5 mm, σ = 50 kPa

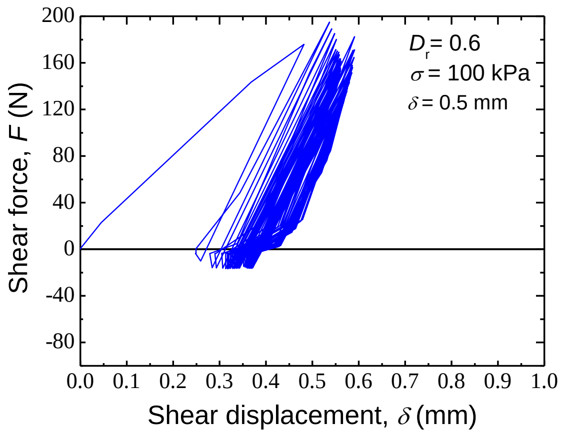

Fig. 14 Shear force vs. shear displacement in cyclic loading with δ = 0.5 mm, σ = 100 kPa

Table 6 Comparison of shear strength parameters of the sand at initial and after cyclic loading

Relative density, D_r	Initial		After cyclic		Increment	
	Internal friction angle, φ (∘)	Unit cohesion, c (kPa)	Internal friction angle, φ (∘)	Unit cohesion, c (kPa)	Internal friction angle, φ	Unit cohesion, c
(1)	(2)	(3)	(4)	(5)	((4)-(2))/(2)	((5)-(3))/(3)
0.6	50.47	76.49	58.66	95.34	16.23%	24.64%

samples having a relative density D_r= 0.6. As for each level of normal stress of 50 kPa and 100 kPa, 50 loading cycles following displacement control manner with the displacement amplitude of about 2 mm were applied. After that, monotonic load tests on the samples were carried out. Note that the amplitude of cyclic displacement here is 2 mm corresponding to a half of the shear displacement to obtain the peak strength as mentioned above. Influence of the amplitude of cyclic load is also investigated in this study and presented in the later section of this paper.

Figs. 9 and 10 show the relationship between shear force and shear displacement in the cyclic load tests under the normal stresses of 50 kPa and 100 kPa, respectively. Figs. 11 and 12 show the relationship between shear force and shear displacement in the monotonic load tests (after the cyclic tests) under the normal stresses of 50 kPa and 100 kPa, respectively.

It is indicated from Figs. 11 and 12 that the shear strength of the coral gravelly sand considerably increases after cyclic load tests. At the beginning of the curve (after cyclic), it is seen that there is a horizontal line representing an increase of the horizontal displacement without an increase of the shear force. The range of the horizontal line coincides with the range of cyclic load amplitude applied in the former step. After the horizontal part, the shear force increases with the increase of the displacement and obtains a considerably higher peak value than that of the initial samples.

Table 6 shows a comparison of shear strength parameters of the coral gravelly sand at the initial status and after the cyclic load test. The results obviously indicate that the shear strength parameters of the sand increase after the cyclic load test.

3.3 Influence of amplitude of cyclic load

The influence of cyclic load on variation of the shear strength characteristics of the coral gravelly sand has been

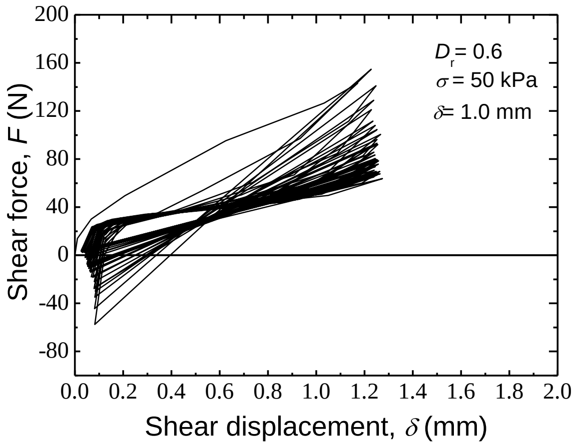

Fig. 15 Shear force vs. shear displacement in cyclic loading with δ = 1.0 mm, σ = 50 kPa

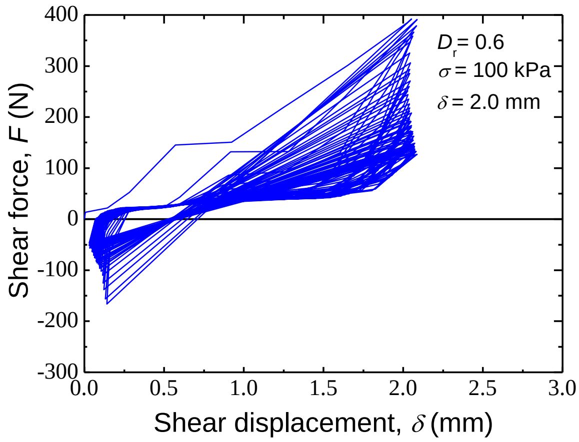

Fig. 18 Shear force vs. shear displacement in cyclic loading with δ = 2.0 mm, σ = 100 kPa

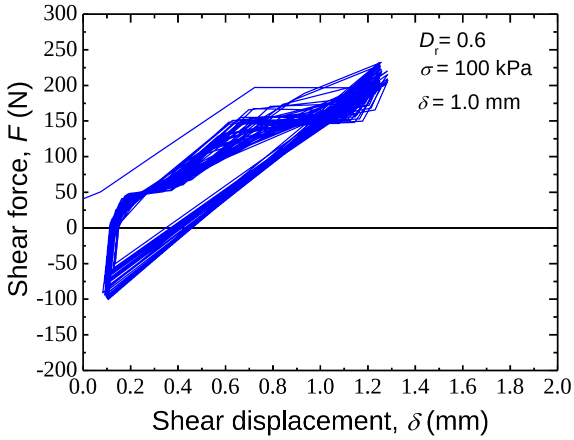

Fig. 16 Shear force vs. shear displacement in cyclic loading with δ = 1.0 mm, σ = 100 kPa

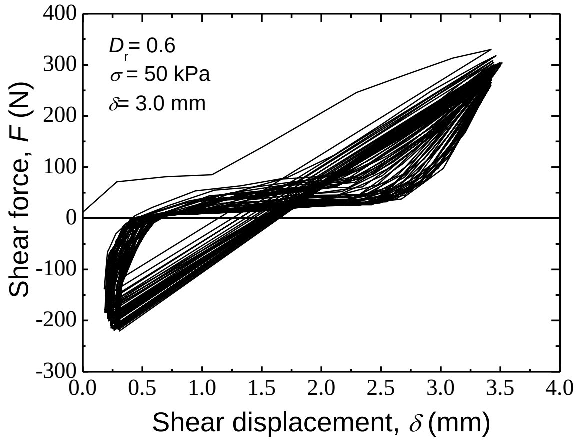

Fig. 19 Shear force vs. shear displacement in cyclic loading with δ = 3.0 mm, σ = 50 kPa

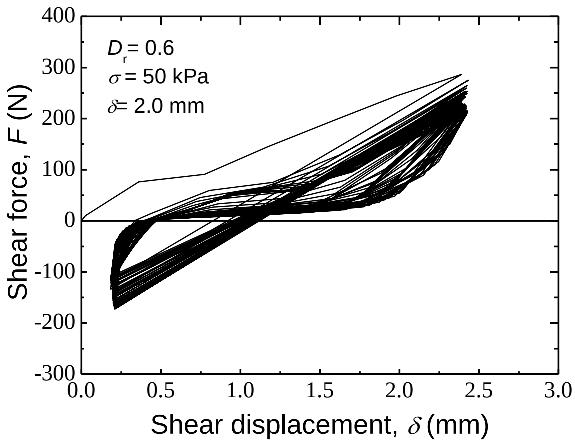

Fig. 17 Shear force vs. shear displacement in cyclic loading with δ = 2.0 mm, σ = 50 kPa

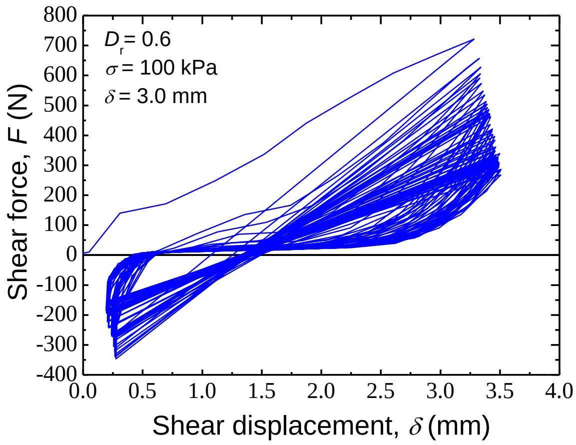

Fig. 20 Shear force vs. shear displacement in cyclic loading with δ = 3.0 mm, σ = 100 kPa

presented in the previous section. The investigation on the influence of amplitude of the cyclic load is shown here.

At first, cyclic direct shear tests on the samples having a relative density D_r= 0.6 were carried out. As for each level of normal stress of 50 kPa and 100 kPa, 50 loading cycles following displacement control manner with the displacement amplitude, δ, of 0.5 mm, 1 mm, 2 mm and 3 mm were applied, separately. Then, monotonic load tests on the samples were conducted. The results from the monotonic load tests in section 3.1 indicate that the samples attained the peak strength at an average value of shear displacement, δ_p, of about 4 mm. Hence, the displacements

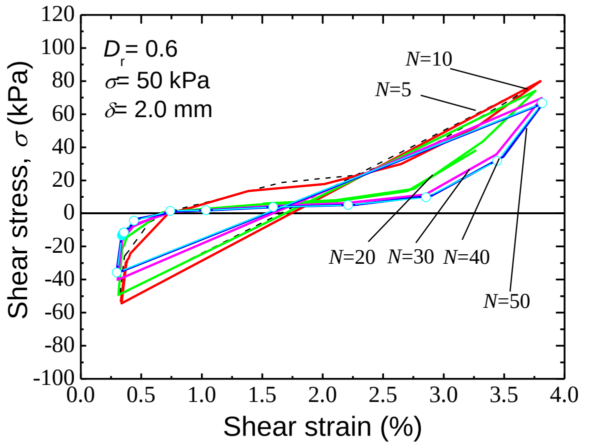

Fig. 21 Shear stress vs. shear strain at typical cycles with δ = 2.0 mm, σ = 50 kPa

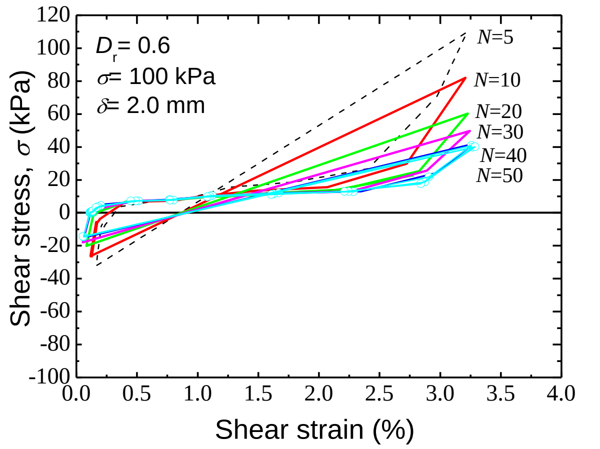

Fig. 22 Shear stress vs. shear strain at typical cycles with δ = 2.0 mm, σ = 100 kPa

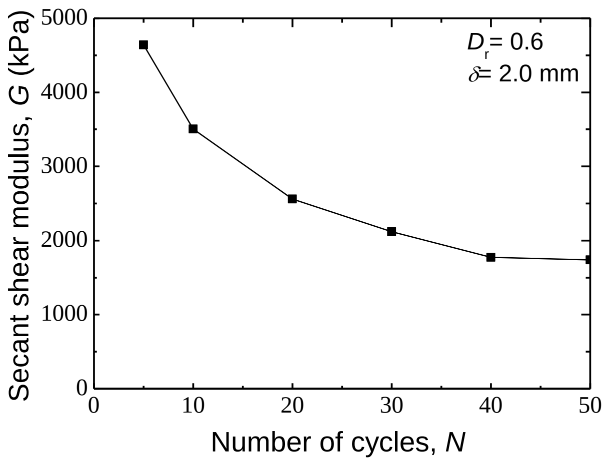

Fig. 23 Secant shear modulus vs. number of cycles with δ = 2.0 mm

0.5 mm, 1 mm, 2 mm and 3 mm correspond to $1\delta_p/8$, $2\delta_p/8$, $4\delta_p/8$ and $6\delta_p/8$, respectively. Figs. 13-20 show cyclic loads with different amplitudes under the normal stress of 50 and 100 kPa. Typical hysteresis loops for different loading cycles (i.e., N= 5; 10; 20; 30; 40 and 50) in the case of δ =

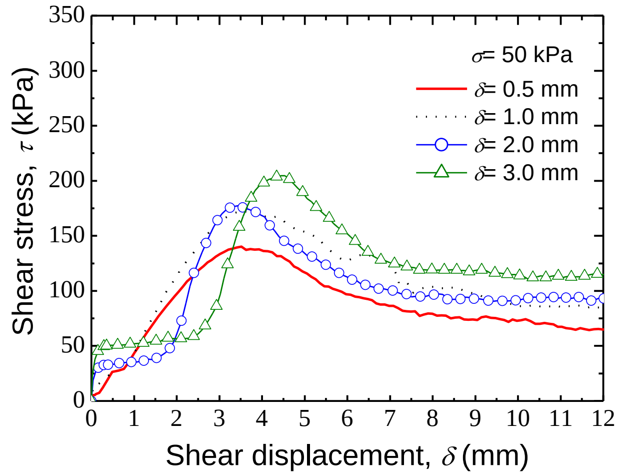

Fig. 24 Shear stress vs. shear displacement after cyclic loading with amplitude 0.5 mm, 1 mm, 2 mm and 3 mm, under normal stress of 50 kPa, D_r= 0.6

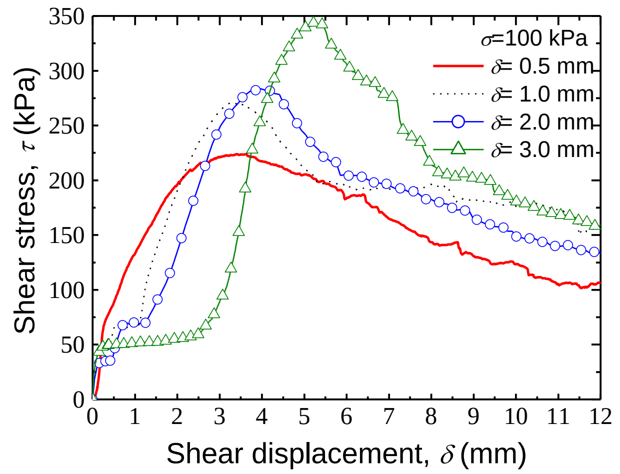

Fig. 25 Shear stress vs. shear displacement after cyclic loading with amplitude 0.5 mm, 1 mm, 2 mm and 3 mm, under normal stress of 100 kPa, D_r= 0.6

2.0 mm are plotted in Figs. 21 and 22. It is indicated that shear modulus decreases as the number of loading cycles increases and the decrease is more obvious in the beginning cycles. It is seen that the hysteresis loop consistently overlapped after 40 cycles. The changes in secant shear modulus with the number of loading cycles are plotted in Fig. 23. The result clearly shows the decrease of the shear modulus with the increase of loading cycles.

Figs. 24 and 25 show the results of the monotonic load tests after the cyclic load tests with the normal stresses of 50 and 100 kPa, respectively. It is indicated that the peak strength and the stiffness are increased with the increase of the amplitude of the cyclic load. It could be explained that the rearrangement of the soil particles as well as the development of smaller particles due to the crushability of the particles by cyclic loading lead to denser state of the soil. Therefore, higher strength and stiffness of the soil are resulted in.

3.4 Influence of loading rate

To investigate the influence of loading rate on the shear

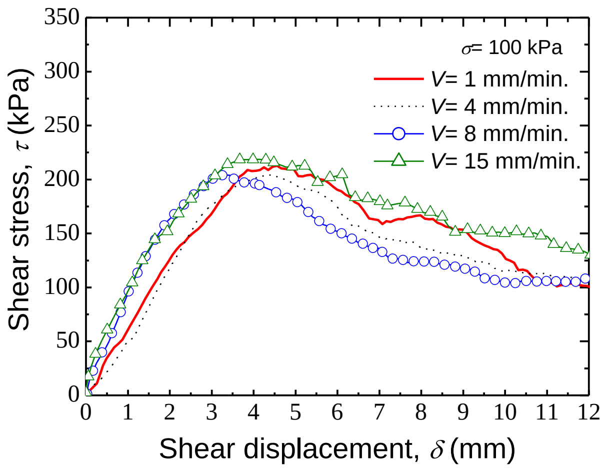

Fig. 26 Shear force vs. shear displacement with different loading rates

strength behaviour of the coral gravelly sand, direct shear monotonic load tests on the specimens having a relative density D_r= 0.6, under the normal stress of 100 kPa and with different loading rates of 1, 4, 8 and 15 mm/min were conducted. It is seen from the result in Fig. 26 that the peak strength values are almost unchanged with the changes of the loading rate. Also, the residual strength values corresponding to the loading rates of 1, 4 and 8 mm/min are nearly the same although the variations are observed after the peaks. Focussing on the load increasing part before the peak, the stiffness of the curve with the loading rate of 1 mm/min are marginally changed comparing with that of the loading rate of 4 mm/min. Meanwhile, the stiffness of the curve corresponding to the loading rate of 8 mm/min is almost the same with that of the loading rate of 15 mm/min, and that stiffness are higher than the stiffness of the loading rates of 1 and 4 mm/min.

4. Conclusions

The paper presents an experimental study on the shear strength behaviour of a coral gravelly sand from Vietnam subjected to monotonic and cyclic loading in which the influence factors as the relative density, the amplitude of cyclic load and the loading rate are considered. It is derived from the results of this study as follows:

• The shear strength parameters of the coral gravelly sand comprise not only internal friction angle, φ, as other normal granular soils but also a considerable value of cohesion, c, called as apparent cohesion. The parameters are larger than those of the silica sand especially the cohesion and it should be considered in the design of structures in the coral sand. As for the particular study, the internal friction angle of the coral gravelly sand varies from 42.55 to 51.65 degrees and the cohesion varies from 45.23 to 88.36 kPa.

• The shear strength of the coral gravelly sand increases with the increase of the relative density. When the relative density is increased from 0.3 to 0.6, the internal friction increases by 19% and the cohesion increases by 69%. When the relative density is increased from 0.3 to 0.9, the internal friction increases by 21% and the cohesion increases by 95%.

• The shear strength and the stiffness of the coral gravelly sand increases considerablly due to cyclic loading. The rearrangement of the soil particles as well as the development of smaller particles due to the crushability of the particles by cyclic loading could be the reason leading to the increases of the shear strength and the stiffness.

• The shear strength and the stiffness of the coral gravelly sand are influenced by the amplitude of the cyclic load. They are increased with the increase of the amplitude of the cyclic load.

• The loading rate has minor influence on the shear strength of the coral gravelly sand.

Acknowledgments

The author thanks Mr. Nguyen Van Khoa, the former master student at Faculty of Civil Engineering, Le Quy Don Technical University for his supports in the experiments.

References

ASTM Standard D 2487-00 (2016), Standard Practice for Classification of Soil for Engineering Purposes (Unified Soil Classification System), Annual Book of ASTM Standards, ASTM International, West Conshohocken, Pennsylvania, U.S.A.

Brandes, H.G. (2011), "Simple shear behavior of calcareous and quartz sands", *Geotech. Geol. Eng.*, **29**, 113-126. https://doi.org/10.1007/s10706-010-9357-x.

Cerato, A.B. and Lutenegger, A.J. (2011), "Specimen size and scale effects of direct shear box tests of sands", *Geotech. Test. J.*, **29**(6), 507-516. https://doi.org/10.1520/GTJ100312.

Chengjie, Z., Peidong, L.U. and Yanghong, W. (2013), "Experiment study on physical properties and motional characteristics of coral sand", *Proceedings of the 7th International Conference on Asian and Pacific Coasts (APAC 2013),* Bali, Indonesia, September.

Coop, M.R., Sorensen, K.K., Bodas F.T. and Georgoutsos, G. (2004), "Particle breakage during shearing of a carbonate sand", *Géotechnique*, **54**(3), 157-163. https://doi.org/10.1680/geot.2004.54.3.157.

Dehnavi, Y., Shahnazari, H., Salehzadeh, H. and Rezvani, R. (2010), "Compressibility and undrained behavior of Hormuz calcareous sand", *Electron. J. Geotech. Eng.*, **15**, 1684-1702.

Goual, I., Goual, M.S., Taibi, S. and Bekr, N.A. (2011), "Behaviour of unsaturated tuff- calcareous sand mixture on drying-wetting and triaxial paths", *Geomech. Eng.*, **3**(4), 267-284. http://doi.org/10.12989/gae.2011.3.4.267.

Hassanlourad, M., Salehzadeh, H. and Shahnazari, H. (2008), "Dilation and breakage effects on the shear strength of calcareous sands based on energy aspects", *Int. J. Civ. Eng.*, **6**(2), 108-119.

Hyodo, M., Aramaki, N., Itoh, M. and Hyde, A.F.L. (1996), "Cyclic strength and deformation of crushable carbonate sand", *Soil Dyn. Earthq. Eng.*, **15**(5), 331-336, https://doi.org/10.1016/0267-7261(96)00003-6.

Ismail, M.A. (2002), "Performance of an offshore stabilised calcareous soils", *Ground Improv.*, **6**(4), 175-186, https://doi.org/10.1680/GRIM.2002.6.4.175.

Morsy, A.M., Salem, M.A and Elmamlouk, H.H. (2019), "Evaluation of dynamic properties of calcareous sands in Egypt at small and medium shear strain ranges", *Soil Dyn. Earthq. Eng.*, **116**, 692-708, https://doi.org/10.1016/j.soildyn.2018.09.030.

Murff, J.D. (1987), "Pile capacity in calcareous sands; State of the art", *J. Geotech. Eng.*, **113**(5), 490-570. https://doi.org/10.1061/(ASCE)0733-9410(1987)113:5(490).

Park, T.W, Kim, H.J., Tanvir, M.T., Lee, J.B. and Moon, S.G. (2018), "Influence of coarse particles on the physical properties and quick undrained shear strength of fine-grained soils", *Geomech. Eng.*, **14**(1), 99-105. http://doi.org/10.12989/gae.2018.14.1.099.

Qureshi, M.U., Bessaih, N., Al-Sadrani, K., Al-Falahi, S. and Al-Mandhari, A. (2014), "Shear strength of Omani sand treated with biopolymer", *Proceedings of the 7th International Congress on Environmental Geotechnics*, Melbourne, Australia, November.

Rezvani, R. (2019), "Shearing response of geotextile-reinforced calcareous soils using monotonic triaxial tests", *Mar. Georesour. Geotec.*, **38**(2), 238-249. https://doi.org/10.1080/1064119X.2019.1566936.

Salem, M., Elmamlouk, H. and Agaiby, S. (2013), "Static and cyclic behavior of North Coast calcareous sand in Egypt", *Soil Dyn. Earthq. Eng.*, **55**, 83-91. https://doi.org/10.1016/j.soildyn.2013.09.001.

Shahnazari, H. and Rezvani, R. (2013), "Effective parameters for the particle breakage of calcareous sands: An experimental study", *Eng. Geol.*, **159**, 98-105. https://doi.org/10.1016/j.enggeo.2013.03.005.

Shahnazari, H., Rezvani, R. and Tutunchian, M.A. (2019), "Post-cyclic volumetric strain of calcareous sand using hollow cylindrical torsional shear tests", *Soil Dyn. Earthq. Eng.*, **124**, 162-171, https://doi.org/10.1016/j.soildyn.2019.05.030.

Shi, J., Haegeman, W. and Andries, J. (2020), "Investigation on the mechanical properties of a calcareous sand: The role of the initial fabric", *Mar. Georesour. Geotec.*, 1-17. https://doi.org/10.1080/1064119X.2020.1775327.

Vu, A.T. and Matsumoto, T. (2019), "Numerical analysis on behaviours of winged monopile subjected to cyclic loading in a calcareous ground", *Proceedings of the 1st Vietnam Symposium on Advances in Offshore Engineering*, Hanoi, Vietnam, November.

Vu, A.T., Matsumoto, T., Kobayashi S. and Shimono, S. (2017), "Experimental study on pile foundations having batter piles subjected to combination of vertical and horizontal loading at 1-g field", *Geotech. Eng. J. SEAGS AGSSEA*, **48**(3), 12-24.

Wang, X.Z., Wang, X., Jin, Z.C., Meng, Q.S., Zhu, C.Q. and Wang, R. (2016), "Shear characteristics of calcareous gravelly soil", *B. Eng. Geol. Environ.*, **76**, 561-573. https://doi.org/10.1007/s10064-016-0978-z.

Wang, X.Z., Wang, X., Jin, Z.C., Zhu, C.Q., Wang, R. and Meng, Q. S. (2017), "Investigation of engineering characteristics of calcareous soils from fringing reef", *Ocean Eng.*, **134**, 77-86. https://doi.org/10.1016/j.oceaneng.2017.02.019.

Wei, H., Zhao, T., He, J., Zhu, Meng, Q. and Wang, X. (2018), "Evolution of particle breakages for calcareous sands during ring shear tests", *Int. J. Geomech.*, **18**(2), 04017153. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001073.

Wu, P., Matsushima, K. and Tatsuoka, F. (2008), "Effects of specimen size and some other factors on the strength and deformation of granular soil in direct shear tests", *Geotech. Test. J.*, **31**(1), 45-64, https://doi.org/10.1520/GTJ100773.

Yap, H.T. (2012), *Coral Reef Ecosystem*, in *Encyclopedia of Sustainability Science and Technology*, Springer, New York, U.S.A., 2489-2509.

CC