Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-108

Effect of cyclic stress ratio on pore pressure and shear modulus response of coal ash

Aparna Shrivastava[1], and Ajanta Sachan[2]

[1]*PhD Scholar, Department of Civil Engineering, Indian Institute of Technology Gandhinagar, Gujarat, India, email: aparna.shrivastava@iitgn.ac.in*

[2]*Associate Professor, Department of Civil Engineering, Indian Institute of Technology Gandhinagar, Gujarat, India, email: ajanta@iitgn.ac.in*

ABSTRACT

Coal ash from the thermal power plant is conveyed to the disposal site, where it can exist in loose to medium-dense conditions. Coal ash is re-used for several engineering applications as fill material for highway and railway embankments. This material is extremely prone to liquefaction when subjected to earthquake loading conditions. Therefore, a detailed investigation is required on the cyclic response of coal ash under different magnitudes (cyclic stress ratios, CSR) of earthquake loading conditions. The three different initial states were chosen to be 86%, 90% and 95% of MDD. These specimens were consolidated under the normal effective overburden stress of 100 kPa. To analyse the effect of overburden stresses, the specimen was consolidated at three different effective vertical overburden stresses (50, 100 and 150 kPa) on a specimen prepared at 95% MDD. The frequency was employed to be 1 Hz for all the cyclic simple shear (CSS) tests. The abrupt increase in the double amplitude shear strain and pore pressure was obtained for the coal ash specimens at higher CSR as compared to lower CSR values. The liquefaction was initiated when the double amplitude shear strain reached 7.5% or the pore water pressure ratio (r_u) reached 0.9, whichever occurred first. With the increase in CSR value, loading cycles at liquefaction were observed to be reducing. A rapid decay in the shear modulus was also observed for the coal specimens subjected to the higher CSR value. The evaluation of damping ratio indicated a slight increase with the increase in CSR value.

Keywords: Coal ash, Cyclic stress ratio, Earthquake, Liquefaction, Shear modulus, Damping ratio

1 INTRODUCTION

One of the most badly results of earthquake phenomenon is the liquefaction of saturated coal ash materials. Jakka et al. (2010) reported that coal ash could exhibit instability and static liquefaction under monotonic triaxial loading conditions. Also, the liquefaction behaviour of both loose and compacted pond ash was investigated under stress-controlled cyclic triaxial conditions (Jakka et al., 2010). A recent study was conducted to investigate the liquefaction response of coal ash under a critical state framework using cyclic triaxial (Baki et al., 2012, 2019; Zhang et al., 2018). Chattaraj and Sengupta (2017) studied the dynamic properties of fly ash using resonant column and cyclic triaxial tests and compared the results with sand. The liquefaction susceptibility of reconstituted pond ash was studied by many researchers (Mohanty and Patra, 2014, 2016). Yoshimoto et al. (2014) studied the applicability of granulated coal ash (GCA) on liquefaction resistance. Singh and Singh (2022) studied the dynamic properties of pond ash at different locations within an ash pond by conducting stain-controlled cyclic triaxial tests. The small and large strain dynamic parameters of fly ash were evaluated under Bender element and strain controlled cyclic triaxial conditions (Ram and Mohanty, 2021). Shrivastava and Sachan (2023) evaluated the effect of stress anisotropy on small strain shear modulus behaviour of coal ash. However, very few studies are available on the effect of different magnitude of dynamic loading on the liquefaction response of coal ash under cyclic simple shear loading conditions (CSS). The coal ash used in the current study was the unutilized ash, which is disposed in the disposal site from the thermal power plant. The CSS condition better simulates earthquake loading as compared to the cyclic triaxial loading conditions.

Hence, the current study focuses on effect of cyclic stress ratio (CSR) on the liquefaction and dynamic properties of coal ash under different states (Different density and vertical effective overburden stress).

2 MATERIAL PROPERTIES AND SPECIMEN PREPARATION

Coal ash used in this study was collected from the Gandhinagar thermal power plant. The basic geotechnical properties of coal ash are listed in table 1. The nature of the coal ash was found to be non-cohesive and the particle shapes were spherical (Figure 1). The specimens used for the cyclic simple shear (CSS) testing were cylindrical with 70 mm diameter and 20 mm height. All the specimens were prepared using the moist tamping method in the cylindrical mould. The prepared specimen was placed over the pinned type of base pedestal. The base pedestal with Teflon-coated rings was stretched with the latex rubber membrane. The base pedestal is then set over the CSS setup. The docking process was done by touching the plunger of the CSS setup with the specimen. After docking, the water flushing of the specimen was conducted to saturate the specimen by applying the docking pressure of 10 kPa. The water flushing was carried out for about 15 hours such that the water coming out of the specimens is twice the volume of the specimen.

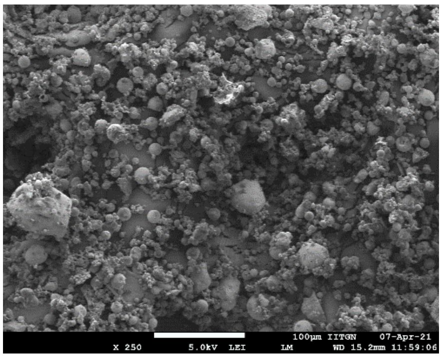

Figure 1. *SEM image of coal ash*

Table 1. *Geotechnical properties of coal ash*

Properties	Values
Visual appearance	Grey
Specific Gravity (G_s)	2.27
Particle Size: 1 mm – 75 µm	14%
Particle Size: 75 µm – 2 µm	86%
Optimum Moisture Content (OMC)	18.9%
Maximum Dry Density (MDD)	1.46 g/cc
Permeability	$3*10^{-5}$ cm/sec
Nature	Non-Cohesive & Hollow from Inside

3 EXPERIMENTAL PROGRAM

The current study used the NGI-type electromechanical cyclic simple shear devise for testing (Figure 2). The setup was equipped with two horizontal shear load cells and one axial load cell. The two LVDTs were provided to measure the displacement of the specimen and system, respectively. The cylindrical specimens were transferred into the Teflon-coated low frictional confining rings fitted above the base pedestal inside the latex membrane. The whole assembly was placed over the setup and the specimen is fully docked. The saturation process was done by the water flushing method under the seating vertical stress of 10 kPa. The saturation was assured when the water comes out of the specimen was equivalent to two times the volume of the specimen. The specimen was further subjected to the consolidation and cyclic shearing process.

In the current study, two series (T1 and T2) of tests were performed on saturated coal ash specimens under stress-controlled CSS loading conditions. The first series T1 was conducted on coal ash specimens prepared under different densities of 86%, 90% and 95% of MDD at various CSR values. The specimens were consolidated at 100 kPa of vertical effective overburden stress. The second series T2 was conducted on specimens prepared at 95% of MDD and consolidated under different vertical effective overburden stress (50, 100 and 150 kPa). The reason behind selecting the 95% of MDD is that the most of the geotechnical engineering applications like highway and railway embankment achieves the 95% of relative compaction. The frequency applied for all the CSS tests was 1 Hz. The test ID was defined by the value of density, CSR, and vertical effective overburden stress. For instance, 86CSR_0.1 indicated coal ash specimens prepared at 86% of MDD and cyclically sheared at a CSR of 0.1. Also, 50kPa_0.1 denoted the coal ash specimen consolidated at vertical effective overburden stress of 50 kPa and cyclically sheared at a CSR of 0.1. More details of the experimental plan are given in table 2.

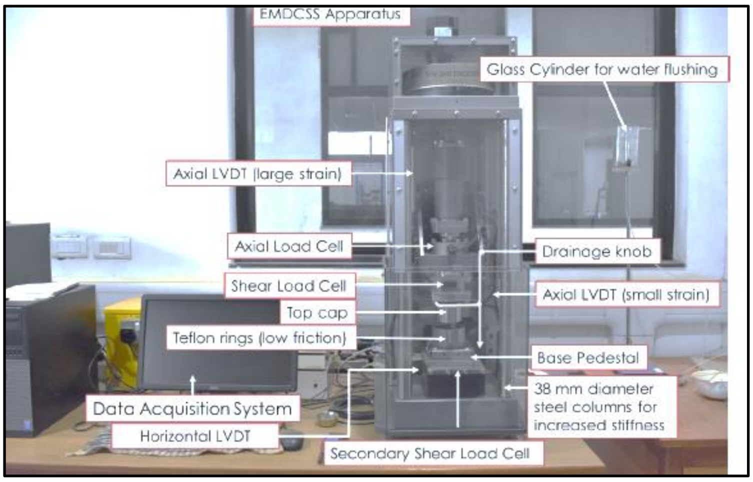

Figure 2. *Cyclic simple shear setup*

Table 2. *Details of the experimental plan under CSS loading conditions*

Series	Specimen ID	Density (%MDD)	Effective vertical overburden stress (kPa)	Number of cycles to liquefaction (N_{Liq})
T1	86CSR_0.08	86	100	65
	86CSR_0.12		100	5
	86CSR_0.14		100	3
	90CSR_0.075	90	100	82
	90CSR_0.1		100	12
	90CSR_0.14		100	4
	90CSR_0.20		100	2
	95CSR_0.1	95	100	39
	95CSR_0.12		100	15
	95CSR_0.14		100	7
	95CSR_0.15		100	5
T2	50kPa_0.1	95	50	76
	50kPa_0.12			25
	50kPa_0.18			5
	100kPa_0.1		100	39
	100kPa_0.12			15
	100kPa_0.14			7

	100kPa_0.15			5
	150kPa_0.1		150	14
	150kPa_0.12			12
	150kPa_0.15			4
	150kPa_0.2			2

4 RESULTS AND DISCUSSION

4.1 Effect of cyclic stress ratio on liquefaction and dynamic properties of coal ash specimens prepared at various densities

The effect of cyclic stress ratio on the hysteresis response of coal ash specimens under various densities (86%, 90% and 95% of MDD) is shown in figure 3. The first cycle of each test is presented for all the specimens. It was observed that with an increase in the CSR, loops became more inclined toward the horizontal axis for all the densities. With an increase in the CSR, the size of the loops was found to be larger for all the densities. The development of double amplitude shear strain (γ_{DA}) with number of cycles for all the coal ash specimens is presented in figure 4. It was seen that, for the lower CSR (86CSR_0.08, 90CSR_0.075, 95CSR_0.1), development of double amplitude shear strain was negligible up to a certain number of cycles. After this, a sudden shear strain was seen to develop for all the specimens. For the higher CSR (86CSR_0.14, 90CSR_0.20, 95CSR_0.15), the shear strain was noticed to be developed after 1st loading cycle itself. The γ_{DA} was found to be 8%, 2% and 0.5% in 2nd cycle for 86CSR_0.14, 90CSR_0.14 and 95CSR0.14, respectively. Thus, indicating a significant effect of loose and dense conditions in coal ash. The pore pressure ratio (r_u) generation with number of cycles (N) for all the specimens is presented in figure 5. The maximum value of pore pressure for each cycle was considered for the analysis, hence the curves are not starting from zero value. A sudden rise in the pore pressures was seen for all the densities at higher stress ratio amplitude. A constant pore water pressure trend was observed for all the specimens after a certain number of cycles. Liquefaction was defined based on the following criteria; (i) $r_u \geq 0.9$ (Khashila et al. 2021) (ii) $\gamma_{DA} \geq 7.5\%$ (Cappellaro et al. 2021). The number of cycles to liquefaction (N_{Liq}) is given in table 2.

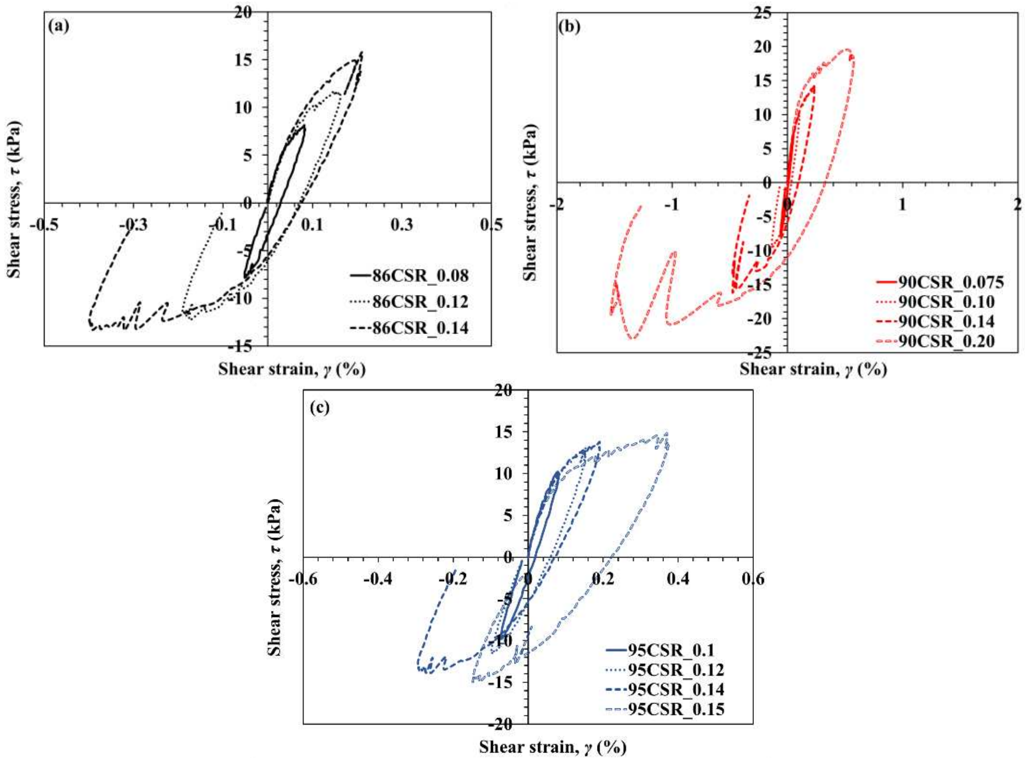

Figure 3. *Effect of CSR on hysteresis response of coal ash specimens at: (a) 86%MDD (b) 90%MDD (c) 95%MDD*

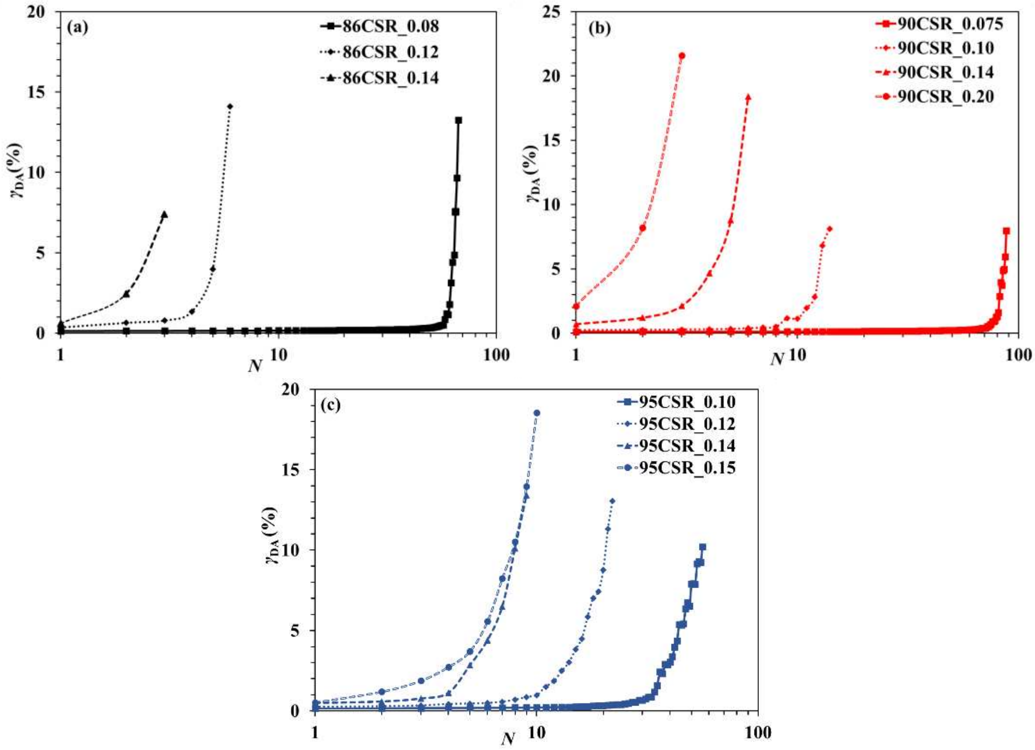

***Figure 4**. Effect of CSR on shear strain response of coal ash specimens at: (a) 86%MDD (b) 90%MDD (c) 95%MDD*

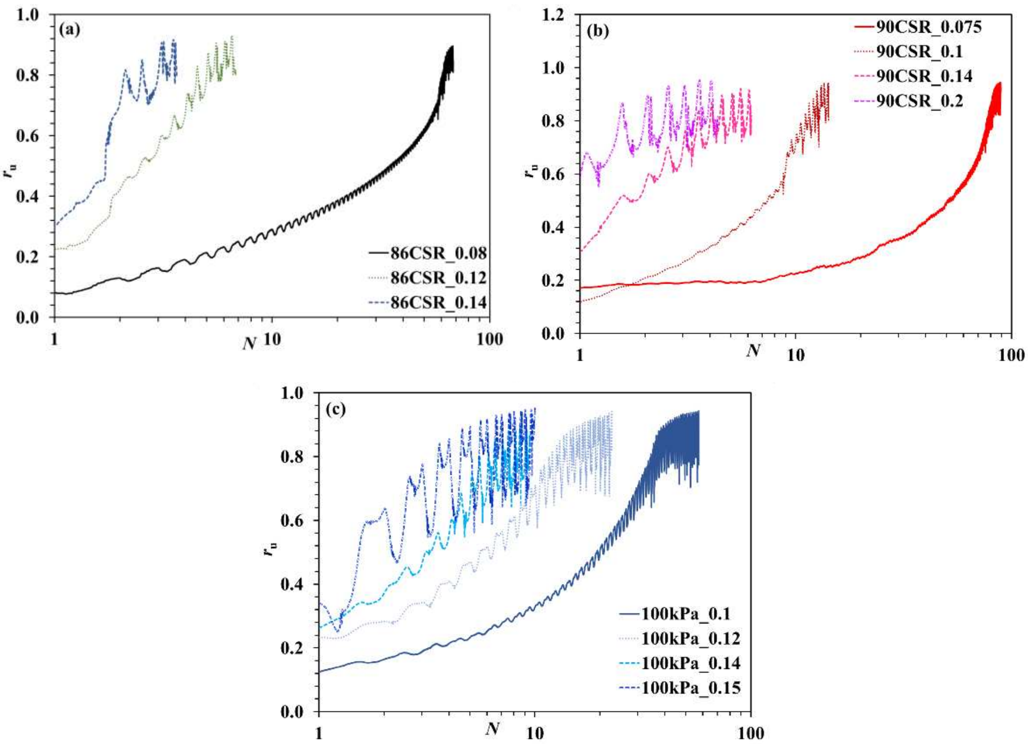

***Figure 5.** Effect of CSR on pore pressure response of coal ash specimens at: (a) 86%MDD (b) 90%MDD (c) 95%MDD*

The effect of CSR on the shear modulus response of coal ash for various densities is depicted in figure 6. The shear modulus (*G*) was found to be reduced very gradually with number of cycles for the specimens 86CSR_0.08, 90CSR_0.075 and 95CSR_0.1. However, at higher CSR, a rapid decrement in the shear modulus was noticed for all the densities. The specimens 86CSR_0.14, 90CSR_0.14 and 95CSR_0.14 exhibited almost a negligible shear modulus value after a few loading cycles. The damping ratio response of all the coal ash specimens is shown in figure 7. All the specimens exhibited almost a constant damping ratio between 30% to 50%.

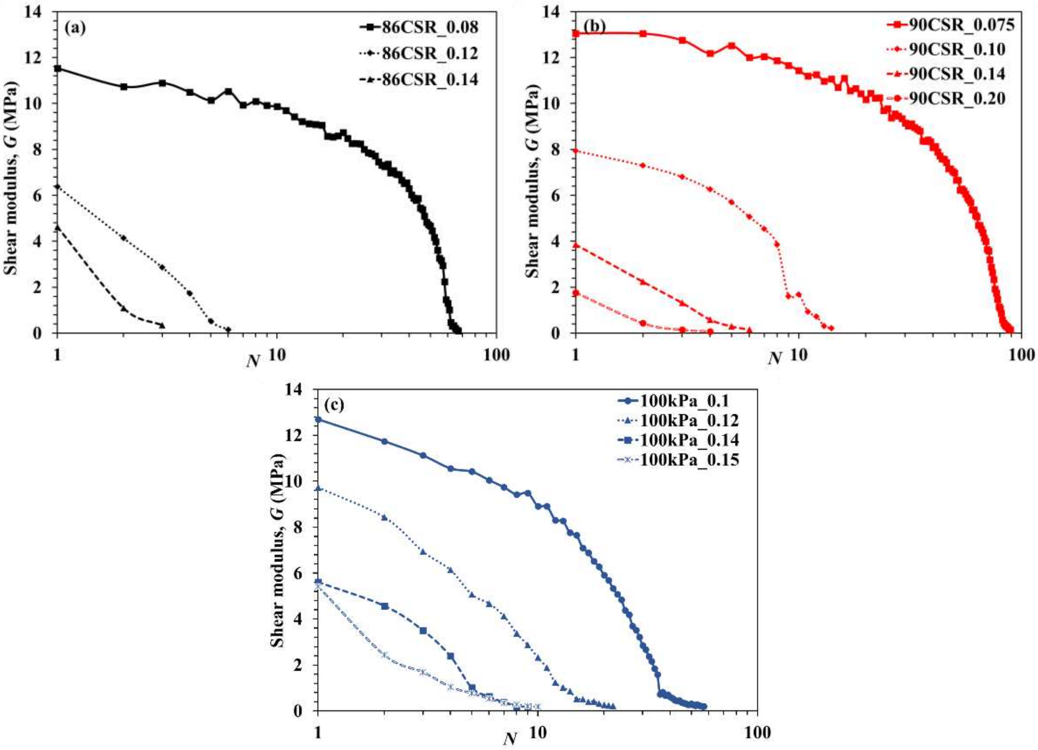

Figure 6. *Effect of CSR on shear modulus response of coal ash specimens at: (a) 86%MDD (b) 90%MDD (c) 95%MDD*

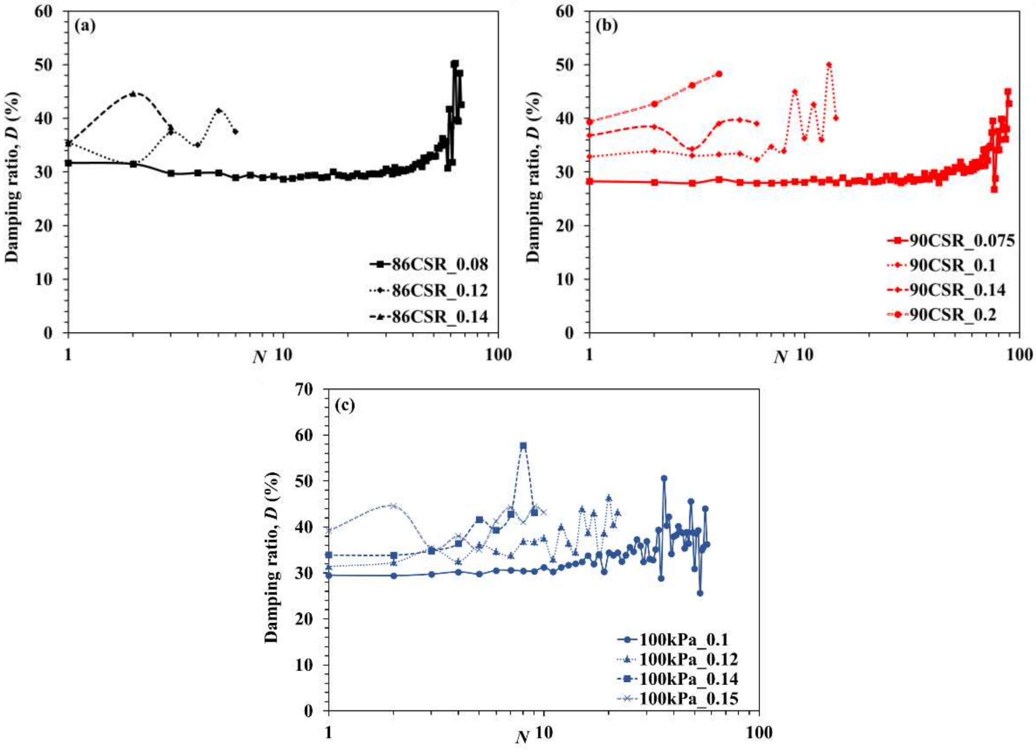

Figure 7. *Effect of CSR on damping ratio response of coal ash specimens at: (a) 86%MDD (b) 90%MDD (c) 95%MDD*

4.2 Effect of cyclic stress ratio on liquefaction and dynamic properties of coal ash under different vertical effective overburden stress

The effect of CSR on the hysteresis response of coal ash specimens consolidated under different vertical effective overburden stress (50, 100 and 150 kPa) is depicted in figure 8. The size of loops was observed to be increasing with an increase in the CSR value. For a particular CSR value, the size of the loops increased with an increase in the vertical effective overburden stress. The response of double amplitude shear strain (γ_{DA}) with number of loading cycles for specimens consolidated at different vertical effective overburden stress is shown in figure 9. A very negligible γ_{DA} was seen to develop till the 60th, 30th and 20th cycles for 50kPa_0.1, 100kPa_0.1 and 150kPa_0.1, respectively. The coal ash specimens 50kPa_0.12, 100kPa_0.12 and 150kPa_0.12 indicated a negligible shear strain development till 10th cycle followed by a rapid shear strain development with increase in the loading cycles. Figure 10 shows the pore pressure development with number of cycles for coal ash specimens. A gradual increase in the pore pressure was observed for the lower CSR, while a sudden pore pressure rise was noticed at higher CSR. A constant pore pressure value was obtained at a lesser number of loading cycles for specimens subjected to higher CSR as compared to lower CSR. The number of cycles to liquefaction (N_{Liq}) is mentioned in table 2.

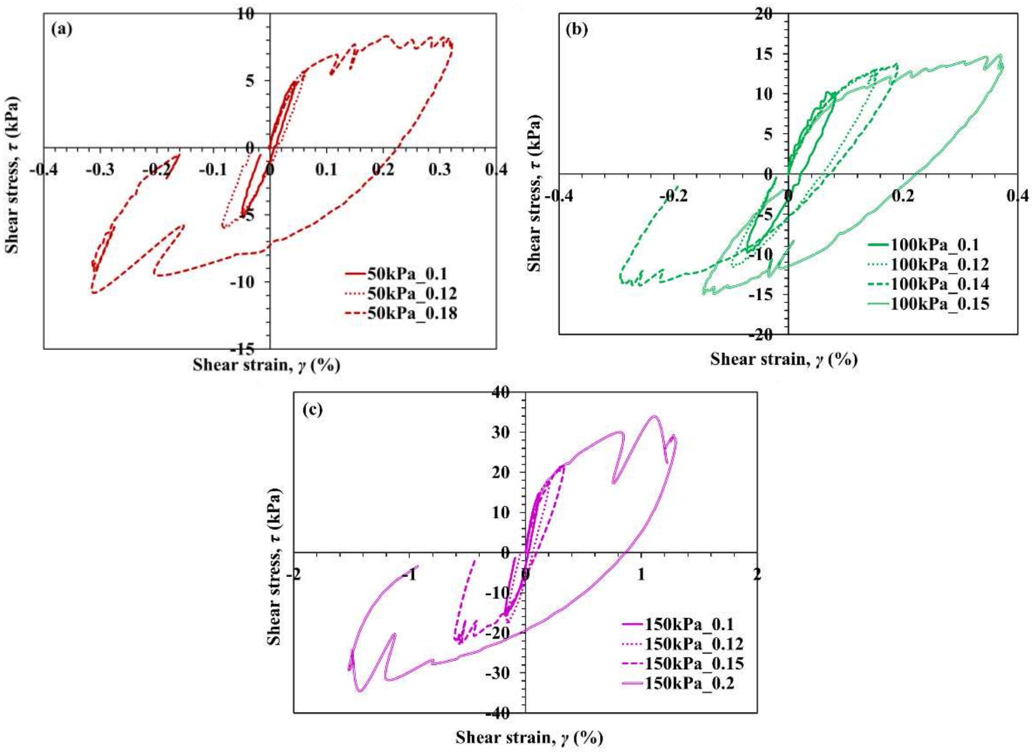

Figure 8. *Effect of CSR on hysteresis response of coal ash specimens consolidated at different vertical effective overburden stress: (a) 50 kPa (b) 100 kPa (c) 150 kPa*

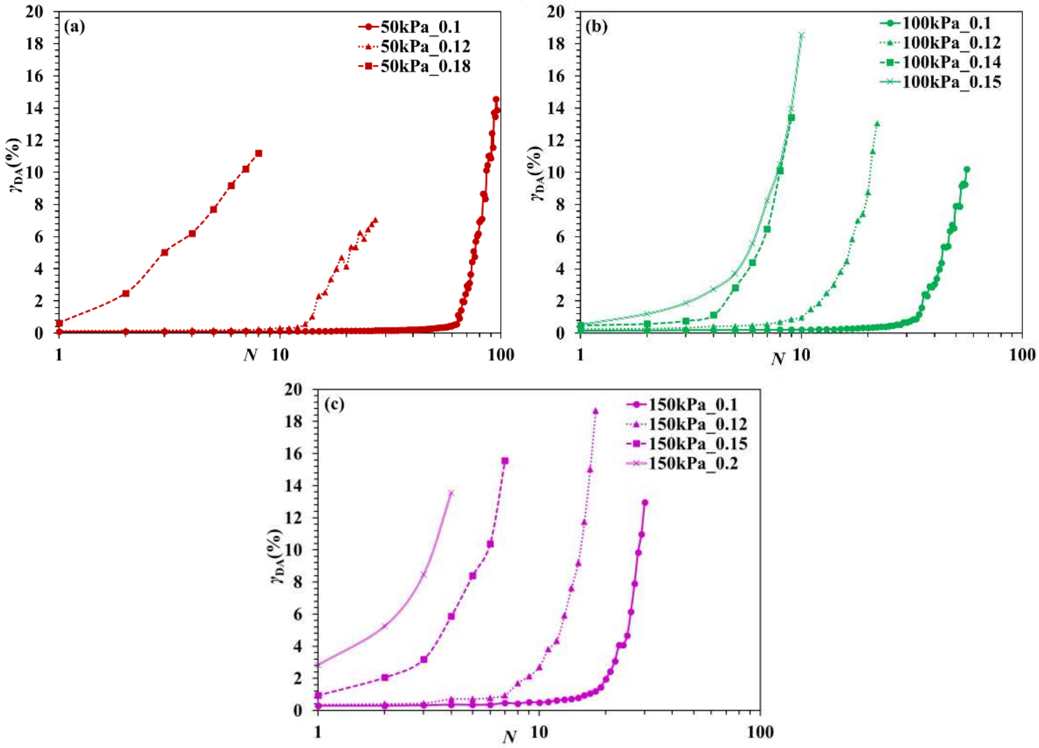

Figure 9. *Effect of CSR on shear strain response of coal ash specimens consolidated at different vertical effective overburden stress: (a) 50 kPa (b) 100 kPa (c) 150 kPa*

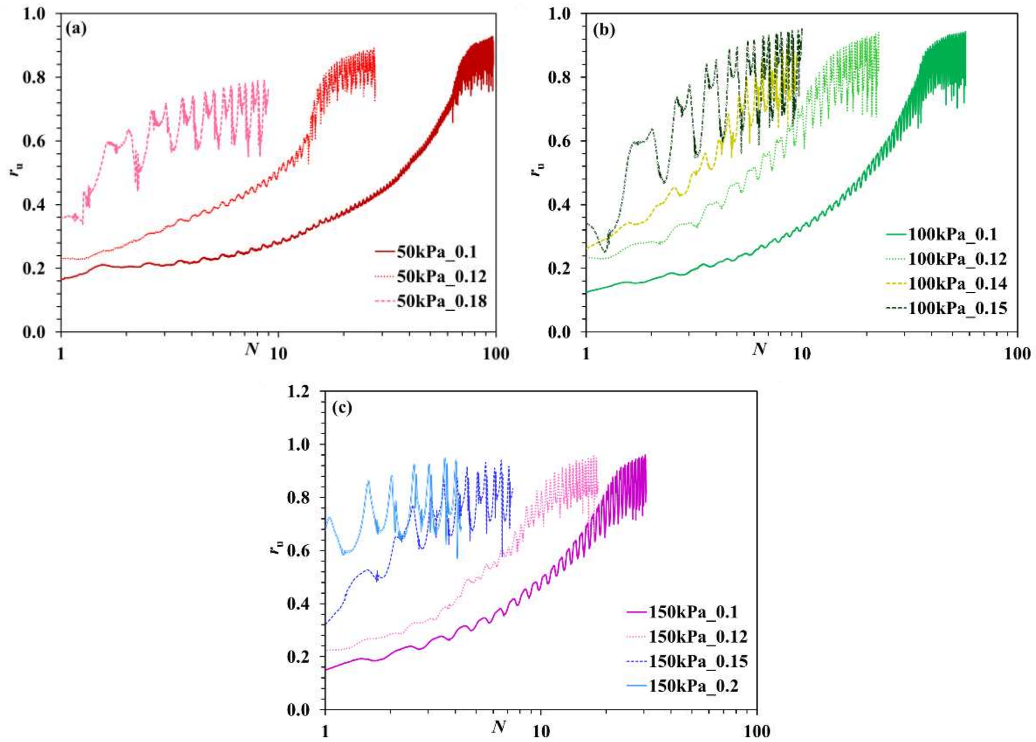

Figure 10. *Effect of CSR on pore pressure response of coal ash specimens at different vertical overburden stress: (a) 50 kPa (b) 100 kPa (c) 150 kPa*

The shear modulus variation with the loading cycles is presented in figure 11. A very gradual reduction in the shear modulus was observed for 50kPa_0.1, 100kPa_0.1 and 150kPa_0.1 specimens. The number of cycles at which the specimens 50kPa_0.1, 100kPa_0.1 and 150kPa_0.1 reached a negligible (almost zero) shear modulus was the 70th, 50th and 30th loading cycles. However, a sudden drop in the shear modulus was observed for the specimens subjected to higher stress amplitudes. The damping ratio was found to be almost constant covering a range between 30% to 50% for all the specimens (figure 12).

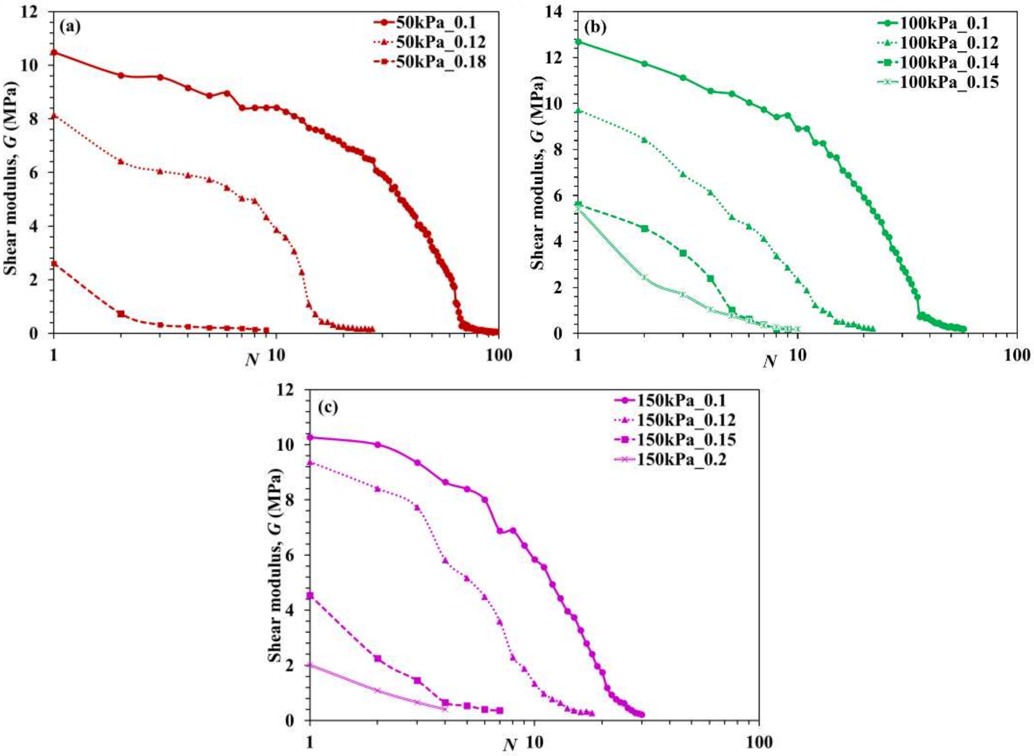

Figure 11. *Effect of CSR on shear modulus response of coal ash specimens at: (a) 50 kPa (b) 100 kPa (c) 150 kPa*

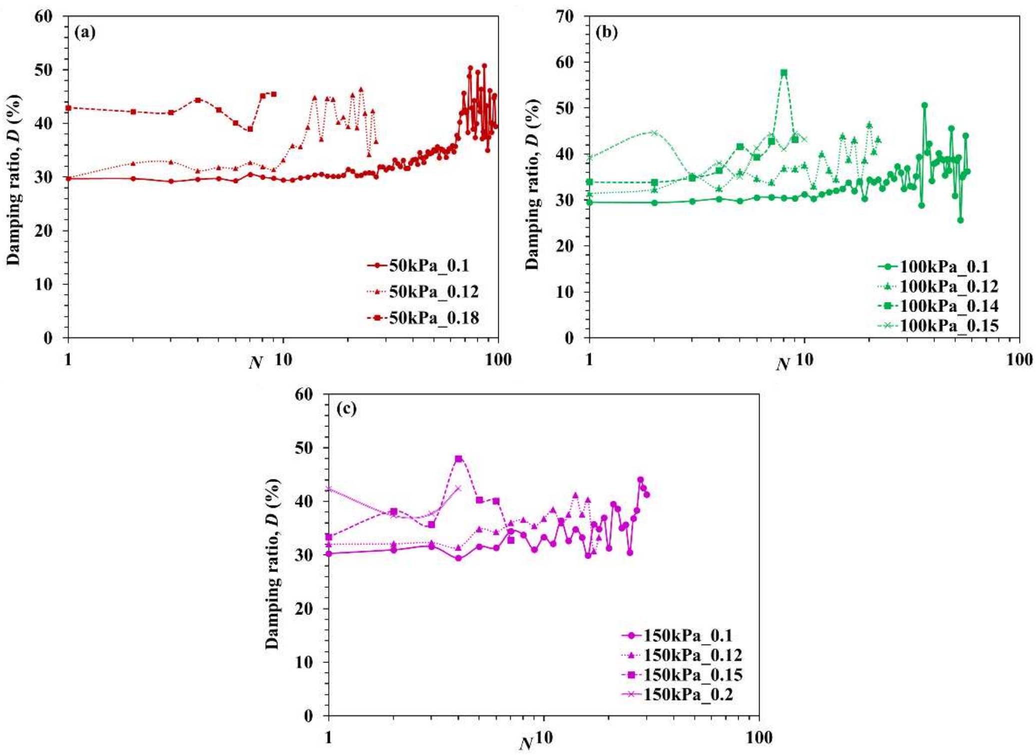

Figure 12. *Effect of CSR on damping ratio response of coal ash specimens at: (a) 50 kPa (b) 100 kPa (c) 150 kPa*

5 CONCLUSIONS

The conclusions drawn from the present study are as follows:

- The abrupt increase in the double amplitude shear strain and pore pressure was obtained for the coal ash specimens at higher CSR as compared to lower CSR values.
- The number of loading cycles at liquefaction was observed to reduce with the increase in CSR value.
- A rapid decay in the shear modulus was observed for the coal specimens subjected to the higher CSR value.
- The evaluation of damping ratio indicated a slight increase with the increase in CSR value.

6 ACKNOWLEDGEMENTS

The author would like to acknowledge the Indian Institute of Technology Gandhinagar for their financial and technical support. Any thoughts, findings and interpretations mentioned in this paper are of the authors and do not reflect the views of IIT Gandhinagar.

REFERENCES

Baki, M. A., Rahman, M. M., & Lo, S. R. (2012). Cyclic instability behaviour of coal ash. In GeoCongress 2012: State of the Art and Practice in Geotechnical Engineering (pp. 849-858).

Baki, M. A. L., Rahman, M. M., & Lo, S. R. (2019). Liquefaction of a coal ash investigated by monotonic and cyclic triaxial tests. *Soils and Foundations*, *59*(5), 1522-1536.

Cappellaro, C., Cubrinovski, M., Bray, J. D., Chiaro, G., Riemer, M. F., & Stringer, M. E. (2021). Liquefaction resistance of Christchurch sandy soils from direct simple shear tests. Soil Dynamics and Earthquake Engineering, 141, 106489.

Chattaraj, R., & Sengupta, A. (2017). Dynamic properties of fly ash. J. Mater. Civ. Eng, 29(1), 04016190.

Jakka, R. S., Ramana, G. V., & Datta, M. (2010). Shear behaviour of loose and compacted pond ash. Geotechnical and Geological Engineering, 28(6), 763-778.

Jakka, R. S., Datta, M., & Ramana, G. V. (2010). Liquefaction behaviour of loose and compacted pond ash. Soil Dynamics and Earthquake Engineering, 30(7), 580-590.

Khashila, M., Hussien, M. N., Karray, M., & Chekired, M. (2021). comparative Liquefaction resistance from cyclic simple and triaxial shearing: a study. Acta Geotechnica, 16(6), 1735-1753.

Mohanty, S., & Patra, N. R. (2014). Cyclic behavior and liquefaction potential of Indian pond ash located in seismic zones III and IV. Journal of materials in civil engineering, 26(7), 06014012.

Mohanty, S., & Patra, N. R. (2016). Dynamic response analysis of Talcher pond ash embankment in India. Soil Dynamics and Earthquake Engineering, 84, 238-250.

Ram, A. K., & Mohanty, S. (2021). Experimental investigation on dynamic behavior of silt-rich fly ash using cyclic triaxial and bender element tests. Innovative Infrastructure Solutions, 6(4), 219.

Shrivastava, A., & Sachan, A. (2023). Effect of stress-induced anisotropy on shear modulus response of compacted coal ash under small-strain dynamic loading conditions. Soil Dynamics and Earthquake Engineering, 170, 107898.

Singh, J., & Singh, S. K. (2022). Dynamic Properties of Spatially-Varied Pond Ash within a Coal Ash Pond. International Journal of Geomechanics, 22(3), 04021309.

Yoshimoto, N., Orense, R. P., Hyodo, M., & Nakata, Y. (2014). Dynamic behavior of granulated coal ash during earthquakes. Journal of Geotechnical and Geoenvironmental Engineering, 140(2), 04013002.

Zhang, J., Lo, S. C. R., Rahman, M. M., & Yan, J. (2018). Characterizing monotonic behavior of pond ash within critical state approach. Journal of Geotechnical and Geoenvironmental Engineering, 144(1), 04017100.

The paper was published in the proceedings of the 9th International Congress on Environmental Geotechnics (9ICEG), Volume 3, and was edited by Tugce Baser, Arvin Farid, Xunchang Fei and Dimitrios Zekkos. The conference was held from June 25th to June 28th 2023 in Chania, Crete, Greece.