Effect of Particle Size Distribution on Creep Characteristics of Calcareous Sand under Confined Conditions

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Abstract. The creep characteristics of calcareous sand under different stress levels and gradations were examined in the study through a series of one-dimensional creep tests using a self-designed acrylic model box. The results demonstrate that, under confined conditions with the same particle gradation, the creep strain and creep rate of calcareous sand increase with the increase of creep stress. Under the same creep stress, the overall creep rate exhibits a nonlinear attenuation over time. Additionally, as the coefficient of uniformity C_u of calcareous sand increases, the content of fine particles increases which can fill in the spaces between the larger particle skeletons, resulting in an increase in interparticle locking and a decrease in particle breakage, hence, the creep deformation is inhibited. That is, the creep rate and creep strain of calcareous sand decrease with an increase in C_u. Optimizing the particle gradation can effectively reduce creep in calcareous sand.

Keywords: calcareous sand ; particle breakage ; creep ; particle size distribution ; coefficient of uniformity

1 Introduction

Calcareous sand refers to a special type of soils with a high content of calcium carbonate or dissolved carbonate[1]. It is widely distributed in various regions, including the South China Sea [2]. The particles of calcareous sands are highly irregular in shape, numerous internal pores, and brittle and easily crumble. Due to the unique characteristics, the engineering mechanical properties of calcareous sands significantly differ from those of typical terrestrial and marine sediments [3-6]. With the development of the South China Sea, calcareous sand plays a crucial role as a foundation material and construction material in various engineering projects. Researchers have conducted extensive studies on the macroscopic characteristics of calcareous sand, such as compression,

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shear, and creep. The effects of different factors, including confining stress[7], water content[8], particle size[9], stress path[10], and particle content[11], on static properties of calcareous sand were also investigated. Furthermore, the behavior of particle crushing has been analyzed[12].

Many researchers[13-20] have discovered that calcareous sand exhibits creep phenomenon with longer duration and larger strain compared to land-sourced sand under specific loading conditions through one-dimensional creep tests and triaxial creep tests. Up to now, there is still limited research available on the influence of particle gradation on the creep characteristics of calcareous sand. In this paper, a series of one-dimensional creep tests are conducted by a self-designed acrylic model box. The creep characteristics of calcareous sand with different particle size gradations are analyzed.

2 EXPERIMENTAL DETAILS

2.1 Test equipment

The experimental setup is illustrated in Figure 1. The pressure is loaded by an MTS universal testing machine with a maximum loading capacity of 90 kN. This system can provide various loading modes, including constant stress loading, step loading, cyclic loading. The model box is a specially designed transparent acrylic board box. The thickness of sidewall and bottom is 20 mm, and its internal dimensions are 50 mm × 50 mm × 100 mm. That is, the size of the calcareous sand sample is 50 mm × 50 mm × 100 mm. The transparency of the acrylic board enables the tracking and recording of the entire test process through the front window by captured image.

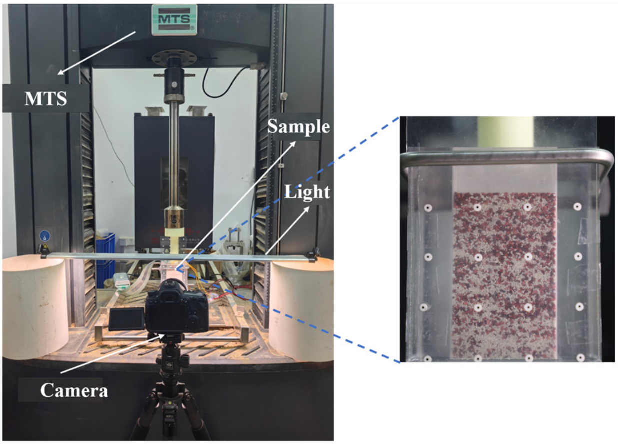


Fig. 1. Experimental setup

2.2 Calcareous sand

The calcareous sand utilized in this study was from an island located in the South China Sea. Given that calcareous sand is a sediment found in marine environments, it tends to have salt adhered to its surface. To minimize the potential influence of salt and reduce test uncertainties, the samples were thoroughly cleaned prior to testing and dried. To investigate the impact of particle size distribution on the creep behavior of calcareous sand, four different graded samples were tested. The corresponding coefficient of non-uniformity C_u for each sample was set to 2, 4, 8 and 12, respectively. The corresponding particle size distribution curves are illustrated in Figure 2. The initial relative density Dr of the samples was maintained at 0.7 throughout the testing process.

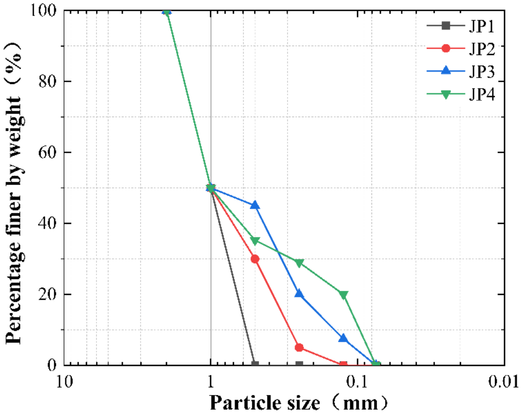


Fig. 2. Particle size distributions of different calcareous sand samples

2.3 Test arrangement

In order to investigate the creep characteristics of calcareous sand under different vertical stress conditions, six levels of stresses, 100, 200, 400, 800, 1200, and 1600 kPa, were selected for the confined creep tests. During the tests, the stress was applied gradually at a constant rate of 10N/s, and each stress level was maintained for a duration of 90 minutes. In order to examine the particle crushing during creep, sieve tests were conducted on each group of samples after creep.

3 EXPERIMENTAL RESULTS

3.1 Stress-strain relationship

Figure 3 depicts the relationship between void ratio e and vertical stress p, represented by the e-lgp curve. It can be seen that, under the same degree of relative density (Dr) condition, as the coefficient of uniformity (C_u) increases, the proportion of fine particles within the calcareous sand also increases. Consequently, the void spaces between the coarse particles are filled with fine particles, resulting in a decrease in void ratio.

Initially, the sample exhibits a relatively stable structure where the load-bearing skeleton is primarily composed by coarse particles. The fine particles fill the voids within the skeleton and contribute to bearing the vertical stress alongside the coarse particles, forming a cohesive structure. At this stage, the applied vertical stress is insufficient to disrupt the stable structure of the sample; instead, it only causes slight adjustments in the particle positions. As a result, the voids within the sample are compressed, leading to minor vertical deformation of the sample as a whole. However, as the vertical stress increases, particularly when it reaches a threshold capable of destroying the original load-bearing structure, the process of coarse particle breakage begins. The sample enters a state characterized by particle breakage, particle movement, redistribution of forces between particles. Under such conditions, a new load-bearing skeleton gradually forms, establishing a new equilibrium state. This can be observed through a significant reduction in void ratio attenuation as vertical stress increases. The inserted figures in Figure 3 shows the steps which is related to the creep deformation.

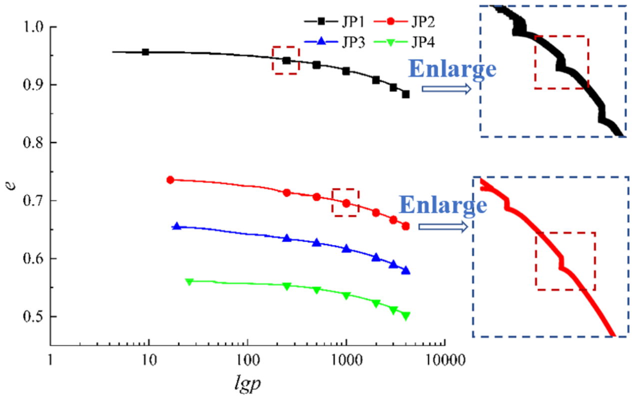
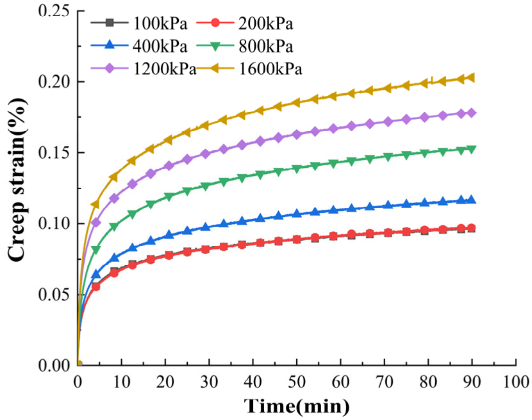


Fig. 3. Compression test results of different graded calcareous sands: e-p curves

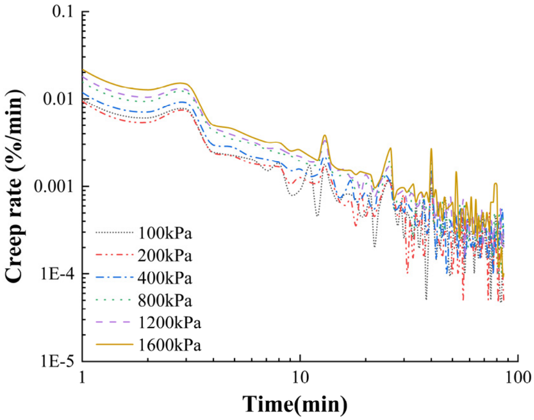
3.2 Creep characteristics

Figure 4 illustrates the creep strain (represented by the vertical strain) and the corresponding creep rate-time curves of represented calcareous sand subjected to different creep stresses. It can be observed that as the creep stress increases, the magnitudes of creep deformation and the creep rate increase. For a given creep stress level, the overall creep rate exhibits a non-linear attenuation over time, as depicted in Figure 4b. Initially, there is an upward trend in the creep rate, followed by a subsequent decline.

Figure 5 presents the partial size distribution effects on creep, in which the partial size distribution is stood by the coefficient of uniformity C_u and the creep behavior is represented by the creep strain as well as the initial creep rate. It is found that both the initial creep rate and creep strain of calcareous sand decrease with an increase in C_u. The increase in C_u corresponds to a higher proportion of fine particles within the sample, which leads to the filling of voids between the coarse particle skeleton. Consequently, the interlocking between particles is intensified, inhibiting the progress of creep and resulting in reduced creep rate and creep strain. Furthermore, the data suggests that under higher vertical stresses, creep deformation exhibits a linear decrease with respect to C_u. When the range of C_u is from 2 to 4, the decline in creep rate becomes more pronounced. However, as C_u continues to increase beyond 4, the diminishing trend of the creep rate slows down.

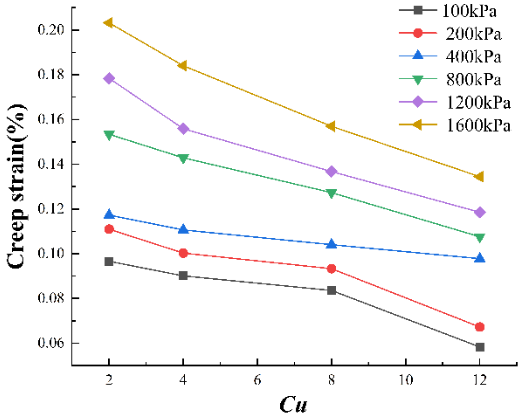


(a)

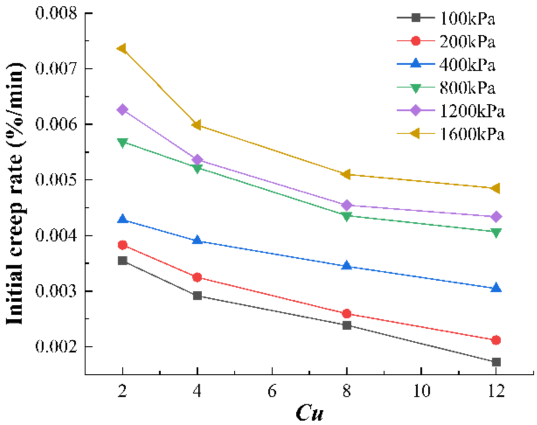


(b)

Fig. 4. Creep strain-time curves (a) and Creep rate-time curves (b) of represented calcareous sand (JP1) under different confined conditions



(a)



(b)

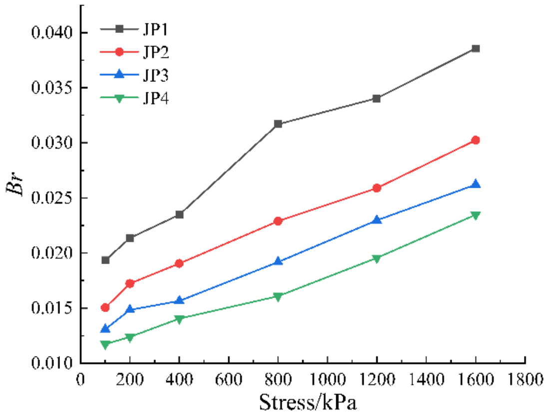
Fig. 5. Relationship of coefficient of uniformity C_u and creep strain (a) and creep rate (b)

4 PARTICLE BREAKAGE DURING CREEP

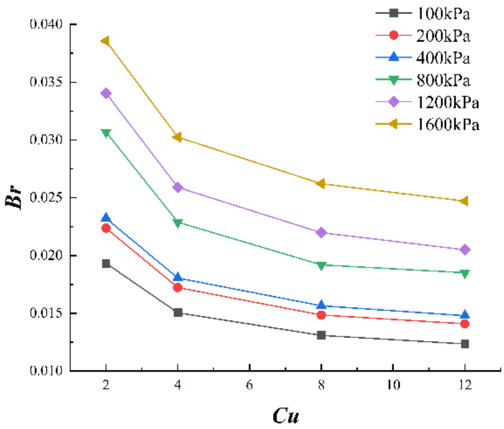
In order to quantify the particle crushing degree of calcareous sand, the samples were sieved after each stress creep test, and the relative crushing rate (B_r) proposed by Hardin[21] was used for quantitative description, following the principle that particles with particle size D<0.074 mm could not be further broken. The area surrounded by vertical line with particle size D=0.074 mm, particle grading curve, horizontal line with mass percentage of 100% and horizontal line is called initial crushing potential (B_{p0}), and the area surrounded by vertical line with particle grading curve and initial curve and D=0.074 mm after being crushed by force is total crushing potential (B_t), $B_r = B_t/B_{p0}$.

Figure 6 illustrates the relationship between the relative crushing rate B_r of calcareous sand particles with different gradations and the vertical stress, as well as the coefficient of uniformity C_u. The findings indicate that B_r of calcareous sand increases with an increase in vertical stress across all levels as shown in Figure 6a. Additionally, as C_u increases, B_r decreases (Figure 6b). This is because that fine particles in sample with higher C_u fill the void spaces between the coarse particles, resulting in a decrease in the initial void ratio of the sample. Additionally, the presence of fine particles enhances the interlocking between particles, thereby increasing the overall bearing capacity of the sample skeleton, which make it more challenging to compress or deform under the same loading conditions. This means that the calcareous sand with a higher C_u requires a greater applied stress to induce particle breakage or deformation.

According to Figure 6b, there is a notable observation that when C_u exceeds a certain threshold value, the value of B_r of calcareous sand particles decreases sharply. This behavior is highlighted by an inflection point in the curve, suggesting that particle gradation unevenness plays a significant role in the fragmentation of calcareous sand particles. Indeed, when C_u is small, it indicates a more homogeneous particle gradation in the calcareous sand sample. In this case, the sample contains a higher proportion of coarse particles, resulting in a significant shelf effect. With fewer contact points between particles, the average contact stress between them tends to be higher, which in turn makes the calcareous sand particles more susceptible to particle crushing. As C_u continues to increase, the particle size range in calcareous sand samples expands. Consequently, the proportion of large particles with irregular shapes decreases, and become scattered among the load-bearing skeletons formed by fine particles with regular shapes. Additionally, the introduction of powder particles fills the intergranular pores within the sample. This filling effect further reduces the stress concentration caused by irregularly shaped particles. As a result of these factors, the particle breakage B_r rate rapidly decreases.



(a)



(b)

Fig. 6. Diagram of the relationship between particle crushing rate B_r and vertical stress (a) and coefficient of uniformity C_u (b)

5 CONCLUSIONS

This study employed a self-designed acrylic test box to conduct a series of one-dimensional creep tests on calcareous sand with different particle gradations. The influence of particle size distribution on the creep process for calcareous sand was investigated. The main conclusions are as follows.

(1) Under confined creep, for calcareous sand with the same gradation, the creep strain and creep rate increase with the increasing creep stress. Under the same creep stress level, the overall creep rate exhibits a non-linear attenuation over time, gradually decreasing.

(2) As the coefficient of uniformity of calcareous sand gradually increases, the proportion of fine particles also increases which fill the spaces between the larger particle skeleton and lead to an increase in interlocking between particles. This increased interlocking inhibits the progression of creep, resulting in a decrease in the creep rate and creep strain of the calcareous sand.

(3) Particle size and gradation have significant effects on the crushing characteristics of calcareous sand. Specifically, under the same termination stress, calcareous sands exhibit a decrease in crushing with an increase in the coefficient of uniformity.

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REFERENCES

1. Liu C Q, Yang Z Q, Wang R. The present condition and development in studies of mechanical properties of calcareous soils [J]. Rock and Soil Mechanics, 1995, 16(4):74-84. (in Chinese)
2. Shen J H, Wang R. Study on engineering properties of calcareous sand. Journal of engineering geology, 2010, 18(S1): 26-32. (in Chinese)
3. Zhu C Q, Chen H Y, Meng Q S. Analysis of structural characteristics of pores in calcareous sand particles [J]. Rock and Soil Mechanics, 2014, 35(7): 1831-1836. (in Chinese)
4. Wu J Q, Chu Y, Lou Z G. Effect of particle breakage on deformation and strength characteristics of calcareous sand [J]. Chinese Journal of Geotechnical Engineering, 1997, 19(5): 51-57. (in Chinese)
5. Wang Y Q, Hong Y, Guo Z. Mechanical properties of macro and micro crushing of calcareous sand in the South China Sea [J]. Rock and Soil Mechanics, 2018, 39(1): 199-206, 15. (in Chinese)
6. Sun J Z, Wang R. Study on particle fracture process of calcareous sand under triaxial compression [J]. Rock and Soil Mechanics, 2003, 24(5): 822-825. (in Chinese)
7. Shen Y, Shen X, Yu Y M. Macroscopic and mesoscopic study on the effect of grain content on the compression deformation properties of calcareous sand[J]. Rock and Soil Mechanics, 2019, 40(10): 3733-3740. (in Chinese)
8. Qian W. Laboratory experimental study on mechanical properties of coral sand on an island reef [J]. Soil Engineering and Foundation, 2016, 30(4): 527-532. (in Chinese)
9. Chen H D, Wei H Z, Feng Z. Study on crushing strength and crushing form of calcareous sand particles [J]. Soil Engineering and Foundation, 2018, 32(6): 637-641. (in Chinese)
10. Zhang J R, Luo M X, Peng W K. Drained triaxial experimental study on mechanical properties of calcareous sand under different stress paths[J]. Chinese Journal of Geotechnical Engineering, 2021, 43(4): 593-602. (in Chinese)
11. Zhang C Y, Chen M, Hu M J. Effect of fine particle content on shear strength of calcareous sand [J]. Rock and Soil Mechanics, 2019, 40(S1): 195-202. (in Chinese)
12. Kjaernsli B, Sande A. Compressibility of some coarse-grained materials[C]. Proe European Conf Soil Mech. and Found Engrg. Weisbaden, 1963:245-251.
13. Sanzeni A, Whittle A J, Germaine J T. Compression and creep of Venice lagoon sands[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2012, 138(10): 1266-1276.
14. Lv Y, Li F, Liu Y. Comparative study of coral sand and silica sand in creep under general stress states[J]. Canadian Geotechnical Journal, 2016, 54(11):1601-1611.
15. Ye J H, Cao M, Li G. Preliminary study on the creep characteristics of calcareous sand from reclaimed coral reef islands in South China Sea[J]. Chinese Journal of Rock Mechanics and Engineering, 2019, 38(6):1242-1251. (in Chinese)
16. Wang Y S, Ma L J, Wang M Y, Lv Y R, Dong L, Fan P X. A creep constitutive model incorporating deformation mechanisms for crushable calcareous sand[J]. Arabian Journal of Geosciences, 2018, 11(20):1-8.
17. Lade P V, Carl D, Liggio J R, Nam J. Strain rate creep and stress drop-creep experiments on crushed coral sand[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2009, 135(7): 941-953.
18. Chen B, Deng J, Hu J M, Zhang J L, Zhang Tao, Macroscopic and microscopic experimental study on fractal fragmentation characteristics of calcareous sand during one-dimensional compression creep[J]. Rock and Soil Mechanics, 2022, 43(7): 1781-1790. (in Chinese)

19. Liu S, Wang J, Kwok C Y. DEM simulation of creep in one-dimensional compression of crushable san[J]. Journal of Geotechnical and Geoenvironmental Engineering, 2019, 145(10):04019060.
20. Edward A, Dijkstra J, Roubin E. A peek into the origin of creep in sand[J]. Granular Matter, 2019, 21(1):1-8.
21. Hardin B O. Crushing of soil particles[J]. Journal of Geotechnical Engineering, 1985, 111(10):1177-1192.

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