

Article

Critical Dynamic Stress and Cumulative Plastic Deformation of Calcareous Sand Filler Based on Shakedown Theory

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Abstract: Calcareous sand is a special marine soil rich in calcium carbonate minerals, characterized by brittle particles. It is, therefore, widely used as a filling material in the construction of islands and reefs. In this study, a series of cyclic tri-axial tests were conducted on calcareous sand taken from a reef in the South China Sea under different confining pressures and cyclic stress ratio (CSR). Then, applying the shakedown theory, the cumulative deformation of calcareous sand under a long-term cyclic load of aircraft was evaluated. Results showed that with the increase in the effective confining pressure, the stress–strain curves of calcareous sand showed a change from the strain-softening to the strain-hardening state; the volumetric strain of calcareous sand showed a change from shear shrinkage and then shear expansion to continuous shear shrinkage. Calcareous sand showed three different response behaviors under cyclic load: plastic shakedown, plastic creep and incremental plastic failure. With the plastic strain rate as the defining index, this study determined the critical CSR of calcareous sand under different shakedown response statuses and found them to increase with the effective confining pressure. The empirical formula for critical stress was established based on the fitting analysis of critical CSR under different confining pressures, taking the confining pressure as the variable. At the early stage of the cyclic load, calcareous sand samples were under compression. When the resilient modulus grew rapidly and the number of loading cycles continued to increase, the particles of calcareous sand samples were crushed, causing the fine particles to fill the voids among coarse particles, further compacting the samples and increasing the resilient modulus of calcareous sand samples. Hardin's breakage potential model was adopted to quantitatively describe the particle breakage of calcareous sand samples before and after tests. The results indicated that calcareous sand samples produced obvious particle breakage when the CSR was small. As the CSR increased, the extent of the breakage of the sample particles first increased and thereafter stabilized. This study provides a theoretical reference for the assessment of the dynamic stability of calcareous sand subgrade subjected to traffic loads.

Keywords: calcareous sand; cyclic load; shakedown analysis; cumulative deformation; critical dynamic stress



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1. Introduction

Calcareous sand is a special kind of sand material formed by the deposition of the remains of coral and other marine organisms (e.g., seaweed and shells) after being transported through the sea, whose main chemical component is calcium carbonate [1–3]. Calcareous sand is widely distributed in the coastal areas of countries along the Maritime Silk Road; in fact, the South China Sea coastal shelf is an area with a complete system of continental shelf coral reef, continental slope coral reef and oceanic coral reef [4]. Coral reef is almost the only land type in the South China Sea. The construction of islands and reefs in the ocean is far away from the land, but filler material resources on the island are limited, so the cost of transporting sand and gravel from the land is quite high. Hence, calcareous sand filler

made in situ has been widely used in subgrade filling and in various types of military and civil infrastructure, such as roads, runways, wharves and tarmacs [5–10].

Transportation infrastructure infilled with calcareous sand bears long-term traffic loads all through its operational life. It has been demonstrated that post-construction subgrade subsidence caused by the cyclic load of traffic during the operational period of the said infrastructure will continue to develop. It also has a significant impact on subgrade service performance and reduces driving comfort, and, in serious cases, it causes large segments of roads to become uneven with subsidence and inadequate pavement [11–13]. Runways also have significant impact on the airworthiness of aircraft. Runway subsidence should never be greater than 200 mm during operation, with post-construction differences being controlled from 0.1% to 0.15%. When calcareous sand is used as runway subgrade filling material, its characteristics of multi-porosity, multi-angularity, high compression and brittle particles make it prone to plastic deformation under cyclic load [14,15]. With particle breakage, coarse particles are gradually broken into finer particles and fill the gap between particles, further compacting the sand and gradually increasing its resilient modulus. This aggravates the subgrade subsidence and the deterioration of the service performance, resulting in excessive subsidence of the runway, which affects its normal operation [16]. Therefore, the investigation of the stress–strain curves and cumulative deformation under cyclic load of calcareous sand as runway subgrade filler is required to provide evidence of the suitability of calcareous sand as subgrade filler or otherwise.

The mechanical performance of marine calcareous sand filler differs significantly from that of terrestrial siliceous sand fillers [1,12,17,18]. The shape of calcareous sand particles is extremely irregular; many of the internal pores of the original marine bones are retained, and the particle strength is much lower than that of siliceous sand. Under traffic load, it has a more complex particle rearrangement and dilatancy [1,19–21]. Furthermore, it is prone to local wear, overall disintegration and other kinds of mechanical breakage [12,18,22]. On account of its special physical mechanical performance, the dynamic characteristics of calcareous sand under cyclic traffic load are significantly different from those of terrestrial siliceous sand, making its long-term cyclic behavior difficult to predict with classical soil mechanics and constitutive theory.

There is a lack of design specification or method for subgrade materials sourced from marine island reclamation in the literature [6]. In view of the advantages of elastoplastic deformation in characterizing structures under cyclic load, the shakedown analysis is widely applied to study the dynamic response of siliceous granular soils under traffic loads [23–29]. Werkmeister et al. [30] found from experiments that under the action of traffic load, calcareous sand bears pressure better than tensile stress. The response behavior of coarse-grained soil under cyclic load can be divided into three: plastic shakedown, plastic creep and incremental plastic failure.

Material that has attained a “shakedown status” only produces plastic deformation after undergoing a small number of cyclic loads. With an increase in the number of loading cycles, when no new plastic deformation is generated in the material, it only shows a pure resilient response. When the external cyclic load exceeds the shakedown load of the material, the material will continue to produce plastic deformation during the whole load cycle, and, eventually, the structure will have incremental plastic failure due to the accumulated plastic deformation [24,31,32]. The shakedown theory was introduced to characterize the dynamic response behavior of runway calcareous sand subgrade and reveal the shakedown status of calcareous sand at different stress levels. Its plastic deformation development was controlled in order to meet the requirements of long-term subsidence control. The findings in this study can provide a theoretical basis for the assessment of calcareous sand subgrade dynamic stability.

In this study, calcareous sand was used as the test material for the dynamic triaxial tests with the GDS Triaxial Testing System. The axial plastic strain and resilient modulus of calcareous sand were the objects of analysis, and the stress–strain curve and cumulative deformation under different confining pressures and CSR were investigated. The Werk-

meister shakedown response status [30] was used to define the criteria for the cumulative plastic deformation and to determine critical cyclic dynamic stress of calcareous sand at different shakedown response statuses under cyclic loads. The empirical formula for the critical stress of calcareous sand was established as a function of confining pressure, and Hardin's breakage potential model was utilized to quantitatively describe the degree of the fragmentation of calcareous sand under different shakedown response statuses. The results of this study can provide a theoretical basis for determining the suitability of calcareous sand as a subgrade filler.

2. Experiments

2.1. Instrument

The GDS Triaxial Testing System (see Figure 1) jointly developed by Zhejiang University of Technology and GDS Company in the UK was adopted for the experimental tests. The basic configuration of the instrument includes the following: hydraulic drive unit, pressure chamber, underwater load sensor, DCS digital control system, confining pressure and back pressure controller, and balance hammer.



Figure 1. GDS Triaxial Testing System.

2.2. Samples

The calcareous sand samples shown in Figure 2a were collected from an island in the South China Sea. The quantity of calcareous sand collected was two or three times of the needed quantity. In order to avoid the loss of small particle size caused by improper sampling, the calcareous sand was mixed evenly and then the sand was sampled using the equipartition method (also known as conical quadratic method, refers to each sample stacked and pressed into a uniform cone and then divided into four equal parts with a cross-shaped frame of a reduction operation method), so that the sand samples obtained were consistent with the original calcareous sand of the island.

The results of the sample analysis are shown in Figure 2b: X-ray diffraction (XRD). Calcareous sand is composed mainly of CaCO_3 and SiO_2 , the content of CaCO_3 and SiO_2 being about 82.8% and 17.1%, respectively, giving it the characteristic grayish-white appearance. The scanning electron microscope (SEM) images are shown for the tested calcareous sand in Figure 3, indicating that in comparison to ordinary terrigenous sand particles, calcareous sand particles have a more irregular shape and a rough, porous surface. This is consistent with the findings of existing research [33,34].

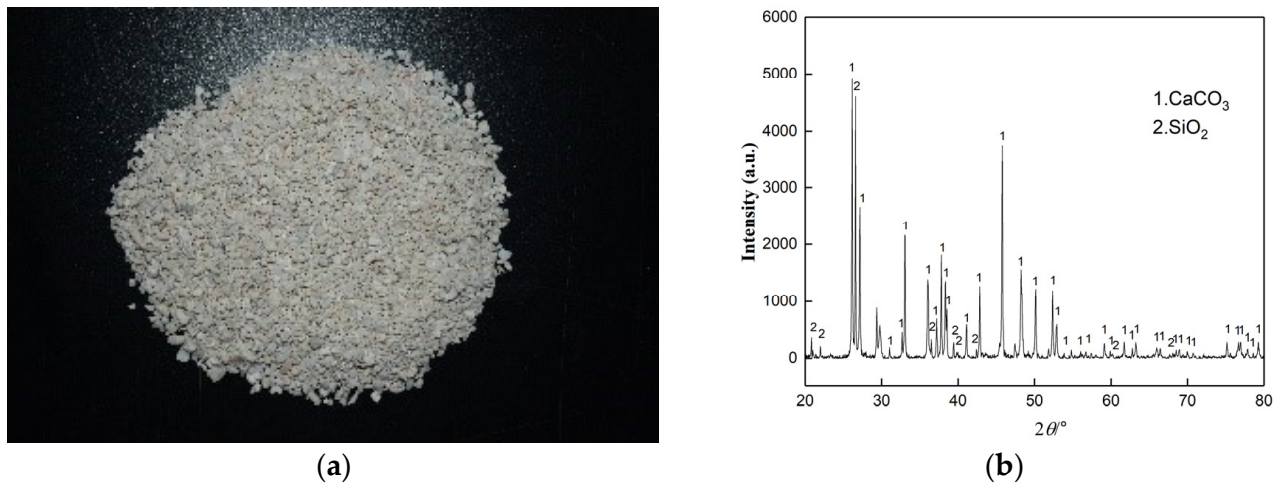


Figure 2. Samples: (a) Calcareous sandstone samples used in this study (particle size = 0.075–5 mm); (b) XRD spectra.

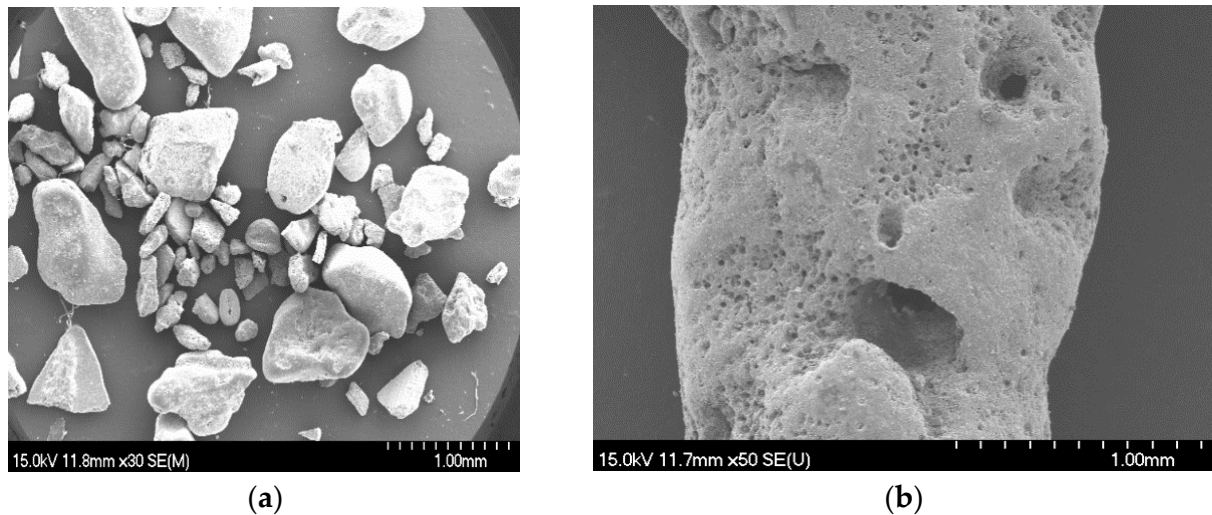


Figure 3. SEM images for the tested calcareous sand: (a) amplification factor of 30; (b) amplification factor of 50.

To meet the requirements of monotonic/cyclic tri-axial test, particles larger than 5 mm were removed from the mix following the recommendations of the *Specification of Soil Tests* manual [35], and calcareous sand with a particle size range of 0.075–5 mm was used to produce tri-axial samples. The particle gradation curve was plotted, as shown in Figure 4. The calcareous sand samples have a coefficient of non-uniformity $C_u = 8$ and a coefficient of curvature $C_c = 2.51$; thus, the soil is classified as well-graded sand (SW) according to Unified Soil Classification System (USCS). Since calcareous sand particles are brittle, the maximum dry density test of calcareous sand particles was conducted with the minimum porosity ratio test method recommended in the *Specification of Soil Test* manual [33]. The maximum dry density and the minimum dry density were calculated with the following results: $\rho_{\max} = 1.703 \text{ g/cm}^3$ and $\rho_{\min} = 1.351 \text{ g/cm}^3$, respectively, based on the minimum dry density test.

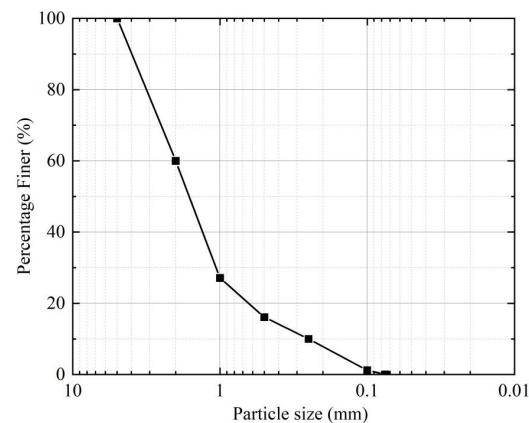


Figure 4. Particle gradation curve.

Figure 5 illustrates the preparation of calcareous sand samples for the tri-axial test. The relative density D_r of all samples was controlled at about 70%, and the corresponding compaction degree was 92%, meeting the compaction degree control requirements of runway subgrade soil, as recommended in the Code for Geotechnical Engineering Design of Airports [36]. The dried calcareous sand was spread into a mold in several separate layers with a zero height of fall, which is fixed within the triaxial apparatus and lined with a 1 mm thick rubber membrane. To obtain the desired density and prevent the particle breakage of the calcareous sand, the method of applying tapping energy to the mold by striking its sidewall and using light hammer blows was used to densify the specimens. The dry density of control samples was $\rho_d = 1.581 \text{ g/cm}^3$. The diameter of the sample was 50 mm and the height, 100 mm. The dry sample method was adopted, and with the sample containing particles less than 0.25 mm in diameter, the sand sample needed to be moistened during layering to prevent dust from changing the particle gradation of the sample. The sample was saturated on the GDS Triaxial Testing System after sample preparation according to the proposed relative density. The porous nature of calcareous sand particles means that the saturation level cannot easily reach 95% with general saturation methods. Therefore, carbon dioxide saturation, water head saturation and back pressure saturation were used for saturation. After flushing CO_2 and exuding de-aired water to the specimens, a back pressure of 200 kPa under an effective pressure of 10 kPa was applied to the samples. The saturation level of the saturation was tested based on B value. If $B \geq 0.95$, the saturation of the sample was considered complete. After that, samples were isotropically consolidated under the desired pressures. The loading procedure was applied at the strain control condition with a rate of 0.5 mm/min in drained conditions [8].

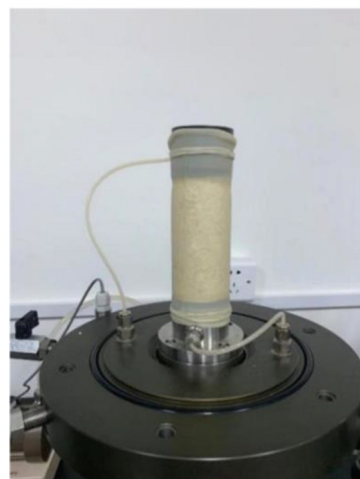


Figure 5. Sample preparation.

2.3. Loading Conditions

Aircraft load is a kind of special traffic load, characterized by large loads, complicated wheel-load forms and diversified load process. Aircraft load can be divided into four types by its runway status: stationary, taxiing, takeoff and landing. In aircraft load studies, more attention has been paid to aircraft static or gliding status. When the aircraft is taxiing on the runway, the aircraft load acts on the runway through the wheel. The force generated by the aircraft load on the runway can be divided into horizontal force from the friction between several wheels and the road surface and vertical force from the plane's self-weight [37,38]. The magnitude and direction of the horizontal force are related to the running status of the aircraft. Wang et al. [39] found that horizontal load had little effect on runway deformation; therefore, the influence of horizontal force of aircraft load was not considered in this study.

2.3.1. Dynamic Load Waveform

The operation status of the aircraft includes take-off, landing and taxiing. The takeoff and landing of an aircraft produce a type of impact load on the runway, but the uncertainty of the landing point of the aircraft makes the form of load action under takeoff and landing status highly uncertain [35]. This paper only considers the load generated on the runway when the aircraft is taxiing. According to the test instrument conditions and research experience [38,39], the cycle of sine wave is widely used for the simulation of aircraft load, as shown in Figure 6, in which σ_d denotes the axial dynamic stress. Given the influencing depth of aircraft load and existing test experience [37,39–41], confining pressure of the test was taken as 40 kPa, 60 kPa, 80 kPa and 100 kPa, and the number of loading cycles was 10,000.

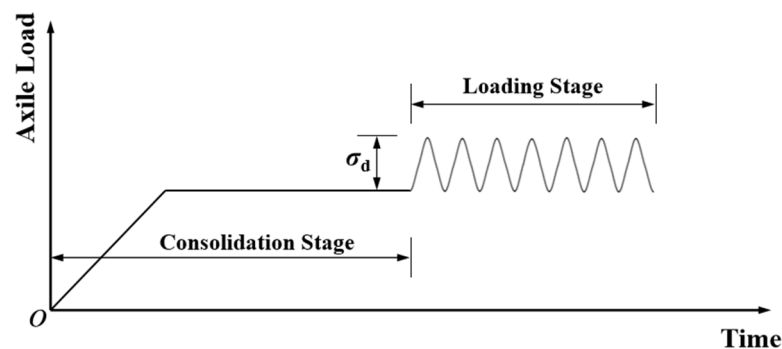


Figure 6. Dynamic load motion used in the test.

2.3.2. Dynamic Load Frequency

When the aircraft taxis, it exerts cyclic load on the subgrade and the frequency of cyclic load is related to the taxiing rate of the aircraft. Generally, the speed of the aircraft in the taxiing process ranges from 20 m/s to 70 m/s. Taking B737-800 as an example, the time for the loading and unloading at the surface of the subgrade is between 0.2 s and 0.6 s. Considering the test equipment conditions, the test time and other factors, and the operation status of subgrade in an airport with calcareous sand subgrade in China, this study set the cyclic load frequency of the dynamic tri-axial test as 3 Hz.

2.3.3. Definition of CSR and Determination of Load Amplitude

The dynamic characteristics of soil are mainly affected by the dynamic stress level. The cumulative plastic strain and resilient modulus in subgrade generally increase with dynamic stress. When dynamic stress reaches a certain value, failure may occur. As the plane taxis on the runway, dynamic stress transmitted to the subgrade decreases with its depth. The study found that the level of dynamic stress in the subgrade was related to the taxi speed of the plane, and the amplitude of runway subgrade dynamic stress could reach 120 kPa [37]. In order to represent the influence of dynamic load amplitude A on the test results, the CSR was defined. This refers to the ratio of axial stress σ_d under dynamic

load test to the maximum deviatoric stress q_{CD} that the sample could bear under the same drainage consolidation condition. Dynamic load sine wave amplitude $A = \sigma_d/2$; therefore, CSR can be expressed as:

$$CSR = \frac{\sigma_d}{q_{CD}} \quad (1)$$

The axial dynamic stress σ_d applied is determined with CSR according to Equation (1). Here, the maximum deviatoric stress q_{CD} that the sample can bear needs to be obtained first with the consolidation drainage (CD) triaxial test. The results of CD tests on samples under different confining pressures are plotted in Figure 7, and the CD strengths are determined as follows: $c_{CD} = 111.4$ kPa and $\varphi_{CD} = 35.8^\circ$, in which the cohesion strength is generated by the occlusal embedding between the particles. The Mohr circle in Figure 7 presents deviatoric stress q_{CD} of samples under different confining pressures upon failure. Using tri-axial CD tests, the maximum deviatoric stress on calcareous sand under different confining pressures was determined, with the results presented in Table 1.

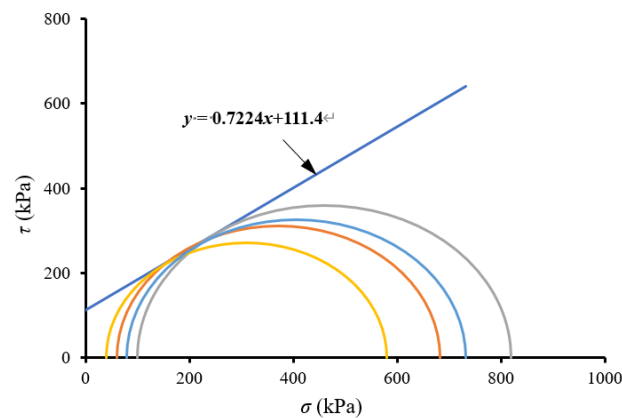


Figure 7. Mohr circles of CD tests on calcareous sand under different confining pressures.

Table 1. Maximum deviatoric stress on calcareous sand under different confining pressures using tri-axial CD tests.

Confining Pressure σ_3 (kPa)	Deviatoric Stress q_{CD} (kPa)
40	541.34
60	622.04
80	657.48
100	719.41

3. Results and Analysis

3.1. Consolidated Drained Test

Figure 8 shows the calcareous sand samples after the test. All tests conducted in this study were terminated when the axial strain reached 15%. As can be observed, calcareous sand samples had significant dilatancy after tri-axial CD test with an obvious shear failure zone.

Figure 9 illustrates the effective stress–axial strain ratio of calcareous sand samples under confining pressures of 60–300 kPa, where the general trend of deviatoric stress–strain curve is the same. At the early stage, deviatoric stress increases with strain and peak stress is achieved at a certain strain. After this, deviatoric stress gradually decreases as strain grows. Under confining pressure of 400 kPa, the significant peak of deviatoric stress of calcareous sand samples becomes unnoticeable and deviatoric stress keeps increasing with strain. The non-uniqueness of the initial slope of the deviatoric stress–strain curve may be attributed to the particle breakage of the calcareous sand. The calcareous sand undergoes severe contraction at the initial shear stage, while it demonstrates great strength and high dilation at the subsequent shear stage because of the irregular particle shape.



Figure 8. Calcareous sand samples after the test.

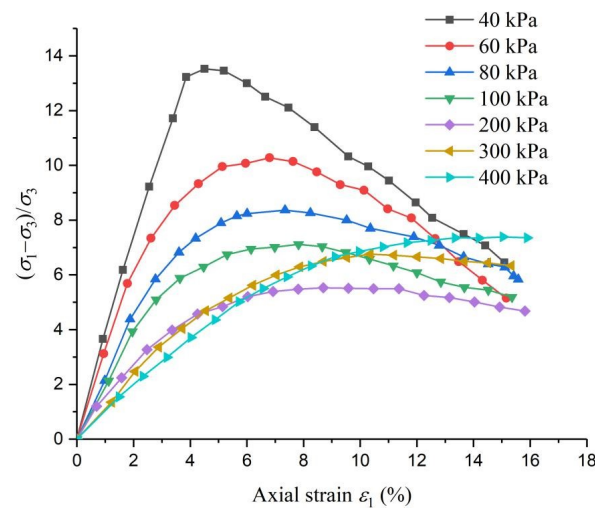


Figure 9. Effective stress–axial strain ratio curve of calcareous sand in tri-axial CD tests.

Figure 10 shows the volumetric strain–axial strain curves of calcareous sand samples with confining pressures of 60, 100, 200, 300 and 400 kPa. With confining pressure of 60–300 kPa, the volumetric strain–axial strain curve of each sample has a generally consistent trend, as follows: The volumetric strain initially starts to increase (compression) with the axial strain, showing contraction. Then, when the axial strain reaches a certain value, the volumetric strain starts to reduce until it has a negative value (dilatancy). When the effective confining pressure is 100 kPa, the maximum positive volumetric strain is 0.68% when the axial strain is 2.8%. As the test continues, the axial strain keeps increasing until it becomes 15%, signifying sample failure. With a maximum negative volumetric strain of -5.38% , the maximum negative dilatation-induced volumetric strain is eight times the maximum positive volumetric strain (contraction). When the effective confining pressure is 400 kPa, no negative volumetric strain (dilatation) is observed despite the increase in axial strain. As shown in Figures 9 and 10, a different mechanical response is observed for the specimen tested at a confining pressure of 400 kPa. This may be attributed to the particle breakage under high confining pressure in which the peak stress of the specimen is controlled by both the breakage and the sliding friction of the particles. With the increase in the confining pressure, the particle breakage gradually occurs in the calcareous sand, which may prevent the stress from reaching the limit state. The specimen hardly reaches the peak stress, and, therefore, exhibits a strain-hardening behavior, which is also consistent with the findings in Shahnazari and Rezvani [1] and Chen et al. [42].

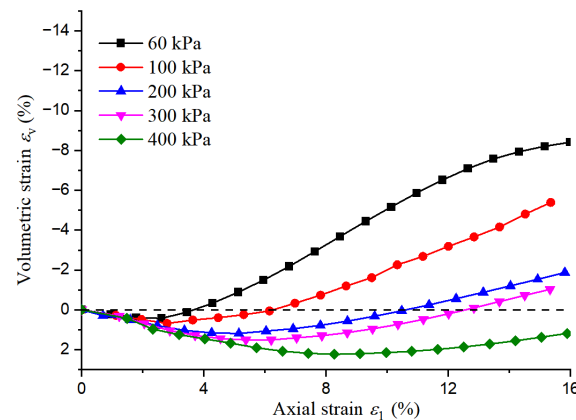


Figure 10. Volumetric strain–axial strain curves under different confining pressures.

3.2. Trend of Calcareous Sand Resilient Modulus

Under cyclic load, the total axial strain ε_1 of the sample can be divided into elastic strain ε_1^{ampl} and unrecoverable plastic strain ε_1^{acc} . The resilient modulus M_r is defined to quantitatively analyze the resilient modulus of calcareous sand filler:

$$M_r = \frac{q_1^{ampl}}{\varepsilon_1^{ampl}} \quad (2)$$

where q_1^{ampl} is the cyclic load and maximum axial stress; numerically, its value is twice that of dynamic load amplitude A , measured in kPa; ε_1^{ampl} is the recoverable elastic strain of the sample, denominated as a %.

Figure 11 illustrates the stress–strain hysteresis loops of samples under the following conditions: effective confining pressure $\sigma_3 = 60$ kPa; $CSR = 0.23, 0.41, 0.57, 0.67$ and 0.72 ; and number of loading cycles $N = 10, 100, 1000$ and $10,000$. It should be noted that the resilient modulus of the sample M_r refers to the inclination of the hysteresis loop, and the initial stress state in each loading cycle corresponds to $q = 0$ (isotropic stress state). The plastic strain is the unrecoverable strain at the completion of a load cycle at $q = 0$ kPa, while the elastic strain can be obtained by subtracting the plastic strain from the total strain. As observed, under different numbers of loading cycles, stress–strain hysteresis loops of all samples show the same variation trend. Under the same number of loading cycles, the stress–strain hysteresis loop of samples increases with CSR . Its area also gradually increases. The damping ratio of the sample is the ratio of the lost energy to the total energy. The damping ratio is numerically proportional to the area of the hysteresis loop, indicating that with increasing CSR , the damping ratio also gradually increases and the energy loss of the sample increases. Additionally, we observed that the inclination of the hysteresis loop increases rapidly during the initial period of cyclic loading while slightly increasing as the number of loading cycles increases. In contrast, the inclination of the hysteresis loop slightly decreases with the increasing CSR for a large number of loading cycles when $CSR \geq 0.41$, demonstrating that the resilient modulus of the sample decreases when increasing CSR from 0.41 to 0.72 . As expected, the resilient modulus for calcareous sand at $CSR = 0.23$ appears to be the lowest among the CSR values considered in this study, which may be attributed to the increased particle breakage for calcareous sand at large values of CSR .

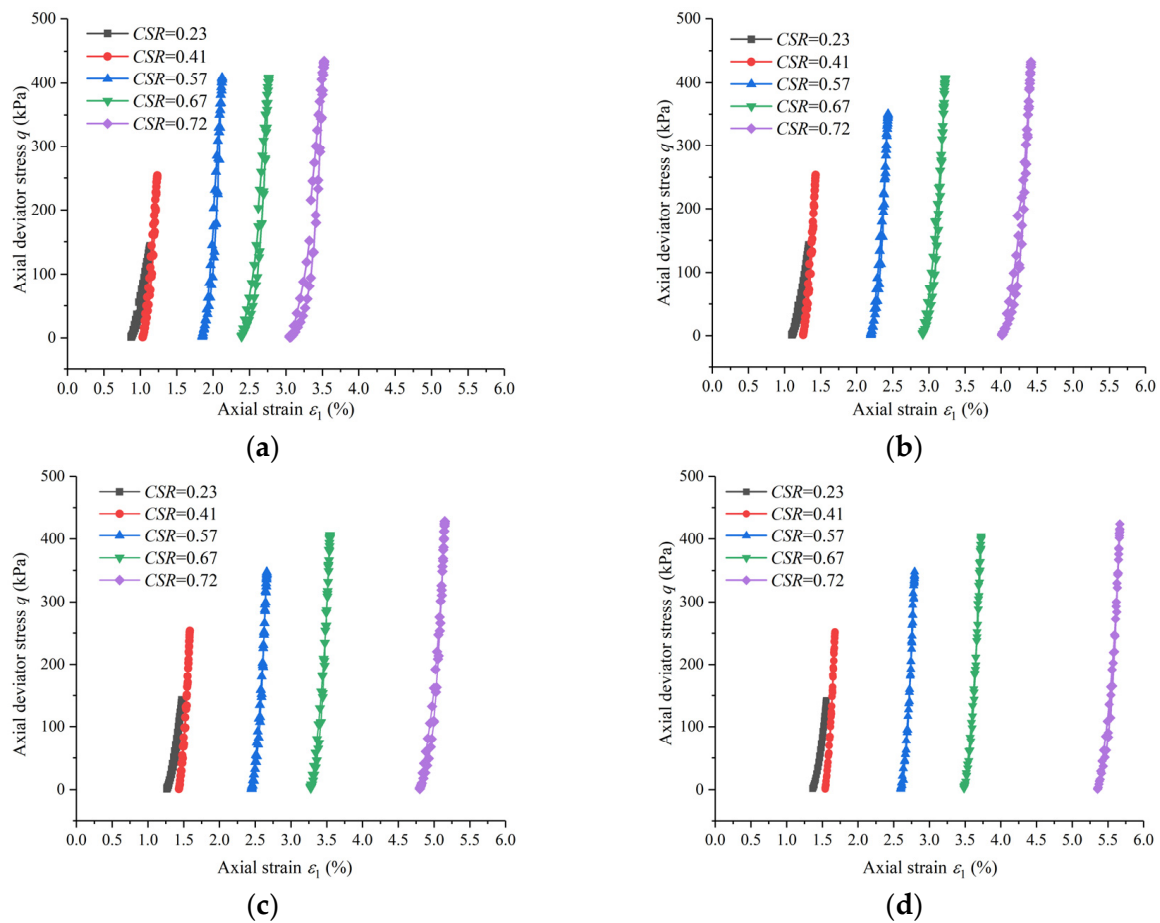


Figure 11. Stress–strain hysteresis loops under a confining pressure of 60 kPa after different numbers of loading cycles: (a) Number of loading cycles $N = 10$; (b) Number of loading cycles $N = 100$; (c) Number of loading cycles $N = 1000$; (d) Number of loading cycles $N = 10,000$.

Figure 12 illustrates the typical stress–strain hysteresis loops under the conditions of effective confining pressure $\sigma_3 = 60$ kPa; $CSR = 0.23$ and 0.72 ; and number of loading cycles $N = 10, 100, 1000, 3000, 5000$ and $10,000$. As anticipated, the axial strain of calcareous sand considerably increases with the rise of the CSR . It should be noted that the axial strain of the two diagrams of Figure 12 are set in different scales to facilitate the interpretation of the stress–strain hysteresis loops. At the initial period of cyclic loading, the area of the stress–strain hysteresis loop of calcareous sand samples gradually decreases and the damping ratio of samples tends to decrease. With a further increase in the number of loading cycles, the area of the stress–strain hysteresis loop still has a decreasing trend but at a decreased rate. This indicates that the damping ratio of calcareous sand samples decreases with an increase in the number of loading cycles, although the change is not obvious in the later period of cyclic loading. The inclination of the stress–strain hysteresis loop of the samples does not change significantly, demonstrating that the resilient modulus of calcareous sand samples quickly reaches a stable value. When the number of loading cycles increases under the same CSR , the stress–strain hysteresis loop becomes more intensive. The results show that the axial plastic strain rate of calcareous sand samples decreases slightly. A comparison of two samples with different CSR shows that the stress–strain hysteresis loop of the sample with $CSR = 0.23$ is more intensive later during cyclic loading, indicating that the axial plastic strain rate of calcareous sand samples increases with CSR .

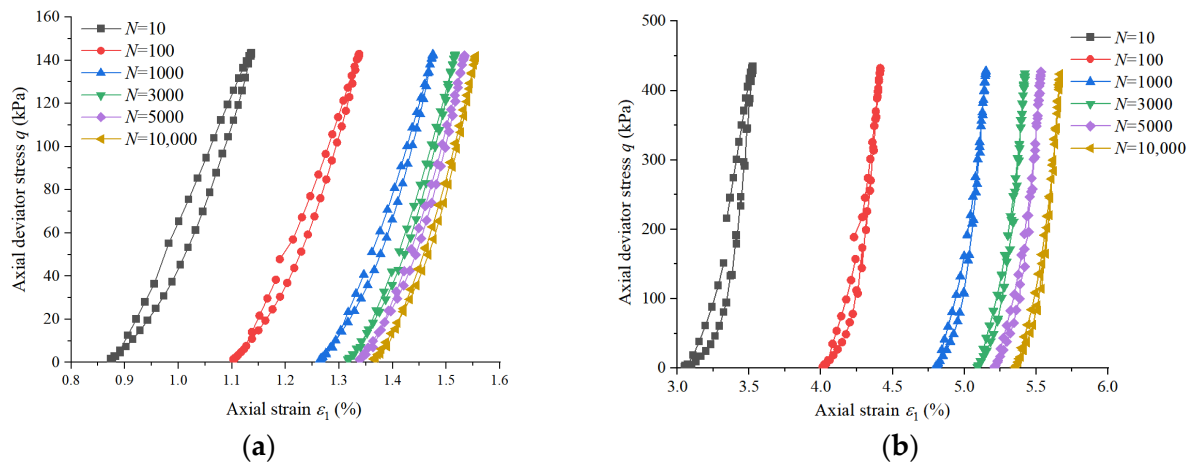


Figure 12. Stress–strain hysteresis loop of samples with different CSR: (a) CSR = 0.23; (b) CSR = 0.72.

Figure 13 illustrates the resilient moduli of calcareous sand samples with different CSR and effective confining pressure $\sigma_3 = 60$ kPa as the number of loading cycles increases. As the figure shows, the resilient modulus of calcareous sand samples increases rapidly during the initial period of cyclic loading (i.e., first 20 cycles) when calcareous sand samples are under compaction. As the number of loading cycles further increases, the resilient modulus of calcareous sand samples still increases, albeit at a reduced rate. The resilient modulus of the samples increases only slightly compared to the rate of increase during the initial period of loading. This is caused by further breakage of calcareous sand particles, with a continual increase in the number of loading cycles. The resulting fine particles fill the space between the coarse particles, making the sample further dense. The samples, therefore, form a particle breakage—recompaction state, leading to the irregular pattern of the resilient modulus for different values of CSR during the initial period of cyclic loading (i.e., the first 20 cycles). Under a constant effective confining pressure, the resilient modulus of calcareous sand decreases with increasing CSR and the resilient modulus at CSR = 0.41 is 1.3 times the resilient modulus at CSR = 0.72.

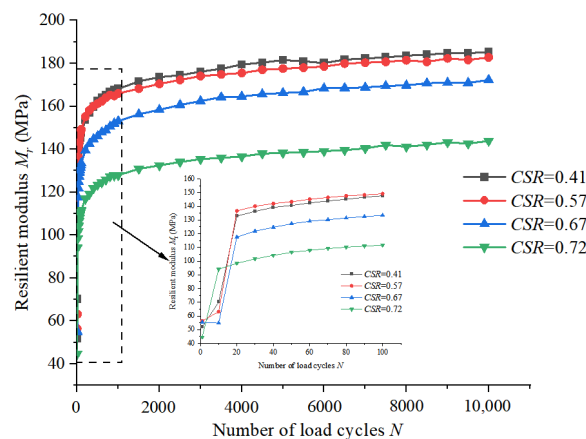
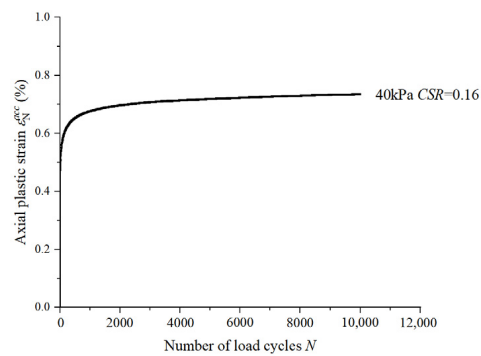


Figure 13. Relationship between resilient modulus and number of loading cycles of samples with different CSR.

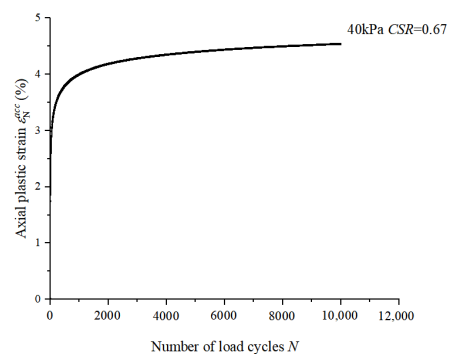
3.3. Definition of Shakedown Status of Calcareous Sand

As Figure 14 illustrates, three response statuses under cyclic load are presented by calcareous sand: plastic shakedown, plastic creep and incremental plastic failure. When the range of the applied cyclic load is small, only a small degree of plastic deformation can be produced at the initial cyclic loading stage, and no new plastic deformation can be

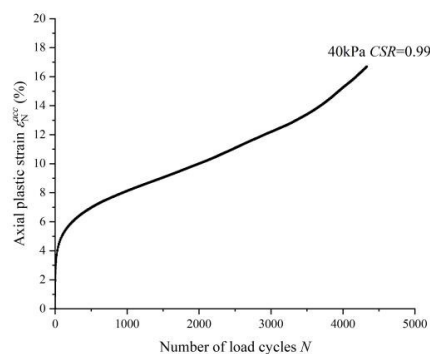
produced at the later loading stage. Calcareous sand presents a pure resilient response, that is, the material reaches a long-term stable status, which is called the plastic shakedown status, as shown in Figure 14a. A further increase in cyclic load results in the accumulation of continuous axial plastic strain in the sample during the whole cyclic loading process. However, no abrupt failure occurs after a small number of loading cycles. This status is called plastic creep status, illustrated in Figure 14b. When subjected to a large amplitude cyclic load, the sample experiences significant axial plastic deformation, the plastic strain rate gradually grows with the number of loading cycles and the sample fails due to overly large plastic deformation after small loading cycles. This status is called incremental plastic failure, as shown in Figure 14c.



(a)



(b)



(c)



Figure 14. Response statuses of calcareous sand: (a) Plastic shakedown status; (b) Plastic creep status; (c) Incremental plastic failure status.

The critical level of loading stress exists between two neighboring shakedown response statuses of the subgrade filler. Take plastic shakedown as an example. When the loading

stress is less than the critical level, the material does not attain plastic shakedown status. That is, it only experiences plastic strain during the initial loading cycles. As the number of loading cycles increases, the plastic strain rate gradually reduces towards zero, causing the pure resilient response of the material in the subsequent loading cycles. When the loading stress is greater than the critical stress, the material continues to develop plastic deformation, and the material will eventually fail as plastic deformation continues and plastic strain accumulates, no matter whether the material is experiencing plastic creep or incremental plastic failure. Werkmeister [30] conducted several cyclic tri-axial tests on different materials, considering gradation, water content, loading confining pressure and other related factors. From these, he derived various types of plastic deformation development laws using a combination of numerical simulation and experimental processes. Three response statuses were defined with strain after 5000 and 3000 loading cycles as the criteria, with details in Table 2.

Table 2. Relationship between manner of elastoplastic response and plastic strain rate of subgrade filler.

Cumulative Evolutionary form of Deformation	Strain Rate	Note
A: Plastic shakedown	$<1 \times 10^{-5}$	Ideal range of design materials
B: Plastic creep	$1 \times 10^{-5} - 8 \times 10^{-5}$	Admissible status within control
C: Incremental plastic failure	$>8 \times 10^{-5}$	Avoid occurrence

This study relies on the findings of Werkmeister [30] to use the plastic strain rates after 3000 and 5000 loading cycles as the limit of the shakedown response of calcareous sand subgrade.

3.4. Analysis of Cumulative Deformation Law of Calcareous Sand

Figure 15 illustrates the relationship between the axial plastic strain of calcareous sand samples and the number of loading cycles under various effective confining pressures, where the axial strain accumulation rate of each sample presents a similar development trend. With cumulative strain rates after 3000 and 5000 loading cycles, the response status can be clearly divided into three types: plastic shakedown, plastic creep and incremental plastic failure. This section shows how the critical stress level of these three shakedown responses can be determined when calcareous sand is used as a subgrade filler. The effects of CSR and effective confining pressure on the development of plastic cumulative deformation of calcareous sand were investigated.

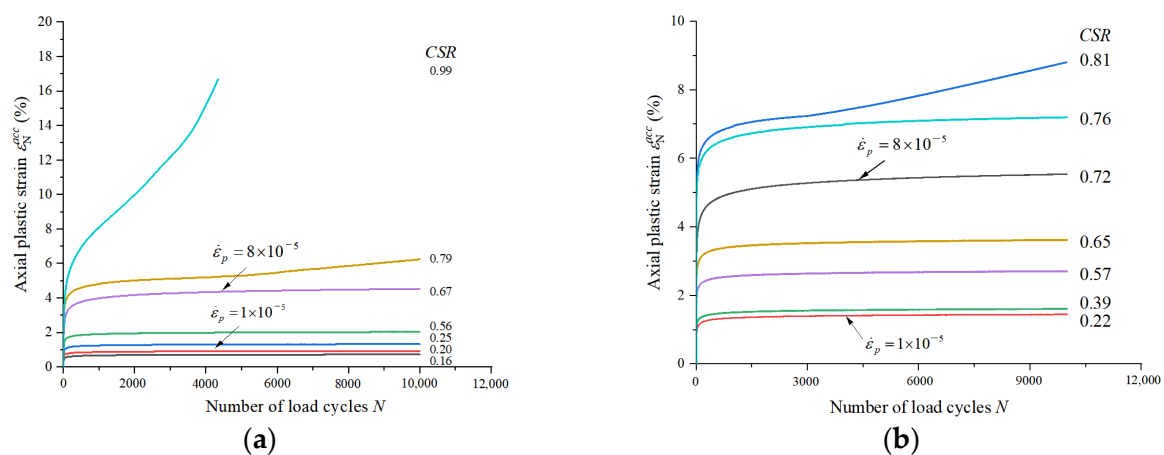


Figure 15. Cont.

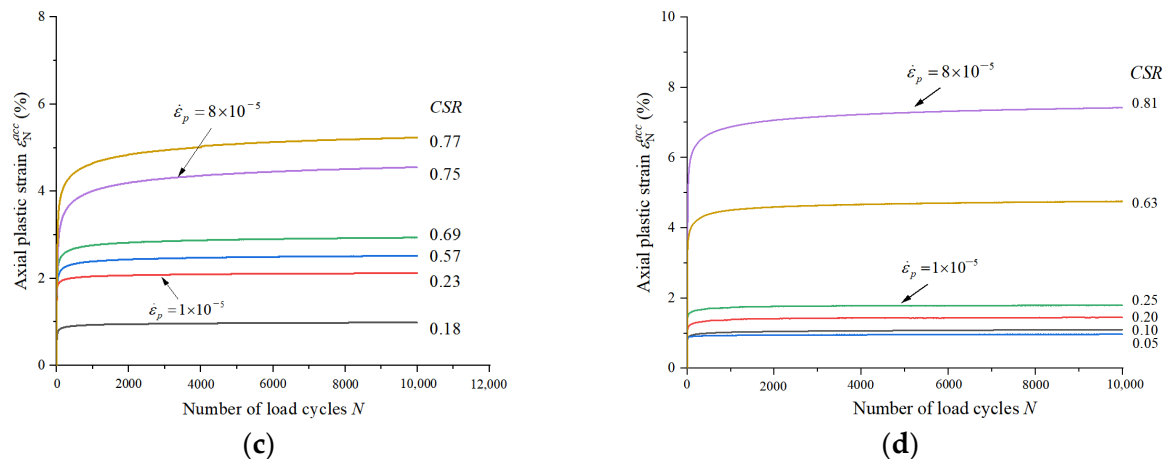


Figure 15. Development of plastic strain of calcareous sand samples: (a) Effective confining pressure $\sigma_3 = 40$ kPa; (b) Effective confining pressure $\sigma_3 = 60$ kPa; (c) Effective confining pressure $\sigma_3 = 80$ kPa; (d) Effective confining pressure $\sigma_3 = 100$ kPa.

3.4.1. Effects of CSR

Figure 15 shows the development of axial plastic cumulative strain of calcareous sand under different confining pressures and CSR. Under the same effective confining pressure, the axial plastic cumulative strain of calcareous sand samples increases with CSR. Since CSR represents axial cyclic stress, it means that the axial plastic cumulative strain of calcareous sand samples increases with the axial cyclic stress. In Figure 15d, the CSR values are 0.05, 0.10, 0.20 and 0.25, and the axial plastic cumulative strain rate of samples is no more than 1×10^{-5} after 5000 and 3000 cyclic loading cycles, indicating that the samples are in plastic shakedown. A comparison of these samples with other samples in plastic shakedown with different effective confining pressures in Figure 15 shows that when calcareous sand samples in plastic shakedown state are in the initial stage of cyclic loading, the axial plastic strain of the samples increases rapidly. Any further increase in the number of loading cycles slows down the axial plastic cumulative strain rate of calcareous sand samples, causing the axial plastic strain accumulation to stabilize, which is indicative of plastic strain accumulation of the calcareous sand samples. However, during the later loading period, the samples display a continuous elastic status in general.

An increase in cyclic stress destroys the internal structure of the sample and continuously increases the axial plastic strain of the sample. As Figure 15d shows, the CSR values are 0.63, 0.77 and 0.81, with the axial plastic cumulative strain rates of the three groups of samples being no greater than 8×10^{-5} after 5000 and 3000 cyclic loading cycles. This indicates that the samples are in a plastic creep state. A comparison of these samples and other samples in plastic creep with different effective confining pressures in Figure 15 shows that calcareous sand samples with plastic creep status are subjected to cyclic load during the entire process. Continuous axial plastic strain accumulation occurs, with the accumulation rate of plastic strain gradually decreasing as the number of loading cycles increases. However, the samples are not damaged by the excessive plastic cumulative strain at the initial stage of loading. Therefore, calcareous sand subgrade structures in the plastic creep state are still considered to be reasonably safe.

A further increase in cyclic stress produces extreme plastic cumulative deformation at the initial stage of loading and eventually results in the sudden collapse in the calcareous sand subgrade structure. In Figure 15a, the CSR is 0.99 and the axial plastic cumulative strain rate is greater than 8×10^{-5} when samples are under 5000 and 3000 cyclic loading cycles. The samples are in the incremental plastic failure state, and during the whole cyclic loading process, plastic strain accumulates at a continuously increasing rate. The final sample is damaged by excessive plastic strain after a number of loading cycles.

3.4.2. Effects of Confining Pressure

If other conditions remain unchanged, an increase in confining pressure leads to more breakage of calcareous sand particles. Calcareous sand particles are porous, and many fine particles are formed once the particles accumulate and are crushed. The single particle strength of these fine particles is greater than that of the coarse particles before crushing. Therefore, under the same level of cyclic stress, the accumulation rate of plastic strain in calcareous sand samples under high confining pressure gradually declined in the later loading period. As shown in Figure 15, calcareous sand samples with a CSR of 0.25 at an effective confining pressure of 40 kPa are compared with those with an effective confining pressure of 100 kPa. For calcareous sand samples with a CSR of 0.25, the cyclic stresses of the two groups of samples are the same. At the initial loading stage, the axial plastic strain of the two groups of samples rapidly accumulates. A further increase in the number of loading cycles reduces the plastic strain rate of calcareous sand samples under 100 kPa, compared to that of calcareous sand samples under effective confining pressure of 40 kPa. Calcareous sand particles break easily; therefore, increasing confining pressure accelerates particle breakage. Coarse particles are gradually broken into fine particles, and the voids between particles fill with fine particles, making the sample much denser as a whole. Hence, the critical CSR of plastic shakedown and plastic creep of the sample will also gradually increase with increasing confining pressure.

3.5. Critical Dynamic Stress of Calcareous Sand

Confining pressure significantly influences axial plastic cumulative deformation of calcareous sand. Therefore, this study attempts to establish the corresponding mathematical relationship between critical stress and effective confining pressure in calcareous sand. From several indoor cyclic tri-axial tests with different subgrade fillers, Dawson et al. [43] obtained a formula of critical stress level as a function of confining pressure, as shown below:

$$\sigma_1 = A \left(\frac{\sigma_1}{\sigma_3} \right)^B \quad (3)$$

where σ_1 is the maximum axial stress in the tri-axial test, σ_3 is the effective confining pressure of tri-axial test and A and B are the fitting parameters.

Figure 16 presents the fitting graph of Dawson's empirical formula for critical stress of calcareous sand in the plastic shakedown and plastic creep states. As seen in the figure, regression models for the critical stresses of plastic and plastic creep shakedown states were also fitted, with coefficients of correlation (R^2) averaging over 94%. Using this formula, the shakedown response status of any calcareous sand subgrade at any depth can be determined when subjected to dynamic load. When calcareous sand subgrade is in plastic shakedown (A), the subgrade is thought to generate a small degree of plastic deformation while remaining dynamically stable in the later period of the runway operation. No excessive plastic deformation occurs in the runway's service life. When the calcareous sand subgrade is in plastic creep (B), a certain degree of plastic deformation persists during the operation period of the runway subgrade, and failure will occur to some extent in the subgrade as the operation continues. Therefore, although the subgrade structure in this state is considered to be reasonably safe, it needs to be maintained regularly during the operation period. When the calcareous sand subgrade attains incremental plastic failure status (C), any further impact by excessive axial stress will cause the subgrade to experience yield deformation, causing instantaneous failure or collapse due to excessive plastic cumulative deformation.

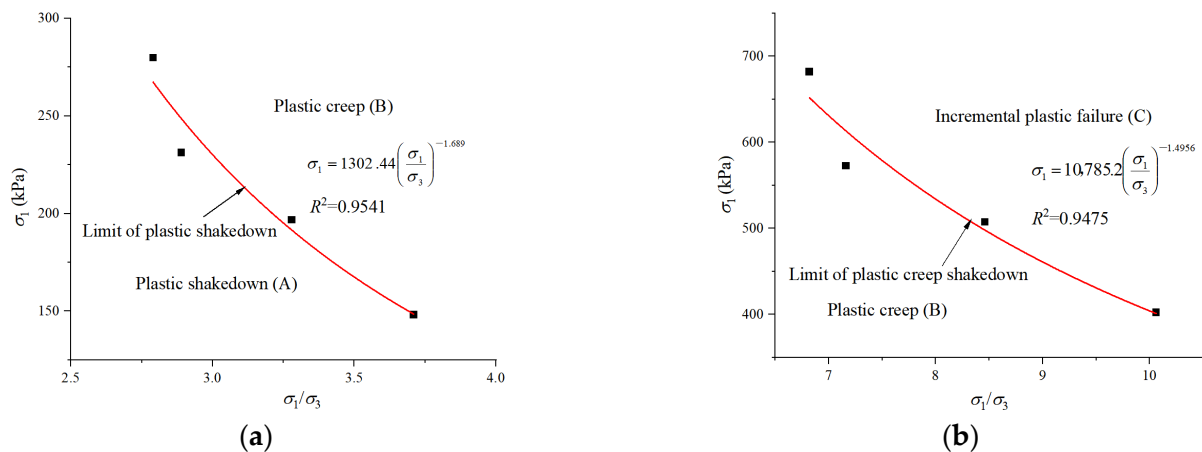


Figure 16. Fitting results of critical stress of calcareous sand: (a) Fitting under plastic shakedown; (b) Fitting under plastic creep.

Critical stress expression for plastic shakedown response status of calcareous sand can be represented by Equation (4) below.

$$\sigma_1 = 1302.44 \left(\frac{\sigma_1}{\sigma_3} \right)^{-1.689} \quad (4)$$

Critical stress expression for plastic creep response status of calcareous sand can be represented by Equation (5) below.

$$\sigma_1 = 10,785.2 \left(\frac{\sigma_1}{\sigma_3} \right)^{-1.4956} \quad (5)$$

3.6. Trends of Particle Gradation under Different Shakedown Response Statuses

Different confining pressures were chosen to study calcareous sand particle breakage trends using shakedown tests. The experimental group samples with plastic shakedown status and plastic creep status under different cyclic dynamic stress ratios were dried and then sieved for particle screening treatment. Figure 17 illustrates the particle distribution curves of calcareous sand with effective confining pressure of 60 and 100 kPa after tests under different critical cyclic dynamic stress ratios. As can be observed, each test sample shows a significant change in particle gradation after the tests, which suggests that calcareous sand sample particles are significantly crushed after each cyclic load. The trend in particle gradation change is consistent: the fine particle content increases while the coarse particle content reduces. This is thought to be due to the crushing of the relatively coarse particles during the test. Hardin's breakage potential model [44] in Figure 18 is used to quantitatively describe particle breakage.

$$B_r = \frac{B_t}{B_p} \quad (6)$$

where B_r is the relative breakage rate; B_p is the breakage potential, which is the area of the upper boundary between the initial gradation and 0.074 mm; and B_t is the extent of breakage, which is the area between the initial gradation and current gradation.

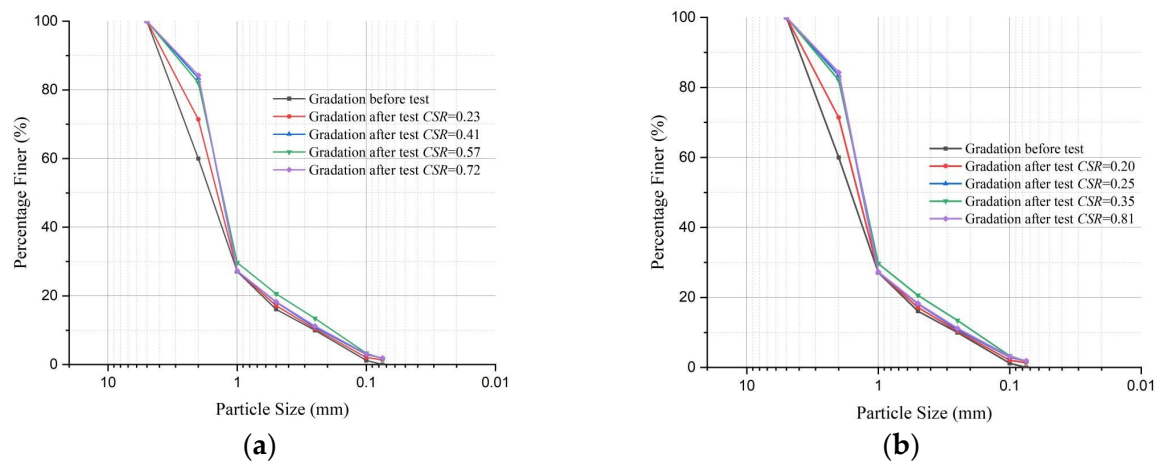


Figure 17. Particle gradation of different CSR samples before and after the test: (a) 60 kPa; (b) 100 kPa.

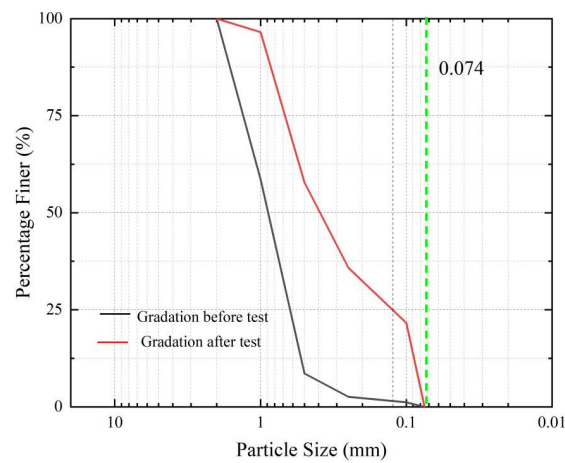


Figure 18. Hardin's breakage potential model.

Samples in test groups with effective confining pressures of 60 kPa and 100 kPa were selected for drying and particle screening, resulting in particle gradation curves for different numbers of loading cycles. According to Table 3 and Figure 19, calcareous sand samples show obvious particle breakage after cyclic tests with smaller CSR values and the relative breakage rates of sample increases with CSR. The increase in the extent of sample particles breakage tends to be negligible when CSR reaches a certain value.

Table 3. Relative breakage rate B_r .

Effective Confining Pressure σ_3	Cyclic Stress Ratio	Shakedown Response Status	Breakage Potential B_p	Extent of Breakage B_t	Relative Breakage Rate B_r
60	0.23	Plastic shakedown status	194.13	23.49	0.121
60	0.41			48.14	0.248
60	0.57			48.92	0.252
60	0.72	Plastic creep status		50.09	0.258
100	0.2	Plastic shakedown status		44.46	0.229
100	0.25			47.17	0.243
100	0.35			56.88	0.293
100	0.81	Plastic creep status		58.82	0.303

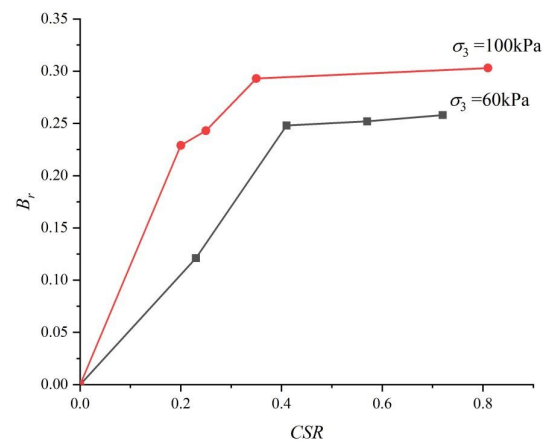


Figure 19. Relative breakage rate Br after cyclic loading.

4. Conclusions

In this paper, the cyclic triaxial test of calcareous sand, a special geotechnical medium under cyclic load was carried out, and the shakedown theory was introduced to systematically investigate the evolution of resilient modulus and axial plastic cumulative deformation of calcareous sand as a subgrade filler under cyclic load. These are some of the results:

- (1) In the tri-axial consolidation drainage shear tests on calcareous sand, with the increase in the effective confining pressure, the particle breakage of calcareous sand intensified and the stress–strain curves of calcareous sand showed a change from the strain-softening to the strain-hardening state; the volumetric strain of calcareous sand showed a change from shear shrinkage and then shear expansion to continuous shear shrinkage.
- (2) The tri-axial test demonstrated that the evolution law of axial plastic strain in calcareous sand under different axial dynamic stress levels can be described by the shakedown theory, and the response behavior of calcareous sand can be grouped into three categories with the increasing of the axial dynamic stress, namely plastic shakedown, plastic creep and incremental plastic failure, respectively.
- (3) The axial plastic strains of calcareous sand increased with the cyclic stress ratio (CSR), while the critical CSR for plastic shakedown and plastic creep increased with an increase in the effective confining pressure.
- (4) The empirical critical stress formula for calcareous sand fillers was obtained with confining pressure as the variable, which could be used to determine the plastic shakedown of calcareous sand subgrade structures at any depth and its critical dynamic stress level under plastic creep.
- (5) At the initial stage of cyclic loading, calcareous sand samples compacted and the resilient modulus increased rapidly. A further increase in the number of loading cycles caused the particles to break; the finer particles filled the gap between coarse particles, further compacting the samples and increasing their resilient moduli. Hardin's breakage potential model was also used to quantitatively describe particle breakage before and after the tests on calcareous sand samples, and the results showed that with an increase in CSR, the degree of breakage of sample particles first increased and then stabilized.

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