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Experimental and Estimation Studies of Resilient Modulus of Marine Coral Sand under Cyclic Loading

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Abstract: Coral sand is an important filler resource that can solve the shortage of terrestrial fillers in coastal areas. Recently, the foundations of many infrastructures in the South China Sea have been built with coral sand as fillers, which have been subjected to wave and traffic cyclic loads. Resilient modulus ($M_r$) is an important design parameter in marine engineering, but there are few studies on the resilient modulus response of coral sand under cyclic loading. A series of drained cyclic triaxial tests were carried out to investigate the effects of the initial mean effective stress ($p_0$) and cyclic stress ratio ($\zeta$) on the resilient modulus response of the coral sand from the South China Sea. The change of fractal dimension ($\alpha_c$) can reflect the rule of particle breakage evolution. The $\alpha_c$ of coral sand shows a tendency of almost maintaining stable and then increasing rapidly with the increase of mean effective stress $p_0$ under each cyclic stress ratio $\zeta$. There is a threshold of $p_0$, when the $p_0$ exceeds this threshold, $\alpha_c$ will increase significantly with the increase of $p_0$. The increase of $p_0$ has a beneficial effect on the improvement of the $M_r$, while the increase of $\zeta$ has both beneficial and detrimental effects on the improvement of the $M_r$. A new prediction model of the $M_r$ considering particle breakage was established, which can better predict the $M_r$ of coral sand in the whole stress interval. The research results can provide guidance for the design of marine transportation infrastructures, which can promote the development of marine transportation industry and energy utilization.

Keywords: coral sand; resilient modulus; particle breakage; fractal dimension; prediction model

1. Introduction

Coral sand is widely distributed in the equatorial and tropical marine areas, which is the foundation soil type encountered in many marine engineering construction [1–3]. Coral sand is formed by the deposition of marine biological debris, and its main component is calcium carbonate. The mechanical properties of coral sand are totally different from that of terrigenous quartz sand [4–7]. For example, its particles are irregular in shape and easy to break under external load. Recently, many reef island infrastructures for land reclamation in the South China Sea have used coral sand as foundation filling materials. Coral sand has now been used as foundation filling materials in the construction of airport runways, flexible road pavements, building foundations, and other infrastructures. In the complex marine engineering environment, the hydraulic filling coral sand foundation will be subject to tens of thousands of low frequency traffic and wave cyclic loads for a long time. Resilient modulus is an important parameter for the evaluation and design of bearing capacity, settlement deformation, and service performance of foundation soil under cyclic loading [8–10]. Therefore, it is of great significance to study the response and prediction model of resilient modulus of coral sand under cyclic loading.
Numerous experimental studies (mainly based on cyclic triaxial tests) have been carried out on resilient behavior of unbound granular materials, which is usually represented by the resilient modulus \( M_r \) [10–12]. The studies, based on the resilient characteristics of unbound granular materials, focused on the terrigenous materials, such as ballast and quartz sand. Hicks [13] stated that frequency has a negligible effect on the elastic behavior of granular materials. Lackenby et al. [14] emphasized that for railway ballast, \( M_r \) increases with the increase of load cycles \( N \), mean effective stress \( p' \), and cyclic deviatoric stress \( q_{ampl} \). Indraratna et al. [15] examined the effect of \( p' \) and \( f \) on \( M_r \). It was found that \( M_r \) increases with the increase of \( p' \) and \( f \), which was due to the increase of packing density. Donohue et al. [16] reported that some coarse-grained soil used as subgrade fillers will undergo particle degradation under cyclic loading. Particle degradation includes particle breakage and fine-grain intrusion mainly caused by particle breakage [17,18]. Particle breakage can lead to adverse effects, such as the reduction in shear strength, interlocking, and stiffness of soil aggregates [19,20]. Different empirical models have been reported for the estimation of resilient modulus \( M_r \) of unbound granular materials under cyclic loading [21,22]. However, Chen et al. [21] found that for some coarse-grained soils degraded under cyclic loading, a good fitting curve based on the full stress interval will obviously underestimate the resilient modulus of the low stress interval. This is a challenging problem, which deserves more research to investigate the \( M_r \)'s prediction model of coral sand under the whole stress interval. Due to its unique mineral composition and mechanical properties, coral sand will undergo more serious particle degradation (i.e. particle breakage) under cyclic loading than terrigenous materials. Current experimental studies on coral sands focused on the static shear behavior [1,3,6], influencing factors for particle breakage [2], and small strain dynamic characteristics [4,23]. At present, the research on resilient behavior of coral sand under cyclic loading is relatively lacking. There is still no clear understanding of the resilient modulus of coral sand in engineering.

In this paper, a series of drained cyclic triaxial tests were carried out on the coral sand of the South China Sea to investigate the resilient modulus \( M_r \) response. The evolution of particle breakage of coral sand was studied by analyzing the variation of fractal dimension \( \alpha_c \) during cyclic loading. The effects of the initial mean effective stress \( p_0 \) and cyclic stress ratio \( \zeta \) on the \( M_r \) were examined. The influence of particle breakage on the prediction model of \( M_r \) was deeply analyzed. Finally, a new resilient modulus prediction model for coral sand considering particle breakage was established. This study can help deepen the understanding of the resilient behavior of coral sand, which is beneficial to the design and safety assessment of marine transportation infrastructures.

2. Materials and Methods

2.1. Test Materials and Sample Preparation

The coral sand samples were taken from an offshore reef in the South China Sea, which were all unbound particles (as shown in Figure 1a). Figure 1b shows the microparticle shape of coral sand obtained by scanning electron microscopy (SEM). It can be seen from Figure 1b that the grain shape of the coral sand sample is irregular and retains a large amount of the internal pores of the original marine biological debris. Figure 2 shows the particle size distribution curve of the coral sand sample. Table 1 presents the basic physical and mechanical parameters of test sand samples.
Materials and Methods

The cyclic triaxial sample in this study was a standard cylinder sample with a height of 100 mm and a diameter of 50 mm. Since the prediction model of resilient modulus is mainly used in the design of compact foundations such as road bases, previous studies on the resilient behavior of soils have used dense samples [11]. Due to the strict requirements of relative density $D_r$ of the road bases, wharfs, and other marine engineering infrastructures, the foundation of hydraulic filling coral sand is very dense. Therefore, in order to meet the actual engineering characteristics, the relative density $D_r$ of the coral sand samples in this study were selected as 80%. The air pluviation method [23] was applied to prepare cylindrical samples of the coral sand. The method of light hammering was used to obtain the designed relative density of sand samples. The samples were remolded for $D_r < 80\%$, depending on the initial consolidation stress, to acquire the target $D_r$ (i.e., 80%) after consolidation. After the preparation of the sample, carbon dioxide (CO$_2$) was used to pass through the sample, and then the sample was saturated with 200 kPa back pressure under the effective confining pressure of 20 kPa. After checking that the $B$-value of the sample exceeded 0.95, the saturation process of the sample ended. Through $K_0$ (static earth pressure coefficient) consolidation module of triaxial apparatus [24,25], the $K_0$-value of coral sand sample was set at 0.4. After the sample was saturated, the sample was consolidated under anisotropic condition. During consolidation, the $\sigma_3/\sigma_1$-value ($\sigma_1$ and $\sigma_3$ are the major and minor principal stress, respectively) was fixed to the $K_0$-value to simulate $K_0$ consolidation.

![Typical sample of the coral sand: (a) coral sand sample; (b) microparticle shape of coral sand.](image)

![Particle size distribution curve of coral sand samples.](image)
The axial deformation is obtained from a displacement transducer attached to the load piston (not shown in Figure 3). The pressure chamber base is connected with various sensors and pressure volume controllers, including back pressure, confining pressure, pore pressure, etc. The axial force is measured at a load cell being located directly below the bottom end plate of the sample, i.e., inside the cell chamber. The axial deformation is obtained from a displacement transducer attached to the load piston (not shown in Figure 3).

Table 1. Basic physical and mechanical parameters of test sand samples.

| Property                        | Coral Sand |
|---------------------------------|------------|
| Specific gravity ($G_s$)        | 2.75       |
| Maximum void ratio ($e_{max}$)  | 1.107      |
| Minimum void ratio ($e_{min}$)  | 0.971      |
| Coefficient of uniformity ($C_u$)| 1.793      |
| Coefficient of curvature ($C_c$)| 0.781      |
| Relative density of samples ($D_s$)| 80%       |

2.2. Test Methods

The cyclic triaxial apparatus [26] developed by GDS company (GDS Instruments Ltd., UK) was used in this study, which includes a loading system, a back pressure volume controller, a confining pressure volume controller, a pore pressure sensor, displacement and force sensors (as shown in Figure 3). The pressure chamber base is connected with various sensors and pressure volume controllers, including back pressure, confining pressure, pore pressure, etc. The axial force is measured at a load cell being located directly below the bottom end plate of the sample, i.e., inside the cell chamber. The axial deformation is obtained from a displacement transducer attached to the load piston (not shown in Figure 3).

Chen et al. suggested using 1 Hz as the frequency of the resilient response tests for granular soils [21]. With reference to previous studies, the effect of frequency $f$ on the resilient behavior of coarse-grained soil can be ignored [14]. In order to ensure the stability of data collection, the frequency $f$ of cyclic loading was selected as 0.5 Hz in this study. In order to study the long-term resilient response of coral sand, the number of cycles $N$ was selected to be 20,000. Referring to the experimental studies of coarse-grained soil under traffic cyclic loading by other scholars, the cyclic loading type of this study used half-sine loading [27–29]. Drained cyclic triaxial tests were performed on coral sand samples at $p_0 = 40, 70, 100, 200, 300, 400$ kPa. The selection range of the cyclic stress ratio $\zeta$, referred to the range of actual loads reported in previous studies [30], and followed the rule that the cyclic stress ratio
decreases as the foundation depth deepens. Table 2 summarizes the drained cyclic triaxial test scheme of this study.

Table 2. Summary of the dynamic test programs.

| Initial Mean Effective Stress, \( p_0 (\text{kPa}) \) | Confining Pressure, \( \sigma_3 (\text{kPa}) \) | Initial Static Stress Ratio, \( \eta_c \) | Cyclic Stress Ratio, \( \zeta \) |
|--------------------------------|----------------|-----------------|----------------|
| 40                           | 26.7           | 1.0             | 1.0, 1.4, 1.8, 2.2 |
| 70                           | 46.7           | 1.0             | 1.0, 1.4, 1.8, 2.2 |
| 100                          | 66.8           | 1.0             | 0.2, 0.4, 0.6, 1.0, 1.8 |
| 200                          | 133.3          | 1.0             | 0.2, 0.4, 0.6, 1.0, 1.8 |
| 300                          | 150.0          | 1.0             | 0.2, 0.4, 0.6, 1.0, 1.8 |
| 400                          | 266.7          | 1.0             | 0.4, 0.6, 1.0, 1.8 |

The strain of sample under cyclic loading includes resilient strain (\( \varepsilon_1^{\text{ampl}} \)) and accumulated axial strain (\( \varepsilon_1^{\text{acc}} \)). The typical hysteresis loop of the sample under cyclic loading is shown in Figure 4. The area of each hysteresis loop represents the energy dissipation per cycle, which characterizes the plastic work in a cycle, reflecting the resistance to deformation in profile. Resilient modulus (\( M_r \)) is an important parameter for the infrastructure of offshore islands and reefs, which is computed (Figure 4) by:

\[
M_r = \frac{q^{\text{ampl}}}{\varepsilon_1^{\text{ampl}}} \tag{1}
\]

where \( q^{\text{ampl}} \) is the amplitude of cyclic deviatoric stress. The definition of cyclic stress ratio \( \zeta \) is the ratio of cyclic deviatoric stress to initial mean effective stress. The definition of initial static stress ratio \( \eta_c \) is the ratio of initial static deviatoric stress to initial mean effective stress.

![Figure 4. Typical hysteresis loop of the sample.](image)

3. Results

3.1. Particle Breakage under Cyclic Loading

According to the fractal theory and Hardin’s definition of relative particle breakage [31], Einav [32] proposed the relative particle breakage index to characterize the degree of particle breakage of coarse-grained soil. In the process of shearing, the gradation of coral sand changes to ultimate fractal gradation under high pressure. The ultimate gradation (as the basic property of the material) is independent of relative density and confining pressure, indicating that the particles will hardly break in the ultimate state. From this point of view, the index proposed by Einav [32] was used as a measure of particle breakage for coral sand:

\[
B_r = \frac{B_t}{B_p} \tag{2}
\]
where $B_r$ is relative breakage index; $B_p$ is total breakage potential; $B_t$ is current total breakage potential. The ultimate gradation was obtained from the triaxial compression test under the maximum mean effective stress of 3 MPa (as shown in Figure 5). The total breakage potential $B_p$ (as shown in Figure 5) can be acquired by integrating the area over the logarithmic scale:

$$B_p = \int_{d_m}^{d_M} [F_u(d) - F_0(d)] d(\log d)$$  \hspace{1cm} (3)$$

where $d_m$ is minimum diameter and $d_M$ is maximum diameter. The total breakage $B_t$ (as shown in Figure 5) can be calculated as:

$$B_t = \int_{d_m}^{d_M} [F_c(d) - F_0(d)] d(\log d)$$  \hspace{1cm} (4)$$

The formulations $F_0(d), F_c(d),$ and $F_u(d)$ (representing the initial gradation (IG), the current gradation (CG) and the ultimate gradation (UG) for coral sand, respectively, as shown in Figure 5) can be calculated as:

$$F_0(d) = \left(\frac{d}{d_M}\right)^{3-\alpha_0}$$ \hspace{1cm} (5)$$

$$F_c(d) = \left(\frac{d}{d_M}\right)^{3-\alpha_c}$$ \hspace{1cm} (6)$$

$$F_u(d) = \left(\frac{d}{d_M}\right)^{3-\alpha_u}$$ \hspace{1cm} (7)$$

where $\alpha_0, \alpha_c,$ and $\alpha_u$ are fractal dimensions of IG, CG, and UG, respectively; $d$ is diameter.

Substitution of Equations (3)-(7) into Equation (2) gives:

$$B_r = \frac{\int_{d_m}^{d_M} [F_u(d) - F_0(d)] d(\log d)}{\int_{d_m}^{d_M} [F_c(d) - F_0(d)] d(\log d)} = \frac{(\alpha_c - \alpha_0)(3 - \alpha_u)}{(\alpha_u - \alpha_0)(3 - \alpha_c)}$$  \hspace{1cm} (8)$$

The initial fractal dimension and ultimate fractal dimension are supposed to 1.44 and 2.46, respectively, which were obtained by fitting the IG and UG (as shown in Figure 5).

**Figure 5.** Definition of relative particle breakage index.

The fractal dimension $\alpha_c$ can be obtained by fitting current gradation using Equation (6). Figure 6 shows the fractal dimension $\alpha_c$ of coral sand at various initial mean effective stresses $p_0$. The larger the
Fractal dimension is, the more serious the particle breakage of coral sand is, and the more the particle gradation tends to the final fractal gradation. Under each \( p_0 \), in the range of lower cyclic stress ratio \( \zeta \), the \( \alpha_c \) increases significantly with the increase of \( \zeta \); in the range of higher \( \zeta \), the rate of \( \alpha_c \) increasing with \( \zeta \) slows down. Under each \( \zeta \), the \( \alpha_c \) of coral sand presents a consistent trend with the increase of the initial mean effective stress \( p_0 \). The \( \alpha_c \) of coral sand shows a tendency of almost maintaining stable and then increasing rapidly with the increase of mean effective stress \( p_0 \). There is a threshold of \( p_0 \) (about 100 kPa), when the \( p_0 \) exceeds this threshold, \( \alpha_c \) will increase significantly with the increase of \( p_0 \). This indicates that \( p_0 \) has a restrictive effect on the particle breakage of coral sand. When \( p_0 \) is small, the \( \alpha_c \) (i.e., particle breakage) cannot grow fast. In actual engineering, it should be noted that when \( p_0 \) is greater than the threshold value, the significant and rapid increase of particle breakage will bring adverse effects on the service safety of the project. As can be seen in Figure 6, under each \( \zeta \), the \( \alpha_c \) can be expressed as a function with \( p_0 \) as a variable:

\[
\alpha_c = \alpha_{p0} + k_\alpha \beta_\alpha \log \frac{p_0}{p_0^a}
\]  

(9)

where \( \alpha_{p0} \), \( k_\alpha \), and \( \beta_\alpha \) are material parameters. The physical meaning of \( \alpha_{p0} \) represents the fractal dimension of the starting particle breakage that can occur when the \( p_0 \) is relatively small at each \( \zeta \). The optimal regression value of \( k_\alpha \) and \( \beta_\alpha \) are 0.00575 and 147.955, respectively. The optimal regression values of \( \alpha_{p0} \) at \( \zeta = 0.2, 0.4, 0.6, 1.0, 1.4, 1.8, \) and 2.2 are 1.452, 1.522, 1.577, 1.619, 1.634, 1.648, and 1.661, respectively.

![Figure 6. Fractal dimension of coral sand at various initial mean effective stresses.](image)

Figure 7 shows the relationship between parameter \( \alpha_{p0} \) and cyclic stress ratio \( \zeta \). The relationship between \( \alpha_{p0} \) and \( \zeta \) can be expressed as:

\[
\alpha_{p0} = \chi_\alpha \zeta^{\mu_\alpha}
\]  

(10)

where \( \chi_\alpha \) and \( \mu_\alpha \) are material parameters. The optimal regression value of \( \chi_\alpha \) and \( \mu_\alpha \) are 1.603 and 0.0550, respectively. Substitution of Equation (10) into Equation (9) gives:

\[
\alpha_c = \alpha_{p0} + k_\alpha \beta_\alpha \log \frac{p_0}{p_0^a}
\]

(11)

Substitution of Equation (11) into Equation (8) gives:

\[
B_r = \frac{(\chi_\alpha \zeta^{\mu_\alpha} + k_\alpha \beta_\alpha \log \frac{p_0}{p_0^a} - \alpha_0)(3 - \alpha_u)}{(\alpha_u - \alpha_0)(3 - \chi_\alpha \zeta^{\mu_\alpha} - k_\alpha \beta_\alpha \log \frac{p_0}{p_0^a})}
\]

(12)
Therefore, a comprehensive understanding of the resilient modulus of coral sand is of great practical significance to the construction of reef island traffic infrastructures and the utilization of energy.

At the end of the drained cyclic triaxial test, the calcareous sand sample was recovered carefully and the particle size distribution curve of the sample after cyclic loading was measured by the sieving test. Based on the observed particle size distribution curve after loading, the observed $B_r$ of calcareous sand was then calculated by Equation (2). Figure 8 represents the relationship between $B_r$ predicted by Equation (12) and observed $B_r$. It can be seen from Figure 8 that the points of predicted $B_r$ and observed $B_r$ are basically in a straight line with the slope of 1, indicating that Equation (12) can well predict the $B_r$ of coral sand under cyclic loading. Substitution of Equation (10) into Equation (12) gives:

$$B_{rp0} = \frac{(\chi_0 \zeta^\chi - \alpha_0)(3 - \alpha_u)}{(\alpha_u - \alpha_0)(3 - \chi_0 \zeta^\chi)}$$

(13)

where $B_{rp0}$ is the starting relative particle breakage index that can occur when $p_0$ is relatively small at each $\zeta$, which represents the ability of coral sand to resist particle breakage under different $\zeta$.

### 3.2. Resilient Behavior under Cyclic Loading

Sun et al. [11] and Indraratna et al. [15] emphasized that understanding the resilient behavior of soil can be helpful to judge and avoid some factors that cause engineering accidents. Resilient modulus is an important design parameter for the safety evaluation of the infrastructures of ocean engineering. Therefore, a comprehensive understanding of the resilient modulus of coral sand is of great practical significance to the construction of reef island traffic infrastructures and the utilization of energy.
Figure 9 reflects the general evolution trend of the hysteresis loop of coral sand during cyclic loading. The cyclic stress ratio has a significant effect on the dynamic stress-strain relationship of calcareous sand. According to the changing trend of the shape and area of the hysteresis loop with the number of cycles \( N \), the development law of the hysteresis loop under different cyclic stress ratios can be divided into two types. When the cyclic stress ratio \( \zeta \) is small (\( \zeta = 0.2 \)), the hysteresis loop is closed at the beginning, and the area of hysteresis loop increases slightly with the increase of the number of cycles \( N \). At the initial stage of cyclic loading, when the \( \zeta \) is large (\( \zeta = 0.4, 0.6 \) and \( 1.0 \)), the opening of hysteresis loop is large and its shape is relatively irregular. With the development of cyclic loading, the opening of hysteretic loop tends to close, which is a long ellipse with two pointed ends. As the number of cycles increases, the dynamic strain accumulates, and the hysteresis loop becomes narrow. The area of the hysteresis loop decreases first and then increases slightly with the increase of \( N \). Under the process of cyclic loading, the shape of coral sand’s hysteresis loop changes rapidly at first, and then tends to be stable gradually. Roughly, in the early stage of cyclic loading, the hysteresis loop of coral sand first rotates anticlockwise, then slightly rotates clockwise in the later stage and finally tends to be stable. This illustrates that the resilient modulus \( M_r \) of coral sand under cyclic loading first increases with the number of cycles \( N \), and then due to the continuous accumulation of particle breakage, the \( M_r \) will decrease to some extent in the later stage as \( N \) increases. Under the long-term cyclic loading, the \( M_r \) will finally tend to a stable value, which is consistent with the results of Sun et al. [11].
Complex e and the particle breakage has an adverse effect on the stiffness; therefore, the cyclic stress ratio has a complex effect on the resilient modulus response of coral sand. This should be paid attention to in practical engineering.

Figure 10a shows the variation of stable resilient modulus $M_r$ with $p_0$. With the increase of $p_0$, $M_r$ basically increases uniformly. This indicates that the increase of $p_0$ is beneficial for the improvement of $M_r$. This conclusion is consistent with the findings of Sun et al. [11] and Lackenby et al. [14].

Figure 10b shows the variation of stable resilient modulus $M_r$ with $\zeta$. Contrary to the conclusion that $M_r$ increases uniformly with the increase of $\zeta$ obtained by the experimental results on terrigenous granular materials [14], the $M_r$ of coral sand only shows a slight growth trend as a whole. That is to say, as the $\zeta$ increases, the $M_r$ does not increase uniformly but fluctuates. This indicates that the increase of $\zeta$ has both beneficial and detrimental effects on the improvement of the $M_r$. This phenomenon may be caused by the complexity and variability due to the particle breakage of coral sand material. It can be seen from Figure 6 that the particle breakage degree of coral sand increases with the increase of $\zeta$ and the particle breakage has an adverse effect on the stiffness; therefore, the cyclic stress ratio has a complex effect on the resilient modulus response of coral sand. This should be paid attention to in practical engineering.
4. Discussion

The reasonable prediction of $M_{rs}^{s}$ is of great significance to the actual engineering design and safety evaluation [10,33,34]. Therefore, Witczak and Uzan [35] established the empirical models for predicting the stable resilient modulus of terrigenous granular soil under cyclic loading. A famous two-parameter model proposed by Witczak and Uzan [33] only considered the cyclic deviatoric stress, not the initial mean effective stress $p_0$. Therefore, by introducing the initial mean effective stress into the model, the predicted resilient modulus $M_{rs}^{ps}$ can be calculated as:

$$M_{rs}^{ps} = k_1 \frac{p_0}{\zeta} k_2$$  \hspace{1cm} (14)

where $p_a = 100$ kPa (i.e., standard atmospheric pressure); $k_1$ and $k_2$ are material parameters. The optimal regression value of $k_1$, $k_2$, $k_3$, and $k_4$ are 40.766, −0.297, −1553.306, and 0.282, respectively.

Figure 11 shows a comparison of the predicted surface of $M_{rs}^{ps}$ calculated from Equation (14) with the observed $M_{rs}^{s}$. As can be seen from Figure 11, the predicted $M_{rs}^{ps}$ deviates greatly from the observed $M_{rs}^{s}$. In the low stress range, the predicted $M_{rs}^{ps}$ is always greater than the observed $M_{rs}^{s}$, which has also
been reported by many scholars when they study the granular soil with easily broken particles [21,36]. It can also be seen from Figure 11 that in the high stress range, the predicted $M_{r, ps}$ is always less than the observed $M_r$. The previous model for conventional terrestrial granular material cannot predict the $M_r^s$ of coral sand with easily broken particles in whole stress interval. Figure 12 shows the relationship between the ratio of predicted resilient modulus $M_{r, ps}$ by Equation (14) and observed $M_r^s$ with the particle breakage level $B_{rp0}/p_a$. It can be obtained from Figure 12 that the particle breakage has a significant effect on the resilient modulus prediction model of coral sand. The $M_{r, ps}/M_r^s$ decreases with the increase of the $B_{rp0}/p_a$, which indicates that the deviation between the predicted resilient modulus and the observed resilient modulus is partly caused by the difference of particle breakage in the high stress range. Coral sand has smaller particle breakage in the low stress range and larger particle breakage in the high stress range. The difference between particle breakage in the high and low stress ranges causes the predicted resilient modulus to regularly deviate from the observed resilient modulus. The starting relative particle breakage index $B_{rp0}$ was introduced into the formula, and the prediction model of $M_{r, ps}$ considering the effect of particle breakage can be expressed as:

$$M_{r, ps} = k_1 \frac{p_0}{p_a} \zeta^2 - k_3 B_{rp0} \left( \frac{p_0}{p_a} \right)^{k_4}$$

(15)

where $p_a = 100$ kPa (i.e., standard atmospheric pressure); $B_{rp0}$ can be calculated by Equation (13); $k_1, k_2, k_3,$ and $k_4$ are material parameters. The optimal regression value of $k_1, k_2, k_3,$ and $k_4$ are 40.766, −0.297, −1553.306, and 0.282, respectively.

Figure 11. Predicted surface of stable resilient modulus calculated from Equation (14).
Figure 12. Relationship between $B_r p_0 / p_s$ and $M_r^{ps}/M_r^s$ calculated from Equation (14).

Figure 13 shows a comparison of the predicted surface of $M_r^{ps}$ calculated from Equation (15) with the observed $M_r^s$. It can be seen from Figure 13 that the prediction model of the $M_r^s$ considering particle breakage can make the predicted $M_r^{ps}$ closer to the observed $M_r^s$. Figure 14 shows the relationship between the ratio of predicted resilient modulus $M_r^{ps}$ by Equation (15) and observed $M_r^s$ with the particle breakage level $B_r p_0 / p_s$. It can be seen from Figure 14 that the $M_r^{ps}/M_r^s$ is basically 1 and has no obvious relationship with the particle breakage level $B_r p_0 / p_s$, which indicates that the prediction model of $M_r^s$ considering particle breakage can better predict the resilient modulus response of coral sand. Therefore, unlike terrestrial granular materials, it is necessary to consider the impact of particle breakage when establishing a resilient modulus prediction model for coral sand. Considering particle breakage can help more accurately predict the resilient modulus of coral sand. In order to evaluate the resilient response of actual engineering more comprehensively and accurately, the effect of different particle sizes and relative densities on the prediction model of resilient modulus will be focused on in the future research. Moreover, the proposed formula will be verified in other types of soils.

Figure 13. Predicted surface of stable resilient modulus calculated from Equation (15).
5. Conclusions

A series of drained cyclic triaxial tests were carried out on the coral sand of the South China Sea to investigate the resilient modulus $M_r$ response and a new prediction model of $M_r$ was proposed. The effects of the initial mean effective stress $p_0$ and cyclic stress ratio $\zeta$ on the $M_r$ were examined. The main conclusions are the following:

(1) The change of fractal dimension $\alpha_c$ can reflect the rule of particle breakage evolution. The $\alpha_c$ of coral sand shows a tendency of almost maintaining stable and then increasing rapidly with the increase of mean effective stress $p_0$ under each cyclic stress ratio $\zeta$. There is a threshold of $p_0$, when the $p_0$ exceeds this threshold, $\alpha_c$ will increase significantly with the increase of $p_0$. The actual project needs to pay attention to the adverse effect of the rapid increase of particle breakage on the engineering safety when $p_0$ is greater than the threshold.

(2) The resilient modulus $M_r$ of coral sand under cyclic loading first increases with the number of cycles $N$, and then due to the continuous accumulation of particle breakage, the $M_r$ will decrease to some extent in the later stage as $N$ increases. Under the long-term cyclic loading, the $M_r$ will finally tend to a stable value. The increase of $p_0$ has a beneficial effect on the improvement of the $M_r$, and the increase of $p_0$ will lead to the increase of $M_r$ uniformly. The increase of $\zeta$ has both beneficial and detrimental effects on the improvement of the $M_r$, and the increase of $\zeta$ will cause the increase or decrease of $M_r$. The effect of $\zeta$ on the resilient modulus of coral sand is different from that of terrestrial granular materials, which is caused by the special material properties of coral sand.

(3) A new empirical prediction model of the $M_r$ considering particle breakage was established, which can better predict the $M_r$ of coral sand in the whole stress interval. Particle breakage has a significant effect on the prediction model of the $M_r$. It was found that if the particle breakage was not considered as an influencing factor in the empirical model, the predicted value of the $M_r$ would deviate greatly from the measured value. Therefore, it is necessary to consider the effect of particle breakage when establishing a resilient modulus prediction model for the coral sand.

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