Experimental research on mechanical property of granite under erosion by seawater

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Abstract. When offshore rock-socketed foundations are constructed, seawater will deteriorate the mechanical properties of fresh granite at the excavation surface of the foundation, thereby reducing the bedrock bearing capacity of the granite. In this paper, elastic P-wave velocity, uniaxial compressive strength, and slake durability tests are used to study the deterioration of the mechanical properties of granite due to seawater. The time effect is also considered by using different immersion durations (3, 7, and 15 days). The results indicate that the mechanical properties of granite deteriorate with an increase in erosion time. After being eroded in seawater for 15 days, dried samples have an elastic P-wave velocity of 4.274 km/s, saturated samples have a uniaxial compressive strength of 68.196 MPa, and the slake durability index is 84.24%. An evident decline is seen in the mechanical properties of granite under the effect of seawater erosion compared with the initial values of each index parameter. Thus, the influence of seawater erosion on rock-socketed foundations needs to be considered.

1. Introduction

Wind energy will play a crucial role in the future energy supply of the world [3]. Compared with onshore wind power, offshore wind power is advantageous in terms of location, power, transport, and construction [13]. The offshore wind speed at a distance of 10 km from a shore is usually about 25% higher than that at the coast. Thus, developing offshore wind power projects from shallow sea areas to deep sea areas in the future is promising. Coastal provinces in China, such as Zhejiang, Fujian, and Guangdong, have 30%–40% of the continental coastline of the country and thus have abundant offshore wind power reserves [7, 16]. Most of the sea beds in these zones are dominated by granite, and the overlying marine sediments, soil layers, and strongly weathered rock layers are thin. Thus, it is usually necessary to use rock-socketed piles as the foundation form in offshore wind power sites; part or all of the pile body is buried in rock to make full use of the bearing capacity of the bedrock and improve the bearing capacity of the single pile.

However, deep-water rock-socketed foundations usually penetrate through the medium and weakly weathered fresh rock layers during drilling and excavation. This enables seawater to seep into the rock-socketed pile hole and the rock at the end of the pile, which leads to the erosion of the fresh bedrock and deterioration of its physical and mechanical properties. Therefore, it is important to accurately describe the degradation effect of seawater on rocks and the degradation process of rocks’ mechanical properties under seawater erosion. Although some researchers have fully studied the weakening of rocks’ physical and mechanical properties under different water and solution environments [10, 12, 17], the influence of seawater and its time effect have not been considered thoroughly. Thus, the main goal of the present research is to explore the degradation laws of the basic mechanical properties of typical marine bedrock after seawater erosion at different times through...
various indoor rock mechanics tests. The findings could provide theoretical guidance for the development of marine pile foundation projects in the future.

In this study, a series of tests was conducted on rock specimens exposed to seawater erosion for different durations (3–15 days). The adopted physical and mechanical tests mainly included elastic P-wave velocity, uniaxial compressive strength, and slake durability tests.

Section 2 describes the experiment, including the specimen preparation and test procedures. Section 3 analyzes the results of the different tests to study the degradation laws of the rock specimens after seawater erosion for different durations through these physical and mechanical tests. Finally, a brief summary is presented to conclude the effect of seawater erosion on the mechanical properties of granite.

2. Experiment

2.1. Specimen preparation

Fresh granite from a project site in Fujian Province was selected as the research object. All specimens were extracted from one granite block with high geometrical integrity and petrographical uniformity [17]. They were processed in accordance with ISRM-specified standards [2]. The natural bulk density of the rock, measured by the volume product method, was 2.613 g/cm$^3$; the dry bulk density was 2.608 g/cm$^3$; the saturated bulk density was 2.615 g/cm$^3$.

All specimens in the elastic P-wave velocity and uniaxial compressive strength tests were cut into cylinders with a diameter of 50 mm and a height of 100 mm; their surfaces were polished to make the roughness less than 0.02 mm. A total of 52 standard specimens were processed, including 10 spare specimens. The diameters were measured at the upper, middle, and lower portions of the height of the specimens, and the height of each specimen was measured simultaneously. The specimens that did not meet the accuracy requirements were eliminated. The measured diameter range of the test piece was 49.72–50.60 mm, the average diameter was 50.01 mm, the height range was 100.20–100.85 mm, and the average height was 100.55 mm.

Each sample in the slake durability test weighed 40–60 g, and each group contained 10 samples. All of them were rounded with an angle grinder.

2.2. Specimen erosion experiment

The seawater was obtained from a coastal city in Fujian Province that had no inland freshwater and domestic sewage injection. The standard specimens for the uniaxial compression test and the specimen groups for the slake durability test were numbered and then immersed in a test box containing seawater in a normal-temperature, normal-pressure environment. The standard test specimens were immersed by the free water immersion method to reach the predetermined erosion time, and the test specimens were subjected to elastic P-wave velocity, uniaxial compressive strength, and slake durability tests. The exposure time of rock-socketed pile holes does not exceed 15 days in marine pile foundation projects, and the degradation effect of seawater on rocks is more evident in the early stage of erosion. Thus, the specimens were immersed for 3, 7, and 15 days in a seawater environment, and the natural, saturated, and dry conditions of the specimens immersed for different durations were studied.

2.3. Test equipment and procedures

2.3.1. Drying part of specimens. According to Zhou et al. [17], water content influences the physical and mechanical properties of rock specimens. Considering that the water content of the granite specimens with different immersion durations would differ, some of the specimens needed to be dried before being subjected to the physical and mechanical tests to exclude the effect of their water content. These specimens were placed in an oven and baked at 105–110 °C for 24 hours.

2.3.2. Elastic P-wave velocity test. An RSM-SY6 acoustic wave detector was used for the elastic P-wave velocity test of the specimens, as shown in Fig. 1. The accuracy of the acoustic time reading was
0.01 μs, and the sampling interval was 0.05–200 μs. A JHP-01 ultrasonic transducer with a frequency of 50 kHz was used to excite and receive sound waves [6, 14]. A TM-100 ultrasonic couplant was used to eliminate the gap between the transducer and the two ends of each standard granite specimen to ensure good contact coupling at the interface. A pressure of about 0.05 MPa was required to test the P-wave velocity of the specimens under unstressed conditions. Steel and plexiglass samples were used to verify the parameter settings and test accuracy of the system, and the measured system delay t0 was 4.1 μs. The exact P-wave velocity value can be obtained from Equation (1) of P-wave velocity theory [17].

\[ V_p = \frac{h}{t - t_0}, \]  

where \( V_p \) is the elastic P-wave velocity (km/s), \( h \) is the height of the sample between the center of the transmitting and receiving transducer (mm), \( t \) is the propagation time of the P-wave in the test specimen (μs), and \( t_0 \) is the system delay of the equipment (μs).

2.3.3. Uniaxial compressive strength test. Granite specimens are prone to structural damage during processing, which will have a certain impact on the results of mechanical tests. The elastic P-wave velocity test can obtain the structural information of a rock initially without damaging the internal structure of the rock sample. Thus, the elastic P-wave velocity test must be performed before the mechanical tests, and samples with large deviations in test results can be removed in advance to eliminate interference caused by the samples themselves. Considering that the elastic P-wave velocity test will not damage the internal structure of a rock sample, the samples in the elastic P-wave velocity test could subsequently be used in the uniaxial compressive strength test. The microcomputer-controlled electrohydraulic servo pressure testing machine shown in Fig. 2 was used in the uniaxial compressive strength test, where the maximum loading value was 2,000 kN. After a granite sample reached the predetermined erosion time, it was removed from the test box, and its surface was. The specimen was placed at the center of the pressure plate of the pressure test machine. A pad was placed on the bottom surface of the test piece, and the placement of the specimen was adjusted. The pressure test machine was loaded at a rate of 0.2 mm/min until the specimen was broken. The damage load of each sample and the phenomena that occurred during loading were recorded, and the failure mode of the sample was described to accurately analyze its failure mechanism. The uniaxial compressive strength and softening coefficient of each rock were calculated according to Equations (2) and (3), respectively [8].

\[ \sigma_c = \frac{4F}{\pi d^2}, \]  

where \( \sigma_c \) is the uniaxial compressive strength of the rock (MPa), \( F \) is the load when the specimen is broken (N), and \( d \) is the diameter of the test piece (mm).

\[ K_p = \frac{\sigma_w}{\sigma_d}, \]  

where \( K_p \) is the softening coefficient, \( \sigma_w \) is the uniaxial compressive strength of the sample under saturated condition (MPa), and \( \sigma_d \) is the uniaxial compressive strength of the sample under dried condition (MPa).

2.3.4. Slake durability test.

The YNB-1 rock slake durability apparatus shown in Fig. 3 was used in the slake durability test. The main machine power was 90 W, and the speed was 20 r/min. The cylindrical sieve had a diameter of 140 mm and a height of 100 mm, and the diameter of the standard sieve hole was 2 mm. The test
objects of the slake durability test included granite sample groups that were corroded by seawater for 3, 7, and 15 days. The specific steps of the test are as follows [5, 9].

(1) The sample group and number are selected, and these details are recorded in a form.

(2) The sample group is placed in the cylindrical sieve of the apparatus and then baked at 105–110 °C. It was then dried for 24 hours, cooled in the oven to room temperature, and weighed.

(3) The cylindrical sieve containing the test piece is placed in the water tank of the slake durability apparatus, and pure water is injected into the water tank such that the water level is at about 20 mm below the shaft. After the cylindrical sieve is rotated at a speed of 20 r/min for 10 minutes, the cylindrical sieve and the residual test piece are dried at 105–110 °C for 24 hours. After the sample is cooled to room temperature in the oven, it is weighed to the nearest 0.01 g.

(4) Step 3 is repeated to obtain the mass of the cylindrical sieve and the residual test piece after the second cycle.

The result of the rock slake durability test is calculated according to Equation (4) [1].

\[ I_{d2} = \frac{m_d}{m_r} \frac{m_2 - m_3}{m_0 - m_3} \]  

(4)

where \( I_{d2} \) is the slake durability index of the rock after the secondary cycle (%), \( m_r \) is the dried quality of the residual sample (g), and \( m_d \) is the dried quality of the original sample (g).

3. Results and discussion

3.1. Elastic P-wave velocity and dynamic elastic modulus

The results of the elastic P-wave velocity test are shown in Table 1. According to the test results, the wave velocity–time relationship of the granite under saturated and dried conditions is plotted on a rectangular coordinate system, as shown in Fig. 4. The P-wave velocity of the granite is closely related
to its water-containing condition, and $V_p$ (saturated) > $V_p$ (natural) > $V_p$ (dried). The relationship between the water-containing condition and the P-wave velocity of the granite could be attributed to the fact that the saturation of the sample rises with the increase in immersion time. Consequently, the pores are gradually filled with capillary water and free water while air gradually escapes. At this time, the disappearance of the water–air interface reduces the wave reflection, thereby making the P-wave velocity increase significantly.

The P-wave velocity of the saturated granite specimens increases rapidly to a peak of 5.4 km/s on the third day, suggesting that the effect of water content plays a leading role in the specimens in this stage. However, the mineral elements in the granite react with seawater to form water-soluble compounds with the prolonged erosion time, causing the rock to become loose. The effect of this loosening overcomes that of the water content; thus, the P-wave velocity decreases slightly in the late stage. Some of the specimens were dried after being immersed so as to exclude the effect of their water content and examine the chemical erosion caused by seawater. Findings show that the P-wave velocity of the dried granite specimen drops steadily during the period. Compared with the P-wave velocity of the dried samples under natural condition, the value of the dried samples that were immersed for 15 days is lower by 0.477 km/s (10.04%), which indicates an evident chemical erosion effect of the seawater.

Table 1. P-wave velocity test results of granite samples

| Sample description                  | Serial number | Sound time (μs) | Wave velocity (km·s⁻¹) | Average wave velocity (km·s⁻¹) |
|-------------------------------------|---------------|----------------|-------------------------|-------------------------------|
| Natural condition                   | #1            | 20.50          | 4.917                   |                               |
|                                     | #2            | 21.10          | 4.757                   | 4.796                         |
|                                     | #3            | 21.30          | 4.713                   |                               |
|                                     | #4            | 21.34          | 4.719                   |                               |
| Dried condition                     | #5            | 21.18          | 4.754                   | 4.751                         |
|                                     | #6            | 21.00          | 4.780                   |                               |
| Immersed for 3 days                 | #7            | 19.00          | 5.265                   |                               |
|                                     | #8            | 18.81          | 5.317                   | 5.420                         |
|                                     | #9            | 17.82          | 5.678                   |                               |
|                                     | #10           | 19.10          | 5.272                   |                               |
| Immersed for 7 days                 | #11           | 18.50          | 5.443                   | 5.312                         |
|                                     | #12           | 19.30          | 5.220                   |                               |
|                                     | #13           | 20.50          | 4.878                   |                               |
| Immersed for 15 days                | #14           | 18.40          | 5.474                   | 5.228                         |
|                                     | #15           | 18.91          | 5.331                   |                               |
|                                     | #16           | 21.39          | 4.675                   |                               |
| Immersed for 3 days and dried       | #17           | 20.73          | 4.824                   | 4.718                         |
|                                     | #18           | 21.48          | 4.655                   |                               |
|                                     | #19           | 21.60          | 4.660                   |                               |
| Immersed for 7 days and dried       | #20           | 21.94          | 4.587                   | 4.672                         |
|                                     | #21           | 21.10          | 4.770                   |                               |
|                                     | #22           | 23.00          | 4.372                   |                               |
| Immersed for 15 days and dried      | #23           | 24.97          | 4.038                   | 4.274                         |
|                                     | #24           | 22.83          | 4.411                   |                               |
The dynamic elastic modulus is the ratio of the stress and strain of the material under a dynamic load [4]. This value is important for the calculation of material deformation under a dynamic load. It is generally measured by dynamic resistance strain gauges and acoustic instruments. The results of acoustic methods are generally higher than elastic moduli measured by static methods. According to the theory of elasticity, there is a definite relationship between the P-wave velocity of a rock and the dynamic elastic modulus [11].

\[ E_d = \frac{(1 + \nu)(1 - 2\nu)}{(1 - \nu)} \rho V_p^2, \]  

where \( E_d \) is the dynamic elastic modulus of the rock (GPa), \( \rho \) is the density of the rock (kg/m\(^3\)), and \( \nu \) is the Poisson’s ratio of the rock. For granite materials, \( \nu \) generally varies between 0.19 and 0.28, and the Poisson’s ratio of the sample under natural condition, 0.27, is measured during the uniaxial compression test.

The calculation results of the dynamic elastic modulus \( E_d \) of the granite rock samples under saturated and dried condition are shown in Tables 2 and 3, respectively. Then, the dynamic elastic modulus–time relationship curves of the granite under saturated and dried conditions in the rectangular coordinate system are drawn in Fig. 5.

**Table 2.** Dynamic elastic moduli of granite under saturated condition

| Condition            | Wave velocity (km\( \cdot \)s\(^{-1} \)) | \( E_d \) (GPa) |
|----------------------|-------------------------------------------|-----------------|
| Immersed for 3 days  | 5.420                                     | 68.191          |
| Immersed for 7 days  | 5.312                                     | 65.500          |
| Immersed for 15 days | 5.238                                     | 63.688          |

**Table 3.** Dynamic elastic moduli of granite under dried condition

| Condition                  | Wave velocity (km\( \cdot \)s\(^{-1} \)) | \( E_d \) (GPa) |
|----------------------------|-------------------------------------------|-----------------|
| Dried condition            | 4.751                                     | 52.396          |
| Immersed for 3 days and dried | 4.718                                     | 51.714          |
| Immersed for 7 days and dried | 4.672                                     | 50.668          |
| Immersed for 15 days and dried | 4.274                                     | 42.403          |

The dynamic elastic moduli of the samples under saturated and dried conditions show that the change trend of the dynamic elastic moduli of such samples is the same as that of the P-wave velocity under the same conditions. According to the theoretical relationship between \( E_d \), density \( \rho \), and P-wave velocity \( V_p \), since the elastic modulus is proportional to the density and proportional to the square of the P-wave velocity, the reduction in the dynamic elastic modulus is larger than the reduction in the P-
wave velocity. The dynamic elastic modulus of the dried samples saturated for 15 days is lower by 19.07% than that of the dried sample under natural condition.

3.2. Uniaxial compressive strength and softening coefficient

The results of the rock uniaxial compressive strength test are shown in Table 4, and the relationship between the uniaxial compressive strength and time under saturated and dried conditions is plotted in a rectangular coordinate system, as shown in Fig. 6. The dispersion of the uniaxial compressive strength of the samples is relatively large, but the uniaxial compressive strength of the samples under saturated condition tends to decrease as the erosion time increases because the mineral elements in granite react with seawater to form water-soluble compounds, making it becomes loose. The rate of decrease could reach 31.10%, indicating that seawater degrades the uniaxial compressive strength over time. Meanwhile, the dried samples show a similar tendency, but their value is greater than that under saturated condition when immersed for the same time.

According to the results of the P-wave velocity test, the decrease in the dynamic elastic modulus of the dried samples that were saturated for 15 days compared with the dynamic elastic modulus of the dried samples under natural condition (19.07%) is similar to the decrease in the uniaxial compressive strength (13.38%) under the same condition. Therefore, it is feasible to characterize the strength reduction of rocks after seawater erosion by the reduction degree of the dynamic elastic modulus. Meanwhile, the relationship between the softening coefficient and time in Fig. 7 reveals that, with the increase in erosion time, the softening coefficient of the rocks generally decreases.

Table 4. Uniaxial compressive strength test results of granite samples

| Sample description       | Serial number | Failure load (kN) | Strength (MPa) | Average strength (MPa) |
|--------------------------|---------------|------------------|----------------|------------------------|
| Natural condition        |               |                  |                |                        |
|                          | #1            | 173.1            | 86.063         |                        |
|                          | #2            | 231.9            | 117.352        |                        |
|                          | #3            | 185.1            | 93.530         |                        |
|                          | #4            | 202.0            | 103.695        |                        |
| Dried condition          |               |                  |                |                        |
|                          | #5            | 163.2            | 82.646         | 93.496                 |
|                          | #6            | 186.3            | 94.148         |                        |
|                          | #7            | 165.4            | 84.257         |                        |
|                          | #8            | 183.9            | 93.671         | 91.023                 |
|                          | #9            | 186.8            | 95.141         |                        |
| Immersed for 3 days      |               |                  |                |                        |
|                          | #10           | 194.4            | 97.732         |                        |
|                          | #11           | 141.6            | 71.823         | 86.950                 |
|                          | #12           | 180.7            | 91.295         |                        |
|                          | #13           | 113.5            | 58.410         |                        |
| Immersed for 7 days      |               |                  |                |                        |
|                          | #14           | 117.5            | 60.034         | 68.196                 |
|                          | #15           | 168.2            | 86.145         |                        |
|                          | #16           | 180.0            | 91.692         |                        |
| Immersed for 15 days     |               |                  |                |                        |
|                          | #17           | 213.3            | 108.631        | 102.214                |
|                          | #18           | 208.8            | 106.319        |                        |
|                          | #19           | 149.6            | 76.540         |                        |
| Immersed for 3 days and dried |     |                  |                |                        |
|                          | #20           | 183.1            | 94.313         | 89.523                 |
|                          | #21           | 191.6            | 97.717         |                        |
|                          | #22           | 142.8            | 71.658         |                        |
| Immersed for 7 days and dried |   |                  |                |                        |
|                          | #23           | 188.7            | 95.012         | 80.987                 |
|                          | #24           | 150.1            | 76.291         |                        |
3.3. Slake durability index

The slake durability index (I_{d2}) is used to classify durability, which can be divided into five levels, as shown in Table 5. The test results of the slake durability index, calculated according to Equation (4), are shown in Table 6. Finally, the slake durability index–time relationship curve of the samples under saturated and dried conditions is shown in Fig. 8. The figure shows that the rock slake durability index drops steadily to reach the lowest level, 4.29\%, on the 15th day. According to the rock durability classification standards in Table 5, when the erosion time reaches 15 days, the rock slake durability index is 84.24\%, which is slightly lower than the cut-off value of 85\%; this reflects a shift from high durability to medium durability.

### Table 5. Division of rock durability levels

| Division of rock durability grade | Extremely high | High | Median | Low | Extremely low |
|----------------------------------|----------------|------|--------|-----|---------------|
| $I_{d2}$ (%)                     | $I_{d2} \geq 98$ | $98 > I_{d2} \geq 85$ | $85 > I_{d2} \geq 60$ | $60 > I_{d2} \geq 30$ | $I_{d2} < 30$ |

### Table 6. Slake durability test results of granite samples

| Sample description               | Dried mass of original sample $m_d$ (g) | Dried mass of residual sample $m_d$ (g) | Slake durability index |
|----------------------------------|----------------------------------------|----------------------------------------|-----------------------|
| Natural condition                | 524.01                                 | 512.63                                 | 97.83%                |
| Immersed for 3 days              | 559.14                                 | 523.81                                 | 93.68%                |
| Immersed for 7 days              | 569.18                                 | 516.79                                 | 90.80%                |
| Immersed for 15 days             | 580.72                                 | 489.22                                 | 84.24%                |

![Figure 6. Uniaxial compressive strength–time relationship curves of granite samples](image1)

![Figure 7. Softening coefficient–time relationship curves of granite samples](image2)

![Figure 8. Slake durability index–time relationship curve of granite samples](image3)
4. Conclusion
Seawater has erosion and weakening effects on the fresh rock mass of the excavated face in the rock-socketed pile foundations of offshore wind power projects. These effects deteriorate the basic physical and mechanical properties of bedrock and reduce the ultimate bearing capacity of the end rock mass. However, current pile foundation design standards consider only a single factor, the uniaxial compressive strength of saturated rocks, in the design of the bearing capacity of the rock-socketed pile. Seawater and its time effect on the deterioration of physical and mechanical property indexes are neglected. Therefore, experimental studies on the elastic P-wave velocity, uniaxial compressive strength, and slake durability of granite under erosion by seawater are conducted, and the following conclusions are obtained:

1. The P-wave velocity under saturated condition increases slightly at first relative to the wave velocity under natural condition because water fills the pores and cracks in the rock, which is conducive to the propagation of the wave. With an increase in erosion time, the wave velocity starts to reduce the erosion effect on granite, and this reduction is beyond the influence of the water alone. Compared with the wave velocity of the dried samples under natural condition, that of the dried samples that were saturated for 15 days is lower by 0.477 km/s, reflecting a decrease of 10.04%. The dynamic elastic moduli of the granite under saturated and dried conditions exhibit the same trend as does the P-wave velocity under the same conditions, but the reduction is greater than that in the P-wave velocity.

2. Compared with the uniaxial compressive strength in the natural water-containing condition, with an increase in erosion time, the uniaxial compressive strength of the samples generally decreases, and the decline could reach 31.10%. Therefore, the uniaxial compressive strength of seawater on granite has a degradation effect that increases with time.

3. The slake durability index of granite decreases significantly with an increase in erosion time. When the seawater erosion time reaches 15 days, the slake durability reduces to 84.24%, indicating a change from high durability to medium durability. Thus, the dissolution effect of seawater on granite cannot be ignored.

4. The reduction in the dynamic elastic modulus of the dried sample that was saturated in seawater for 15 days compared with the dynamic elastic modulus of the dried sample under natural condition (19.07%) is relatively close to the reduction range of the uniaxial compressive strength under the same condition (13.38%). Hence, it is feasible to use the change in the dynamic elastic modulus to characterize the reduction in the strength of granite after seawater erosion.

This paper conducts experiments on the influence of seawater as an environmental medium on the basic physical and mechanical properties of granite. However, further study could be conducted because this study does not consider the impact of seawater pressure on rocks’ mechanical properties. Seawater in the pressure environment will accelerate the rate of rock erosion, thereby accelerating the degradation of rocks’ mechanical properties. Furthermore, the erosion effect on wind-powered rock-socketed pile foundation bedrock is mainly subject to unidirectional erosion. Thus, studying the evolution process of rocks’ microstructure is of great significance for assessing the degree of deterioration of the mechanical properties of different parts of rocks.

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