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Experimental Study on the Anti-Scouring Characteristics of Bedrock in Engineering Reservoir Areas That Are Conducive to Sustainable Development

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Abstract: High-speed water flow conditions can cause erosion of the bedrock in engineering areas. Due to the lack of accurate evaluation of bedrock scour and erosion rates, there has been a consumption of manpower and resources without achieving satisfactory engineering outcomes. Therefore, studying the scouring and erosion effects of water flow on bedrock is of significant importance for maintaining the sustainable development and safety of engineering projects. Using the bedrock prototype from the Xiaonanhai site in the upper reaches of the Yangtze River, a model test device was developed to conduct anti-scour tests on the bedrock. The study quantitatively examined the basic physical properties, incipient erosion velocity, and erosion rates of different types of bedrock. The study found that the prototype bedrock under natural exposure, submerged immersion, and alternating wet and dry conditions showed a trend of decreased tensile strength, with the alternating wet and dry conditions being the most detrimental to maintaining the physical properties of the rock mass. The anti-scour velocity of silty claystone and clayey siltstone samples increased with the increase in tensile strength, and the erosion rate increased with the increase in shear stress. If the shear stress is kept constant, the erosion rate decreases with the increase in tensile strength. The erosion rate is inversely proportional to the ratio of the bedrock's tensile strength to the riverbed shear stress, with the fitting relationship showing a piecewise linear distribution. The research results can provide guidance for the safe production of engineering involving bedrock erosion in engineering reservoir areas that are conducive to sustainable development.

Keywords: engineering safety sustainability; bedrock erosion; model test device; anti-erosion characteristics; erosion rate

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Academic Editor: Kaihui Li

Received: 10 December 2024
Revised: 19 January 2025
Accepted: 24 January 2025
Published: 25 January 2025

Citation: Li, Z.; Wang, Y.; Yao, S.; Jin, Z.; Hu, Z. Experimental Study on the Anti-Scouring Characteristics of Bedrock in Engineering Reservoir Areas That Are Conducive to Sustainable Development. *Sustainability* **2025**, *17*, 977. https://doi.org/10.3390/su17030977

1. Introduction

The process of scour and erosion of bedrock plays a crucial role in the evolution of river channels and the safety of engineering production, such as the scour and erosion in unlined open channels, spillways, and flood release openings [1–3]. One of the notable characteristics of many alluvial rivers is the presence and exposure of bedrock, which may be subjected to natural exposure conditions and frequent flood erosion during the flood season. In some cases, bedrock with good rock conditions that do not require reinforcement has been subjected to extensive reinforcement and lining measures, wasting a significant amount of manpower, material resources, and financial resources without achieving satisfactory engineering results. On the other hand, if the bedrock does indeed face the possibility of severe scour, it could lead to the destruction of bridge pier foundations, diversion structures, and other infrastructure, thereby threatening the safety of people's lives and property.

In the past decade, models of mountain landscape evolution have developed rapidly, but the analyses aimed at specific issues are not uniform, and the methods also have defects and limitations. Currently, there are no mature theoretical analysis methods or a unified modeling approach. The research on bedrock erosion is still in the exploratory stage [4–6]. Generally speaking, there are many factors that affect bedrock erosion, and the physical processes are complex. The main mechanisms of bedrock erosion include natural weathering, hydraulic scour (the scouring of rock fragments by fluid shear stress or fluid differential pressure), and abrasion scour (the interaction between rock and moving sediment particles) [7].

Understanding the factors influencing bedrock erosion rates is crucial for predicting feedbacks between climate, erosion, and tectonics. The generally accepted view of the mechanisms of bedrock scour failure is that pulsating pressure within rock fissures and its propagation are the two main causes of bedrock failure [8]. The failure mechanism is generally described as three processes: first, rock disintegration, where the riverbed bedrock undergoes hydraulic fracturing along joints and fissures or joint planes under the dynamic water pressure of the plunging water jets; second, rock extrusion, where the rock blocks move and eventually extrude from their sockets when the instantaneous uplift force on the rock block is greater than the weight of the rock block in water and the interlocking force between rock blocks; third, plucking to form pits, as the rock blocks are pulled out, the scour pits begin to form, and at the same time, the extruded rock blocks roll and collide within the pits, breaking apart, and are finally washed out and deposited, causing the scour pit to expand rapidly [9]. As stated by Sklar and Dietrich [2], hydraulic scour may be an important mechanism for weak or highly fractured rocks. Tomkin et al. [10] and Sklar and Dietrich [11] also provide additional reviews. Whipple et al. [12] discuss how to qualitatively determine erosion mechanisms on river reaches. However, it is important to note that these mechanisms are interconnected. Hydraulic scour can occur without the assistance of sediment particles, but it is influenced by sediment particle-rock collisions and sediment deposition. Similarly, water flow scour is closely related to hydraulic flow characteristics such as shear stress and turbulence, but research in this area is currently lacking.

This study, taking the bedrock at the Xiaonanhai site in the upper reaches of the Yangtze River in China as a representative, developed a model test device that addresses the issues encountered in open channel hydraulic bedrock erosion tests considering hydraulic erosion. The model device can achieve constant high-speed flow conditions for an extended period, featuring a simple structure and convenient testing, providing effective technical support for bedrock erosion research. Based on the model test results, a quantitative analysis of the anti-scour characteristics of various prototype bedrocks was conducted, offering a theoretical basis for the judgment of bedrock scour and erosion conditions in natural river channels.

2. Materials and Methods

2.1. Research Region

The upper reaches of the Yangtze River cover the area from the Three Gorges Dam to the source of the Yangtze River (as shown in Figure 1a), with a basin area of about 105,000 square kilometers and a total population of 160 million, accounting for 58.9%

of the total basin area and 35% of the population, respectively [13]. More than 90% of the land in the region is mountainous and plateau, and the ecosystem is very fragile and highly vulnerable to soil and bedrock erosion due to improper land use. On the other hand, the Yangtze River Basin is of great economic importance, with its economic productivity accounting for almost half of China's gross national product (GNP) in the 1990s. In addition, in the Yangtze River basin, the problem of bedrock erosion related to energy projects such as the Three Gorges Dam and the South-to-North Water Diversion project is more prominent [14].

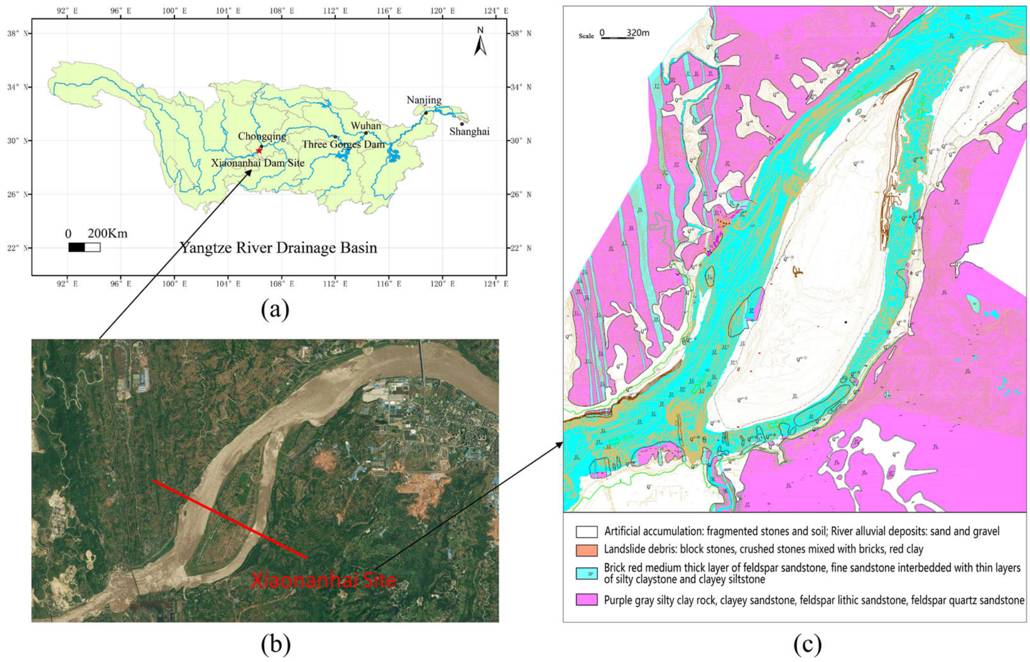


Figure 1. Schematic diagram of the research region. (**a**) Yangtze River Basin; (**b**) Xiaonanhai site; (**c**) Geological overview of Xiaonanhai site.

The Xiaonanhai site is located in the upper reaches of the Yangtze River in Chongqing. The rock body exposed at the site is mainly the Upper Jurassic Suining Formation (J3s), and the lithology is mainly purplish red silty claystone, clayey siltstone, and medium-thick feldspar lithology sandwich-sandstone (as shown in Figure 1b,c). The foundation surface rocks are mainly relatively soft claystone, and the characteristics of this lithology can be used as representative bedrock of the upper reaches of the Yangtze River. In this study, the in-situ bedrock was selected for drilling core sampling (cylinder with a diameter of 7 cm) as the rock mass sample for the bedrock anti-scour property test (as shown in Figure 2).

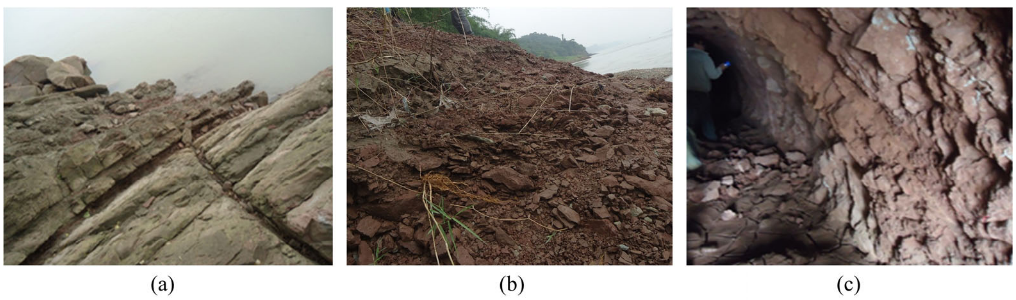
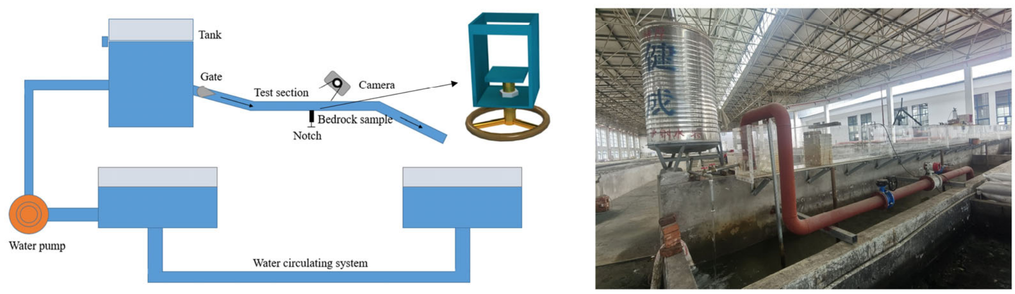


Figure 2. Bedrock samples from Xiaonanhai site: (**a**) silty claystone; (**b**) clayey siltstone; (**c**) feldspathic lithic sandstone.

2.2. Experimental Method

The bedrock weathering tests were conducted in the laboratory of the Changjiang Scientific Research Institute. In order to quantitatively analyze the bedrock physical property under different conditions and provide physical data support for determining the model scour material, the tests used samples that were retrieved from the site and sealed to represent a slightly weathered state. Samples that were left exposed to the air for 3 days represented the natural exposure state. Samples that were soaked in water for 3 days represented the submerged state. Samples that were soaked in water for 1 day, then exposed to the air for 1 day, and finally soaked in water for another 1 day represented the wet-and dry alternation state. All samples were wrapped with tape around the circumference and one bottom face of the cylindrical samples before the tests, while the other bottom face was left untreated. This was primarily performed to reduce the differences in weathering characteristics between the cylindrical samples used and the prototype bedrock and also to correspond with the subsequent bedrock scour model tests.

The bedrock incipient scour and erosion tests were conducted in a glass flume (Figure 3). The sink is made of plexiglass, 0.4 m wide and 20 m long. In order to integrate the experimental study with the field conditions, the model test device includes a storage tank, water tank, water pump, tilt flume, and return tank. The water inlet and the water outlet of the storage tank are through the return pipe and the return tank. In the upper part of the storage tank, the water inlet of the water tank communicates through the water inlet pipe and the storage tank, and the water inlet pipe of the pump is arranged. The outlet of the water tank is communicated with the inclined tank through the inclined outlet pipe, and the inclined outlet pipe is provided with an arc flow control outlet door. The end of the inclined water tank leads to the return water tank, and the test section of the inclined water tank is provided with a flow velocity measurement device.



(a) (b)

Figure 3. Illustration of the flume used to conduct bed erosion experiments. (**a**) Model schematic diagram; (**b**) Physical model.

The slope of the bed of the test section can be adjusted in the range of 0.001~0.04 according to the experimental requirements. The high head water tank upstream of the tank can produce a high speed with a maximum of 6.0 m/s. The discharge flow of the test open channel was measured by an electromagnetic flowmeter (accuracy 0.3%). The depth of the open channel was measured with a ruler (error ±1 mm). The flow rate was measured with a rotary slurry current meter (accuracy 3%). The flow pattern was recorded by visual observation and video recording, and the weight of the bedrock was measured by a digital electronic scale (error ± 1 mg). By weighing the corrodible samples before and after the experiment, the mass loss was obtained, and the erosion magnitude was determined.

Before the test began, the flow rate for the test section was calibrated to determine the relationship between the water level in the high-head water tank and the flow velocity in the test section. Bedrock samples of different types and weathering degrees were selected, and a red marking layer was applied to the surface in contact with the water flow using a marker pen. They were then placed in a top-sample device for the scour test. The flow velocity in the test section was continuously increased, and the movement state of the bedrock samples was observed using a multi-channel particle imaging system. Based on the incipient motion states observed in the test, the incipient scour of the bedrock was divided into different critical states to determine the upper and lower limits of the critical incipient scour state of the bedrock and to ascertain the incipient flow velocity of the bedrock. Typical bedrock samples were selected, and scour tests were conducted under typical flow velocity conditions to determine the scale of scouring on the bedrock at different flow velocities and to obtain the corresponding bedrock scour rates.

2.3. Test Conditions

Firstly, considering the weathering and erosion of bedrock by the natural environment, we define the samples taken on site as slightly weathered. Before the tests, three different conditions for bedrock were designed: natural exposed state, submerged state, and wet and dry alternation state. The basic mechanical parameter characteristics of the rock mass under different conditions were analyzed, as shown in Table 1.

Table 1. Design of working conditions for different types of bedrock.

Run	Sample	Types of Bedrock	State
1	A-1	silty claystone (A)	Slightly weathered
2	A-2		Natural
3	A-3		Underwater immersion
4	A-4		Alternation of dry and wet
5	B-1	clayey siltstone (B)	Slightly weathered
6	B-2		Natural
7	B-3		Underwater immersion
8	B-4		Alternation of dry and wet
9	C-1	feldspathic lithic sandstone (C)	Slightly weathered
10	C-2		Natural
11	C-3		Underwater immersion
12	C-4		Alternation of dry and wet

After conducting measurements of the incipient flow velocity for bedrock, to further study the anti-scour characteristics of bedrock and determine the relationship between bedrock scour rate and flow velocity, typical bedrock samples of silty claystone and clayey siltstone were selected. Under typical flow velocity conditions, scour rate tests were conducted on the bedrock. A total of 18 erosion experiments were carried out, during which hydraulic conditions and bedrock strength were varied (Table 2). The steps for each experiment are as follows: the erodible sample is weighed and placed in a tank with its top surface flush with the water bed, and the tank is filled with standing water until the sample is completely saturated with water (after 48 h of this work). During the descent, we recorded the depth, velocity, and slope of the fluid. The duration of the experiment is chosen long enough to obtain significant wear, but not so long that the degradation of the erodible sample is significantly lower than that of the water bed. At the end of each run, samples are taken out, checked for wear marks, and weighed on subsequent days until they balance out with the dry weight. Due to heavy wear, the same sample is usually only run once before replacement, but, if possible, we run the same sample multiple times to test repeatability.

Table 2. Hydraulic parameters of model test conditions.

Run	Sample	Mean Velocity (m/s)	Flow Depth (cm)	Water Slope	Eroded Mass (g)	Duration (s)
2-1	A-1	3.0	6.7	0.035	27.60	7200
2-2		3.5	14.0	0.035	25.92	5200
2-3		4.0	22.9	0.035	25.52	3400
2-4	A-2	3.0	6.7	0.035	26.48	8000
2-5		3.5	14.0	0.035	27.36	6000
2-6		4.0	22.9	0.035	26.24	4200
2-7	A-3	3.0	6.7	0.035	26.88	8800
2-8		3.5	14.0	0.035	27.36	6800
2-9		4.0	22.9	0.035	27.04	5000
2-10	B-1	3.0	6.7	0.035	27.28	9200
2-11		3.5	14.0	0.035	26.16	7400
2-12		4.0	22.9	0.035	26.40	5600
2-13	B-2	3.0	6.7	0.035	28.16	10,000
2-14		3.5	14.0	0.035	26.08	8200
2-15		4.0	22.9	0.035	26.24	6400
2-16	B-3	3.0	6.7	0.035	27.60	10,800
2-17		3.5	14.0	0.035	26.72	9000
2-18		4.0	22.9	0.035	26.32	7200

3. Result and Analysis

3.1. Physical Characteristic

As can be seen from Table 3, the physical properties of various types of bedrock change under the set conditions, but the natural weathering conditions have little effect on the physical properties of the rock blocks. The density of the rock samples slightly decreases, and the porosity slightly increases. The wet and dry alternation condition is the most unfavorable for maintaining the physical properties of the rock mass, followed by the submerged condition, with the natural exposed condition being the most favorable. From Figure 4, it can be observed that under naturally exposed, submerged, and wet–dry alternation conditions, the tensile strength of the rock blocks decreases. Overall, the degree of deterioration in the mechanical strength of the rock blocks obtained under different test conditions is not significant. The naturally exposed bedrock has the lowest reduction in tensile strength, followed by the submerged bedrock, with the wet–dry alternation bedrock showing the greatest reduction in tensile strength.

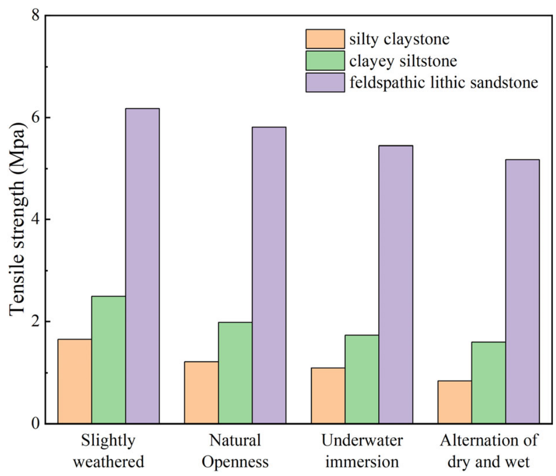


Figure 4. The tensile strengths corresponding to various types of bedrock samples.

Table 3. Physical characteristics of test conditions.

Sample	State	Physical Property		Tensile Strength	Shear Strength	
		Block Density (g/cm^3)	Porosity		f	c (Mpa)
A-1	Slightly weathered	2.58	8.27	1.67	0.78	3.62
A-2	Natural	2.49	8.89	1.21	0.75	3.25
A-3	Underwater immersion	2.45	9.64	1.09	0.73	2.73
A-4	Alternation of dry and wet	2.34	10.3	0.85	0.7	2.48
B-1	Slightly weathered	2.6	6.89	2.47	0.92	4.82
B-2	Natural	2.52	7.41	1.96	0.87	4.26
B-3	Underwater immersion	2.47	8.35	1.74	0.82	3.84
B-4	Alternation of dry and wet	2.36	9.82	1.58	0.77	3.53
C-1	Slightly weathered	2.62	5.56	6.17	1.37	9.75
C-2	Natural	2.54	6.64	5.81	1.32	9.26
C-3	Underwater immersion	2.52	7.15	5.42	1.28	8.79
C-4	Alternation of dry and wet	2.48	8.49	5.16	1.25	8.56

Additionally, it can be observed that all types of rock bodies show a decrease in the shear strength friction coefficient and the cohesion. This indicates that the degree of reduction in the shear strength parameters of the rock bodies under the naturally exposed condition is the smallest, followed by the degree of reduction under the submerged condition, while the wet and dry alternation condition is the most unfavorable for maintaining the shear strength parameters of the rock bodies.

3.2. Starting Erosion Characteristics

As shown in Figure 5a, at the beginning of the test, the weight of the bedrock sample is first measured. Then, the water flow velocity in the flume starts from a relatively low speed of 1.0 m/s and is gradually increased in steps. Considering the accuracy of the test and the workload, the increment of the flow velocity is 0.2 m/s. The bedrock is continuously scouring for 30 min at a constant flow velocity, which is considered to be an optimal observation time for scouring [15]. If no scouring is observed on the marked layer of the bedrock sample, the flow velocity is increased to the next level until scouring damage to the bedrock surface is observed within 30 min at a certain flow velocity, as shown in Figure 5b,c. At this point, the current flow velocity is determined to be the anti-scour velocity of the bedrock sample. The test scouring is then concluded, and the bedrock sample is removed to be drained and weighed again, as shown in Figure 5d.

(a) (b) (c) (d)

Figure 5. Bedrock incipient scour test sample conditions: (**a**) Weighing before the test; (**b**) Placing it in the top sample device before releasing water; (**c**) Observing scouring during the test; (**d**) Weighing the sample after removing it from the test.

Figure 6 lists the test results of the anti-scour velocities for various types of bedrock initiation. From the results, it can be observed that, in general, the anti-scour velocity of silty claystone (A) is lower than that of clayey siltstone (B), while the anti-scour velocity of feldspathic debris sandstone (C) is the highest. For the four samples of feldspathic debris sandstone (C), there were still no signs of initiation scour at a flow velocity of 6.0 m/s, so it is determined that the anti-scour velocities for all four samples of feldspathic debris sandstone (C) are greater than 6.0 m/s. The set conditions for the test scenarios show a trend of decreasing anti-scour velocities for the bedrock, with the smallest anti-scour velocity under alternating wet and dry conditions, followed by submerged immersion. The natural exposure and natural weathering conditions have a similar and minimal impact on the anti-scour velocity.

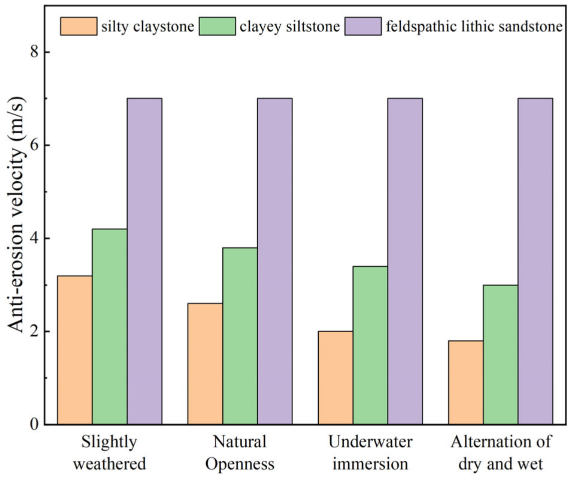


Figure 6. The corresponding anti-scour velocities of bedrock under various conditions.

As can be seen from Figure 7, the anti-scour velocities of silty claystone and clayey siltstone samples increase with the increase in tensile strength. The higher the tensile strength of the rock mass, the more difficult it is for the water flow to erode, and thus the anti-scour velocity is greater. The anti-scour velocities of silty claystone (A) and clayey siltstone (B) are nearly linearly distributed with respect to tensile strength, a pattern that is more pronounced when the tensile strength of the bedrock is less than 3 MPa. The feldspathic debris sandstone (C) has a higher tensile strength; therefore, its anti-scour velocities are also greater, all exceeding 7 m/s, and do not show an obvious linear distribution pattern.

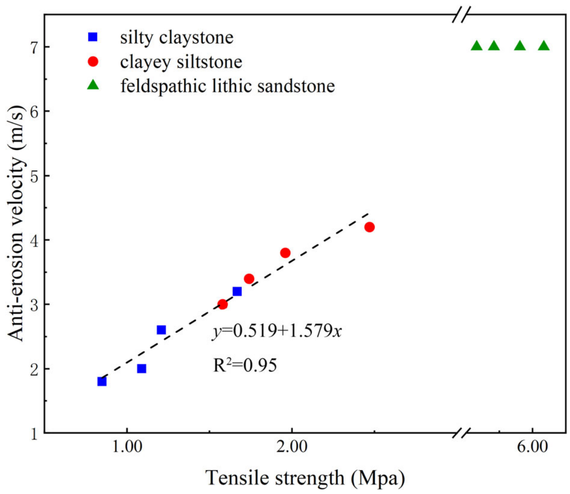


Figure 7. The relationship between the anti-scour velocity and tensile strength of the bedrock samples.

3.3. Scour and Erosion Characteristics

To analyze the scour and erosion process under different conditions, we define the erosion rate as the ratio of the eroded mass and the erosion duration and calculate the bed shear stress by $\tau = \rho g h J$, where ρ is the density of water, g is the gravity acceleration, h is the flow depth, and J is the water slope. Figure 8 shows the plot of erosion rate versus bed shear stress for different bedrock samples. It can be observed that the erosion rate of all samples typically increases with the increase in shear stress, and the trend of erosion rate increase intensifies as the shear stress increases.

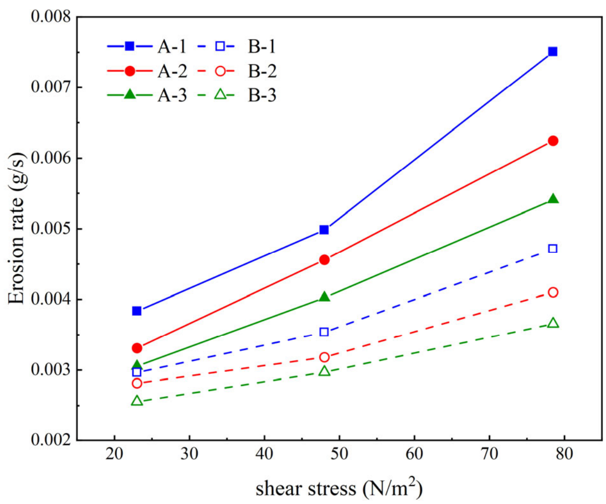


Figure 8. Plot of erosion rate versus bed shear stress for different bedrock samples.

Figure 9 shows the relationship between the erosion rate and tensile strength under different bed shear stresses. The results indicate that if the shear stress is kept constant, the erosion rate decreases with the increase in tensile strength. Previous studies have shown that the erosion rate of bedrock increases with the increase in shear rate and decreases with the increase in tensile strength. In this study, our experiments used prototype bedrock samples and high-velocity open-channel flow conditions, which are closer to natural scales, and our findings are consistent with the results of Hsu et al. [16].

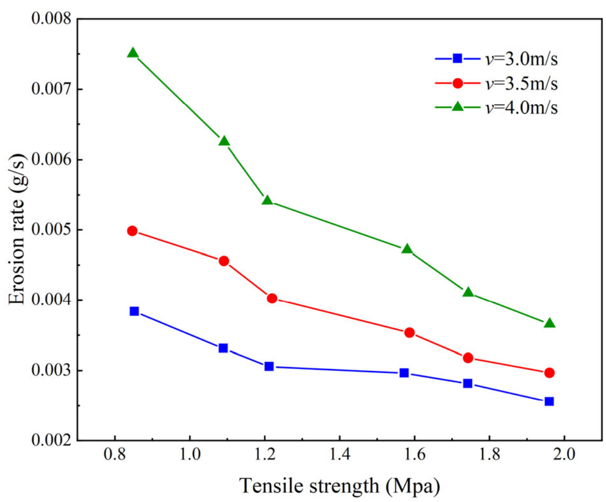


Figure 9. Plot of erosion rate versus tensile strength for different bed shear stresses.

Figure 10 illustrates the relationship between the scour erosion rate (E_r) of bedrock test measurement data and the ratio of tensile strength (σ) to bed shear stress (τ). From Figure 10, a general decreasing trend in E_r with σ/τ increases are observed. More specifically, for small values of σ/τ ($\sigma/\tau < 0.024$), E_r increases rapidly as σ/τ decreases, and as the value of σ/τ further decreases, it is expected that E_r would be infinitely great. While for large values of σ/τ ($\sigma/\tau > 0.024$), the trend of E_r decreased slightly. We used three different functions to fit the relationship between erosion rate (E_r) and the ratio of tensile strength (σ) to bed shear stress (τ). As can be seen from the graph, the linear relationship has the lowest fitting goodness, with $R^2 = 0.608$; the exponential relationship has the next best fitting goodness, with $R^2 = 0.915$, and the piecewise linear function has the highest fitting goodness, with $R^2 = 0.952$. The expression for the piecewise fitting curve is as follows:

$$\begin{cases} E_r = -0.24881\sigma/\tau + 0.00972 \ x \leq 0.024 \\ E_r = -0.01903\sigma/\tau + 0.00418 \ x > 0.024 \end{cases} \tag{1}$$

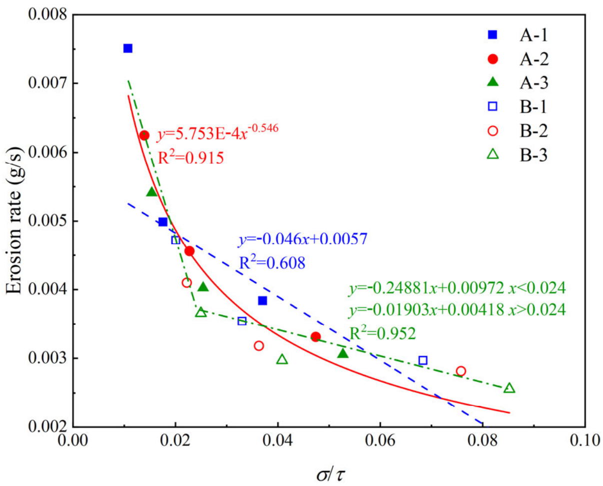


Figure 10. The erosion rate against the ratio of tensile strength to bed shear stress.

This study quantitatively identified the relationship between the scour erosion rate of bedrock at the Xiaonanhai site and the tensile strength of the bedrock versus riverbed shear stress by introducing Equation (1), which had not been discovered previously. With this formula, it is possible to assess the bedrock scour erosion rate after collecting data on flow and bedrock.

4. Discussion

In the field, bedrock is subject to a variety of factors, including rock type, climatic conditions, topography, and erosion. Conditions such as natural exposure or submersion in water can lead to changes in the physical and chemical properties of bedrock, which in turn affect riverbed erosion and landscape evolution. This paper quantitatively analyzes the basic physical properties of different types of bedrock at the Xiaonanhai site under various natural conditions. The physical properties of various types of bedrock change under the set conditions, with alternating wet and dry conditions being the most unfavorable for maintaining the physical properties of the rock mass, followed by submersion, and the most favorable being natural exposure. Under conditions of natural exposure, submersion, and alternating wet and dry, there is a decrease in the tensile strength of rock blocks, with the greatest decrease observed in the bedrock under alternating wet and dry conditions. The degree of reduction in shear strength parameters of the rock mass is the smallest under natural exposure, followed by submersion, with alternating wet and dry cycles being the most unfavorable for maintaining the shear strength parameters of the rock mass [17–19].

Research on bedrock scour is still in the exploratory stage, and engineers do not have precise calculation formulas and theories to determine whether to line the diversion bedrock. The assessment of scour hazards still primarily relies on personal experience and engineering analogy. Due to the lack of research in this area, some bedrock with good rock conditions that do not require reinforcement have nonetheless undergone extensive reinforcement and lining measures, wasting a significant amount of manpower, material resources, and financial resources without achieving good engineering results. On the other hand, if the bedrock does have the potential to suffer severe scour, it could lead to safety accidents during construction. The evaluation of bedrock scour erosion rates requires the quantification of bedrock characteristics and the hydrodynamic process. Therefore, existing theoretical methods are insufficient to describe the relationship between bedrock erosion rates and hydraulic action. Sklar and Dietrich [20] developed an experimental bedrock abrasion mill, aimed at replicating the small-scale interaction between coarse bed load and the rocky riverbed in active cutting channels. Hsu et al. [16] placed granular material in a rotating drum with a diameter of 56 cm to explore the relationship between erosion of synthetic bedrock samples and variables such as particle size, shear rate, water content, and bed strength [21]. These valuable experiments have helped inspire the current work, but they are limited to cases of one-dimensional average inertial stress values and single grain size flows. Chatanantavet and Parker [22] conducted experiments in an inclined flume that more closely matched actual field conditions, but the bedrock samples used were not natural but made from a mixture of sand, cement, and vermiculite. More importantly, previous experiments have mainly focused on abrasive scour [23], and the process of bedrock erosion caused by water flow in natural environments is not well explored.

This study addresses the challenges encountered in open-channel hydraulic bedrock scour tests by developing a model test device that considers hydraulic scour. The model device can maintain constant high-speed flow conditions for extended periods and has the advantages of a simple structure and convenient testing, providing effective technical support for bedrock erosion research. Using this device, we conducted experimental research on the initiation scour and scour erosion of bedrock at the Xiaonanhai site, comprehensively analyzed and determined the anti-scour characteristics of various prototype bedrocks, and quantitatively identified the relationship between the anti-scour velocities, scour erosion rates, and the tensile strength of the bedrock and riverbed shear stress at different types of bedrock at the Xiaonanhai site. Studies by Hsu et al. [16] and Stein and Nett [24] found that the bedrock erosion rate increases with the increase in shear rate applied by the water flow and decreases with the increase in the tensile strength of the bedrock, but the relationship between the bedrock erosion rate and the tensile strength and riverbed shear stress has not been clarified. This research provides the relationship between the three, allowing for the prediction of bedrock scour erosion rates after collecting data on flow rates, water flow, and bedrock.

Additionally, an insufficient number of experimental groups may weaken the explanatory power of the experiment and increase the risk of unexpected variables affecting the results. The purpose of the experimental research in this paper is to reveal the anti-scour characteristics and scour erosion rates of prototype bedrock. Before conducting this experiment, we performed multiple pre-experiments and finally selected these typical operating conditions for the test to illustrate the experimental phenomena and conduct comparative analysis. Moreover, during the test, multiple runs on the same sample were conducted to test for repeatability and avoid experimental errors. The flume tests used prototype bedrock, and the hydrodynamic characteristics revealed by the research, such as flow velocity, Reynolds number, and Froude number, are instructive for natural geological environments.

5. Conclusions

This study conducted anti-scour tests on bedrock by developing a model test device, using bedrock from the Xiaonanhai site in the upper reaches of the Yangtze River as the test samples, and quantitatively researched the basic physical properties, incipient scour velocity, and scour erosion rates of different types of bedrock. The study found that under natural exposure, submerged immersion, and alternating wet and dry conditions, the bedrock showed a trend of reduced tensile strength, with the alternating wet and dry conditions during flood seasons being the most unfavorable for maintaining the physical properties of the rock mass. The anti-scour velocities of silty claystone and clayey siltstone samples increased with the increase in tensile strength, and the feldspathic debris sandstone had the highest tensile strength, with its anti-scour velocity also being relatively high, all exceeding 7 m/s. The scour erosion rate of the bedrock increased with the increase in shear stress; if the shear stress remained constant, the erosion rate decreased with the increase in tensile strength. The scour erosion rate was inversely proportional to the ratio of the bedrock's tensile strength to riverbed shear stress, and the fitting relationship showed a piecewise linear distribution. Through the research of this paper, the results can predict the scour erosion state of bedrock in natural open channels and provide theoretical guidance for engineering lining.

Author Contributions: Conceptualization, Z.L. and Y.W.; methodology, Z.L. and S.Y.; validation, Y.W. and S.Y.; formal analysis, Z.H.; investigation, Z.L.; resources, Z.L.; data curation, Z.J.; writing—original draft preparation, Z.L. and Y.W.; writing—review and editing, S.Y. and Z.J.; funding acquisition, Z.L. and Y.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Natural Science Foundation of China (52479058, 52239007, U2240226, 52409082), the Central Public-Interest Scientific Institution Basal Research Fund (CKSF20241011/HL, CKSG2024985/HL).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are available upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

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