

Article

Seepage Characteristics and Failure Prediction during the Complete Stress–Strain Process of Limestone under High Water Pressure

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Abstract: The seepage characteristics during the complete stress–strain process of limestone under high water pressure were simulated via an experimental study of limestone post-peak penetrating behavior, and an approach to predict the formation of the seepage channel, namely, acoustic emission positioning technology, is proposed. The results showed that (1) whether in the experiment or in the numerical simulation, the sudden drop in the stress–strain curve after peaking indicated the full formation of shear fractures and seepage paths. (2) By using acoustic emission positioning technology in the simulation, the entire stress–strain process of limestone, from microfracture initiation and compaction to transfixion, could be monitored to observe the dynamic and real-time development of the microfractures. (3) The combination of acoustic emission technology with seepage monitoring revealed the real-time location and growth direction of micro ruptures and predicted the depth of penetration. The developed approach can improve forecast accuracy for landslides involving a low-permeability rock mass with cracks. In this study, limestone post-peak seepage characteristics were analyzed, and a method to forecast the formation of rock seepage paths before transfixion is provided. This work could provide a reference and guiding elements for ensuring the safety of slopes with high internal water pressure.

Keywords: fractured limestone; hypertonic pressure; complete stress–strain process; permeability characteristics; acoustic emission; damage prediction



Citation: Bao, C.; Yin, Y.; Tang, S.; Jiang, A.; Li, H. Seepage Characteristics and Failure Prediction during the Complete Stress–Strain Process of Limestone under High Water Pressure. *Appl. Sci.* **2022**, *12*, 6041. <https://doi.org/10.3390/app12126041>

Academic Editor: Muhammad Junaid Munir

Received: 6 May 2022

Accepted: 10 June 2022

Published: 14 June 2022

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1. Introduction

Energy shortage is one of the bottlenecks that restrict national economic development. China ranks first in the world in terms of water resources, most of which are distributed in Southwestern Sichuan, Yunnan, and Tibet Provinces where the terrain is challenging. The construction of large and extra-large water conservancy and hydropower projects in these areas faces the stability problem of high and steep slopes, resulting in considerable personnel safety concerns and possible property losses [1]. Although the permeability of rock engineering slopes is low [2], such slopes have many joints and cracks that provide channels for water infiltration. In China, especially in slopes in the southern region, the existence of water reduces the effective stress and changes the saturation of the slopes, leading to instability of slopes subjected to engineering work.

Studying the seepage law of water in rocks is essential to analyze the influence of water on the stability of rock slopes. Since Darcy's law was put forward 150 years ago, researchers have achieved fruitful results in the study of rock seepage. Theoretical and experimental research results for single-fracture seepage under the condition of saturated seepage are abundant and include the influence of fracture surface geometry and extension

characteristics on the seepage law of fractures, the applicable conditions and correction of the seepage cubic theorem, and the change in the seepage characteristics and seepage law of fractures under deformation or load conditions [3–6]. Studies on the seepage characteristics and seepage movement of fractured rock mass have mainly adopted equivalent continuum, discrete network, and mixed models [7–12]. Many scholars [12–15] studied the evolution of the permeability characteristics of rock blocks in the process of deformation and progressive failure, and their results revealed a strong permeability scale effect. However, due to the complexity of rock structures and the differences in physical experimental conditions and environments, the test results are not generalizable and thus are limited. Effective geophysical research methods must be developed to study the influence of slope rock mass damage and fracture on rock mass permeability in the process of rock mass excavation and loading [16].

Rock permeability has two components [17]. One is the permeability of the primary pores and cracks in rocks, and the other is the permeability change caused by rock failure. Experimental and numerical research on the permeability of primary pores and cracks in rocks is extensive, but studies on the entire process of permeability change caused by rock failure are relatively scarce. Li Shiping [13] conducted many sandstone total stress–strain–permeability experiments and obtained the rock permeability–strain relationship equation. This article mainly studied the influence of the stress level on rock permeability and the permeability–strain equation of rock. It studied the permeability characteristics of fractured limestone under high osmotic pressure (>1 MPa). A method combining acoustic emission location with seepage measurement was proposed to determine the formation of seepage channel. Yang Tianhong et al. [18] studied the relationship between rock permeability and damage evolution (fracture) from the perspective of seepage–stress–damage coupling by using a numerical method. Although these studies deepened our understanding of the effect of rock fracture on rock permeability, most of them focused on rocks with good permeability (e.g., sandstone), whereas minimal attention has been devoted to rocks with low permeability [19] (e.g., limestone and granite). Rocks with low permeability are difficult to observe at the initial stage of loading. Only when a rock is cracked under a load and broken through will permeability increase sharply, which is extremely unfavorable to the stability of the slope. Given that the seepage and failure processes of rocks are time-dependent, studying the seepage characteristics of rocks in relation to time and fracture is also essential. Such investigations can improve stability and rock slope predictions by identifying the seepage characteristics of low-permeability rocks during the fracture process.

In this study, a non-Darcy steady-state seepage test was conducted on limestone samples after the peak by using the triaxial seepage test system produced by TOP INDUSTRIE Company in France. The relationship between the seepage velocity and pressure gradient and the curve of axial strain and water head pressure under different hydrostatic pressures after the peak were obtained, and regular results were achieved. Unlike in the numerical test method, in the physical test method, the specimen is wrapped in a closed cylinder. The entire failure process of the specimen cannot be observed, and even the occurrence of failure cannot be judged by the naked eye. Therefore, this study used a special numerical simulation method to establish a plane model of non-uniform rock sample seepage, and the whole failure process was investigated from the meso perspective. The specific research contents are as follows. (1) Limestone is dense in texture, and its permeability is mainly fracture permeability. Therefore, prefabricated weak surface and prefabricated weak zone models were adopted in the current study, and the seepage channel was formed by axial loading. The stress state change of the rock samples and the evolution law of permeability in the process of damage and failure under high osmotic pressure were studied. The analysis focused on the variation of the stress–strain–permeability coefficient during the whole process and of the permeability law during crack initiation, propagation, and coalescence. (2) The prefabricated weak surface was similar to the crack formed by artificial splitting, so the biting effect of the crack surface was worse than that of the natural crack,

and the roughness and fluctuation of the natural crack surface could not be effectively simulated. Therefore, the shear crack formed by the force of the complete model was also regarded as the seepage channel to simulate the permeability characteristics of the natural crack. (3) Rock as a brittle material exhibits the acoustic emission phenomenon during its failure process. The failure of rock samples can be predicted by monitoring and collecting acoustic emission information during the failure process. By collecting acoustic emission information during the failure process of the three models mentioned above, the failure and seepage catastrophe of the samples in this study were predicted. (4) Through numerical simulation, the whole stress process, micro-fracture distribution, crack development direction, and permeability of the rock samples were revealed to vividly and concretely reflect the crack situation. The results can provide a reference for the real-time control and prevention of accidents.

2. Calculation Method of Seepage Velocity in the Rock Total Stress–Strain Process

The key task in rock seepage–stress coupling is to study the variation in the permeability coefficient during deformation and failure. Experimental studies play an irreplaceable role in examining the seepage characteristics of rock fractures. Limestone is dense in texture and it is permeable mainly in cracks [20]. Permeability changes in limestone specimens during deformation are directly caused by the initiation, opening, and connection of cracks [21].

Many studies have shown that for a fractured rock mass, the coupling of stress and seepage fields is based on the fluid–solid coupling problem of a single fracture. The cubic law is the basis for studying the seepage of a single fracture [22]. When a fractured surface exists in a completely impervious rock mass, it is completely parallel and smooth. Poiseuille derived the theoretical formula of fluid motion in a smooth parallel plate gap under the condition of homogeneous constant motion for a viscous incompressible fluid, as follows [23]:

$$u = \frac{gb^2}{12v} J \text{ or } q = \frac{gb^3}{12v} J \quad (1)$$

where u is the average velocity (m/s) of the fluid in a fracture with opening b , g is the gravitational acceleration (m/s^2), v is the viscous coefficient of fluid motion, J is the hydraulic gradient, and q is the flow rate (m^2/s).

He Yulong et al. [24], applied the cubic criterion to rock fracture seepage and found that it is effective, as shown in Figure 1. In the implementation process of this test scheme, when the water pressure difference between the two ends of the rock sample is large, the fissure water pressure causes additional deformation of the rock surface on both sides of the fissure runoff, which increases the width of the fissure. Hence, the cubic criterion is still valid for open rough joints. The following formula is used to calculate seepage velocity:

$$u = \frac{Q}{A} \quad (2)$$

where u is the seepage velocity, Q is the flow, and A is the cross-sectional area of the specimen.

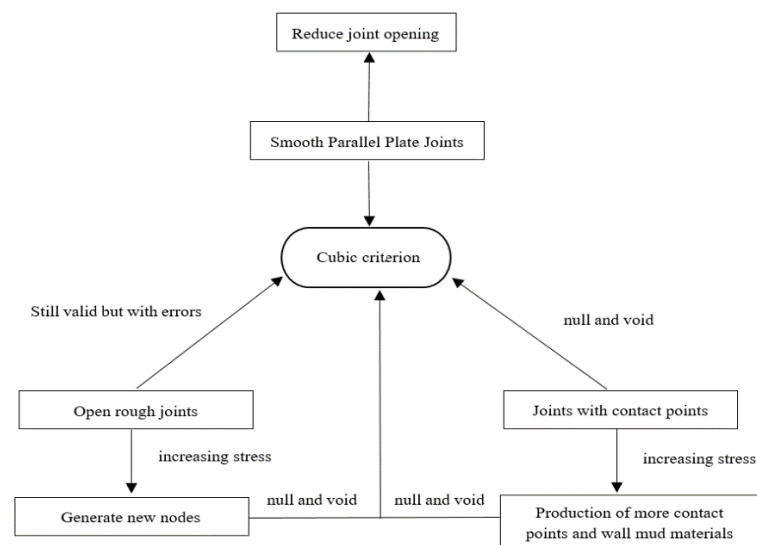


Figure 1. Validity of the cubic law for different fractured joints.

3. Brief Introduction to the Physical Test for Limestone Specimens

3.1. Test System and Procedures (The Numerical Simulation Method Uses the FEM)

The triaxial rheological test system developed by Lille University of Science and Technology and produced by TOP INDUSTRIE Company in France (Figure 2) was used in this experiment. The test system has three independent loading devices for confining pressure, axial pressure, and pore water pressure. It has the following functions and characteristics. (1) The specially designed water pressure application system has a high flow rate and stable flow and pressure and can directly output up to 70 MPa of water pressure, thus meeting the requirements of the steady-state seepage test under high permeability pressure. (2) The specially designed fluorinated rubber sleeve ensures the complete isolation of pore water pressure and confining pressure. (3) The high confining pressure (up to 70 MPa) and high axial pressure (up to 100 MPa) can realize strain and stress loading control, and the control precision is ± 0.01 MPa. (4) Data collection is fully automatic.

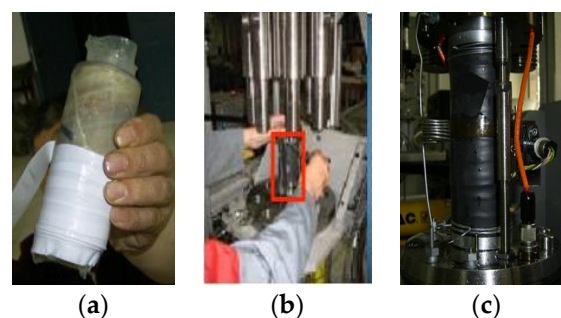


Figure 2. Experimental system and specimen installation. (a) Air exhaust. (b) Entering the loading room. (c) Installation specimen.

The specific test steps implemented in this study were as follows. First, a 2 MPa net confining pressure was applied to the rock sample, followed by axial displacement (0.05 mm/min). Second, a net confining pressure was applied, and stress control was implemented and maintained at 3 MPa. The first-order water pressure was 0.3 MPa (the classification standard is 1/10 points of the confining pressure at all levels) at the inlet, and the outlet was maintained at atmospheric pressure. Third, the first-order water pressure was maintained for a certain period. After the deformation of the specimen stabilized, the deformation of the specimen was recorded, and the seepage velocity and axial and circumferential strains were measured. Fourth, the next level of water pressure was applied.

After the application of all levels of water pressure under the net confining pressure of each level was completed, the second level of confining pressure and all water pressure levels under it were applied.

The deformation of rock mass under the action of stress and humidity includes the deformation ε_σ caused by stress and the deformation ε_{sh} caused by humidity; the total deformation is

$$\varepsilon_{sh} = \alpha_{sh} \Delta h = \alpha_{sh} h_0$$

In the formula α_{sh} is the contraction coefficient; h_0 is the initial relative humidity (100%).

When the relative humidity is higher than 50%, the relationship between the strain of rock mass and the variation of relative humidity can be approximately considered as linear:

$$\sigma = \lambda I_t \varepsilon + 2\mu \varepsilon - (3\lambda + 2\mu) + \varepsilon_{sh} I$$

In the formula. λ and μ are Latin constants, i.e., $\mu = \frac{E}{2(1+\nu)}$, $\lambda = \frac{2\nu\mu}{1-2\nu}$.

3.2. Test Results and Analysis

The test results showed that when the hydrostatic pressure was simulated by a 2 MPa net confining pressure, and 1 MPa seepage pressure was applied to the specimen under uniaxial loading, the failure of the specimen was manifested in shear cracks, which were closer to the natural cracks than those formed by artificial splitting (Figure 3). Owing to the limitation of the test methods, Darcy's law is generally used in tests of rock permeability. It requires the setting of a stable water pressure difference and seepage velocity, and the seepage velocity is converted by the amount of seepage water in a certain period. Given the limitation in the number of tests and the length of the article, the following shows only the test results for Specimen 2#. The stress–strain curve for Specimen 2# during uniaxial compression under hydrostatic pressure is shown in Figure 4a. The stress–strain curve began to decline after the peak value, and the amplitude was large. Given that the rock sample was located inside the instrument and could not be observed with the naked eye, the method for judging shear cracks was as follows. First, a sudden decrease in stress meant that the rock sample could be damaged. Second, because the limestone used in this study had a dense texture and poor permeability, the permeability of the intact rock block relative to the permeability of the fracture could be ignored. Therefore, in the axial loading process, the pore water pressure remained unchanged, and the outlet valve was opened. At this time, the amount of seepage water could be observed. When the outlet pore water pressure decreased then slowly increased, the shear fracture had penetrated; otherwise, the test failed.

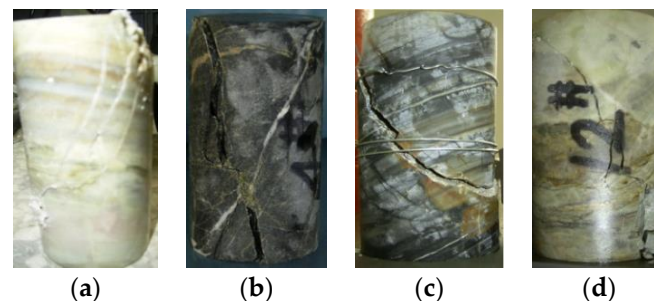


Figure 3. Shear damaged limestone samples. (a) 1# test specimen, (b) 4# test specimen, (c) 8# test specimen, (d) 12# test specimen.

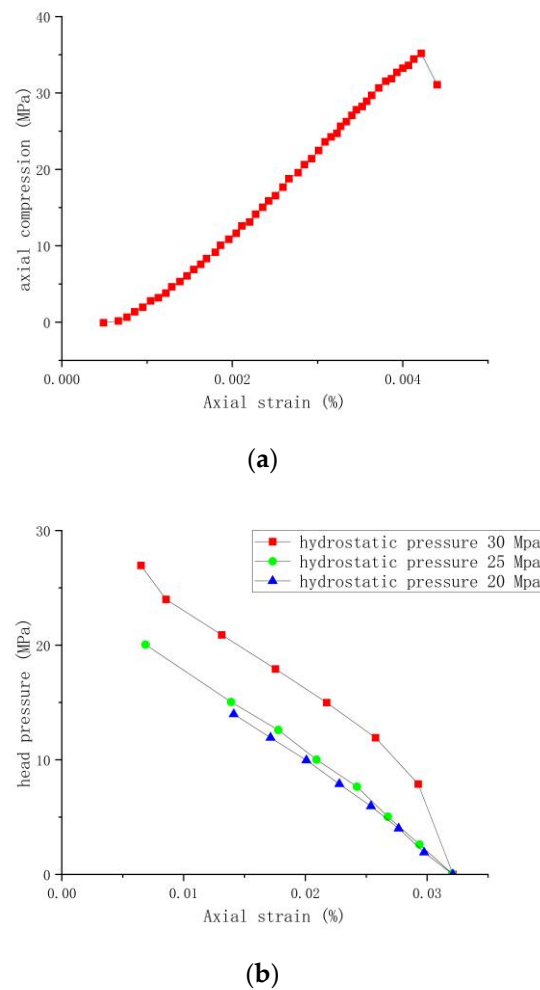


Figure 4. Experiment results for Sample 2#. (a) Stress–strain curve. (b) Post-peak strain–head pressure curve.

Figure 4b shows the experimental curve of axial strain and head pressure under different hydrostatic pressures after the peak. When the stress–strain reached its peak value, shear cracks were completely formed. With the further increase in the axial strain of limestone, the formed fracture pressure closed, the fracture width decreased, and the permeability decreased. This phenomenon can be seen in Figure 4b. Under the three hydrostatic pressures, the head pressure decreased with the increase in strain. Similarly, with the increase in hydrostatic pressure, the width of the cracks and the amount of seepage decreased. Moreover, under the three hydrostatic pressures, the strain and head pressure test curves of the specimens were basically consistent.

4. Numerical Simulation of Permeability in the Whole Process of Rock Fracture under High Permeability Pressure

4.1. Numerical Calculation Method and Numerical Model

The seepage–failure characteristics of limestone can be obtained from test results. However, due to the limitations of the physical test itself, observing the whole process of crack initiation and propagation in the specimen and revealing the flow process of water in the shear cracks are difficult. Therefore, this study used a numerical method to simulate the whole process of seepage–damage–failure of limestone. The sample size used in the numerical model was consistent with that adopted in the test, namely, $H \times W = 100 \text{ mm} \times 50 \text{ mm}$. The model was divided into 400×200 units, with pads at both ends. In this calculation, the permeability coefficient of the cushion plate was assumed to be larger than that of the sample so that the water could penetrate into the rock sample through

the cushion plate as soon as possible. The model size and loading are shown in Figure 5, Section 1-1. The mechanical parameters of the sample are shown in Table 1.

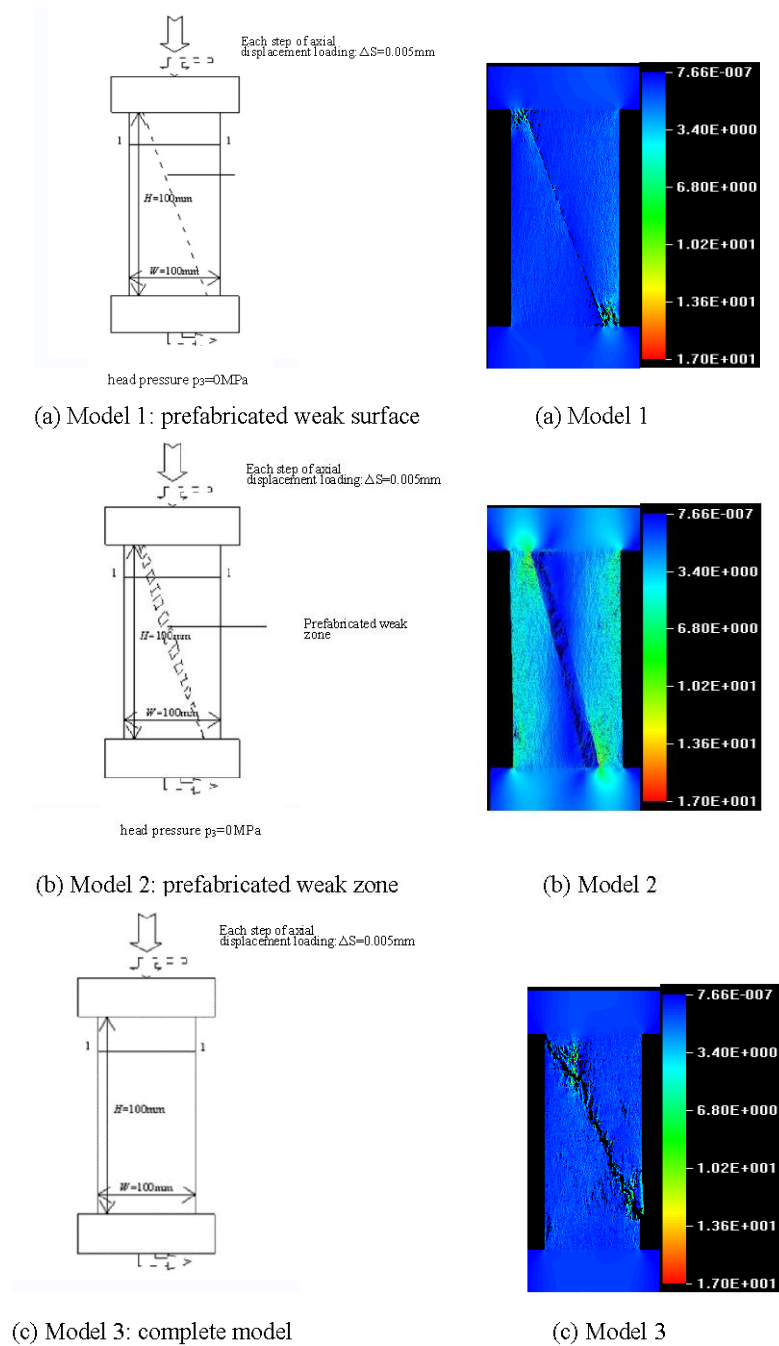


Figure 5. Loading diagram of the numerical simulation test and image of the model failure stress (MPa).

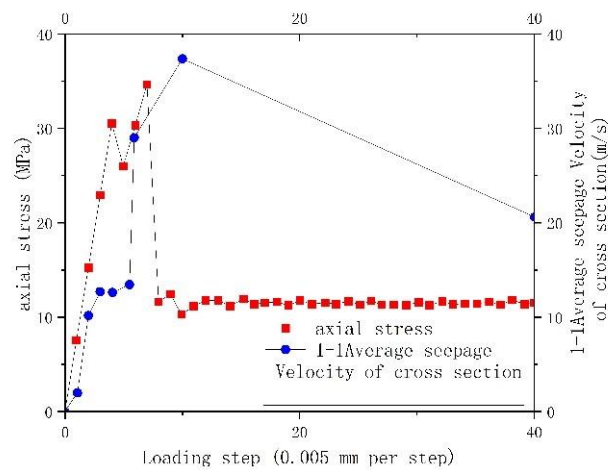
Table 1. Sample mechanical properties (average value).

	Parameter Name	Unit	Numerical Value
Parameters of the specimen (m = 2)	Mean elastic modulus E	MPa	50,000
	Intensity	MPa	100
	Poisson ratio μ		0.25
	Permeability coefficient	m/d	1.00×10^{-8}
Pad parameters (homogeneous)	Parameter Name	Unit	Numerical Value
	Mean elastic modulus E	MPa	150,000
	Intensity	MPa	300
	Poisson ratio μ		0.2
Prefabricated weak surface (weak zone) parameters (m = 3)	Parameter Name	Unit	Numerical Value
	Mean elastic modulus E	MPa	20,000
	Intensity	MPa	20
	Poisson ratio μ		0.25
	Permeability coefficient	m/d	1.00×10^{-8}

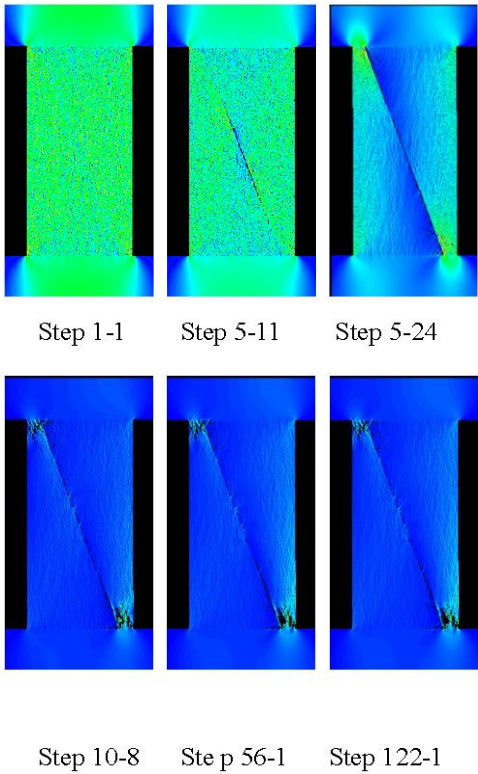
4.2. Evolution Law of the Permeability Coefficient in the Whole Process of Model Stress-Strain

The final failure modes of the prefabricated weak surface model (Model 1), prefabricated weak zone model (Model 2), and complete model (Model 3) are shown in Figure 6, and the stress–strain–permeability curves are shown in Figures 7a, 8a and 9a, respectively. Comparison of the post-peak curves in Figure 6a–c with those in Figures 7a, 8a and 9a indicated that when macroscopic shear cracks appeared in Models 1 and 3, the overall stress level decreased, and only the local area underwent high stress, which was due to the existence of some contact points in the shear failure zone. Both models had a certain shear slip after failure. However, the overall stress level of Model 2 did not decrease significantly because, although a shear failure zone formed in the weak area, the rocks on both sides of the failure zone were still intact and could continue to be loaded, and the model did not exhibit interlayer dislocation. Usually, sandstone has large pores high permeability. With axial displacement loading, the pores of sandstone closed. Therefore, the permeability coefficient began decreased slightly from the initial value at first. However, compared with sandstone, limestone has a dense texture, a small permeability coefficient, and almost no water permeability. Therefore, in accordance with the permeability characteristics of limestone, the permeability process of limestone can be divided into the following stages.

1. First stage: With axial displacement loading, some elements were destroyed because the load reached its failure strength. At this time, a micro-fracture occurred and formed a small seepage channel, and the permeability coefficient of the model increased.
2. Second stage: The axial displacement loading continued to increase. When the microcracks reached a certain number, the previous microcracks closed, and the permeability coefficient decreased slightly.
3. Third stage: With the increase in external load stress, failure occurred rapidly, and the cracks interconnected to form a shear failure zone. The penetrating cracks provided a favorable channel for seepage, and the permeability coefficient was greatly improved at this stage.
4. Fourth stage: The shear failure zone was gradually compacted under axial load, and the permeability coefficient decreased. This change in permeability coefficient could be clearly seen in both the experimental results (Figure 4b) and the numerical results. The prefabricated weak zone model (Figure 5b) was not compacted because the intact rock on both sides of the failure zone could continue to withstand the external load, and the decrease in the permeability coefficient was not obvious.



(a)



(b)

Figure 6. Cont.

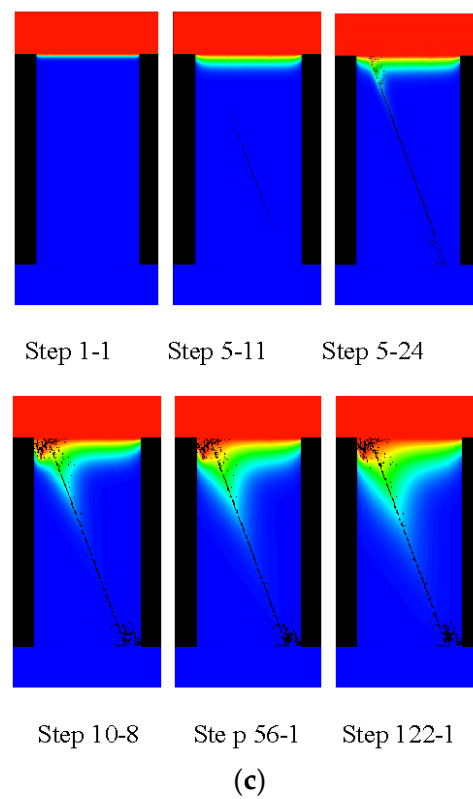


Figure 6. Numerical results of the cracked mode. (a) Whole process curve of load step-stress-permeability coefficient. (b) Stress results of the model failure process (MPa). (c) Results of water pressure distribution in the model failure process (m).

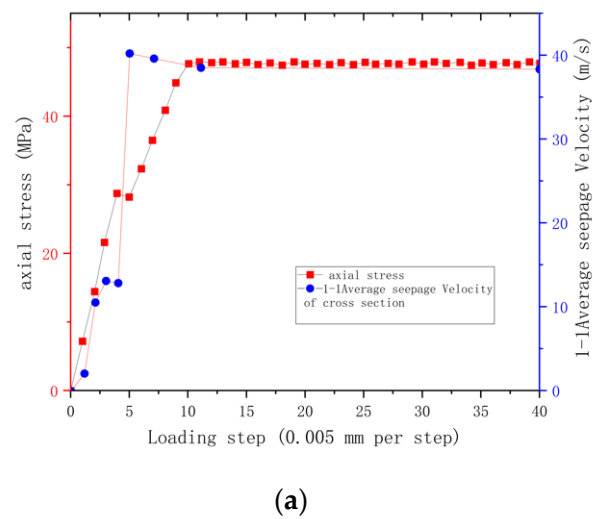


Figure 7. Cont.

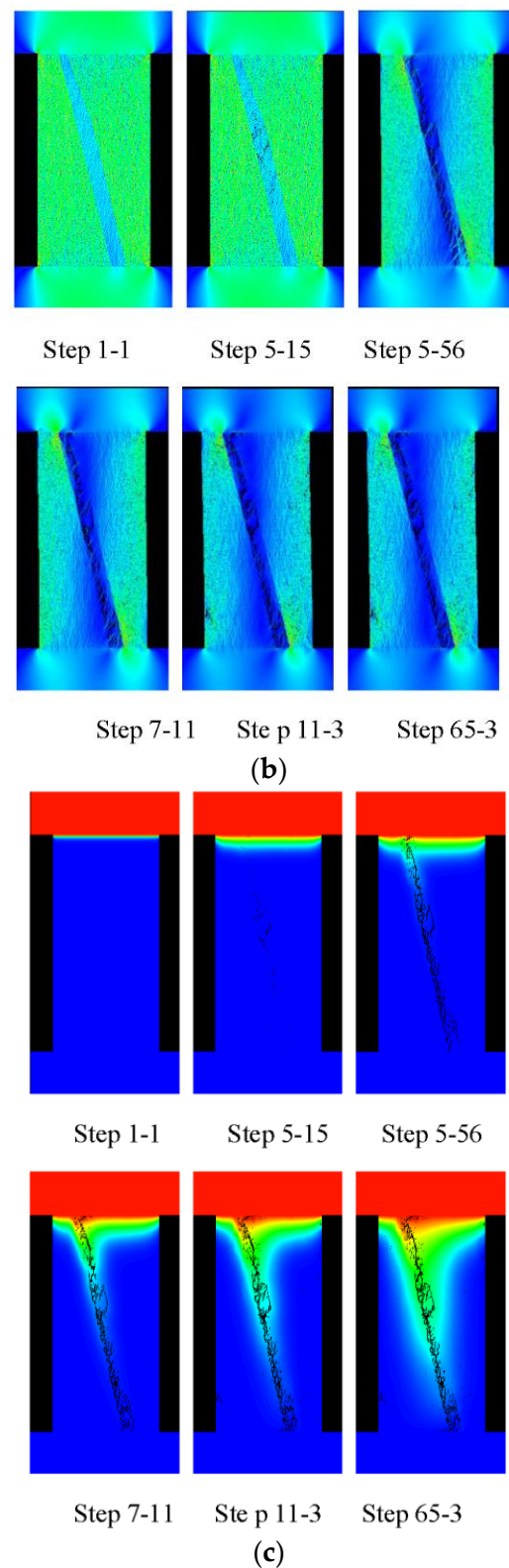


Figure 7. Numerical results of the model with a weak zone. (a) Whole process curve of load step-stress-permeability coefficient. (b) Presupposed weak zone model failure process stress results (MPa). (c) Results of water pressure distribution during crack formation (m).

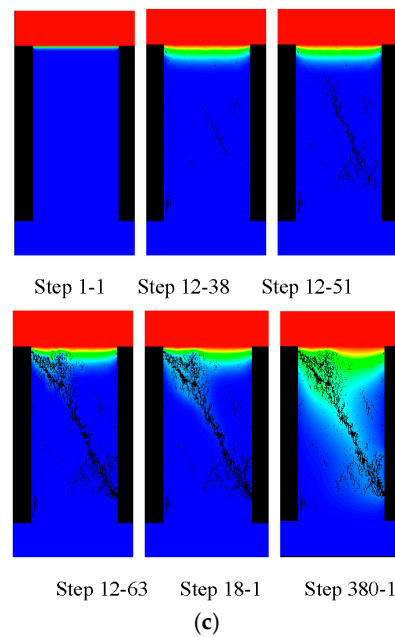
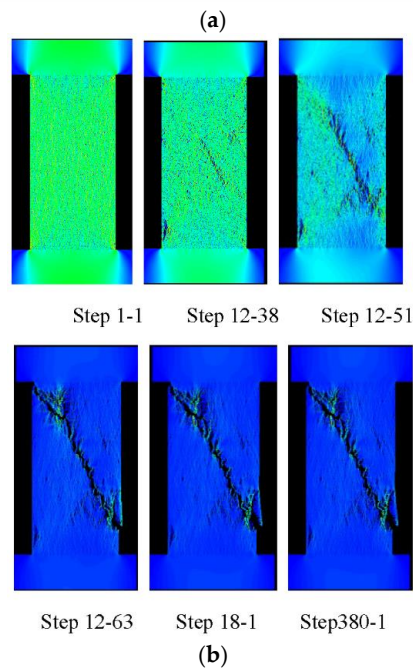
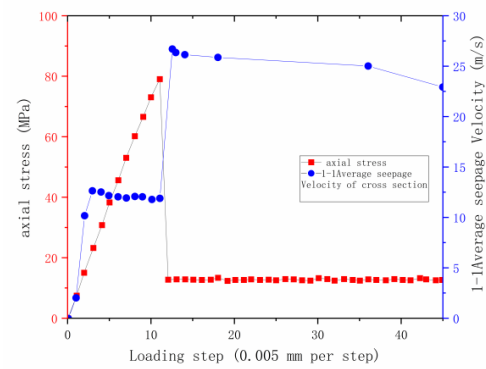


Figure 8. Numerical results for Sample 3. (a) Whole process curve of load step-stress-permeability coefficient. (b) Stress results for the intact specimen during the failure process (MPa). (c) Results of water pressure distribution during crack formation (m).

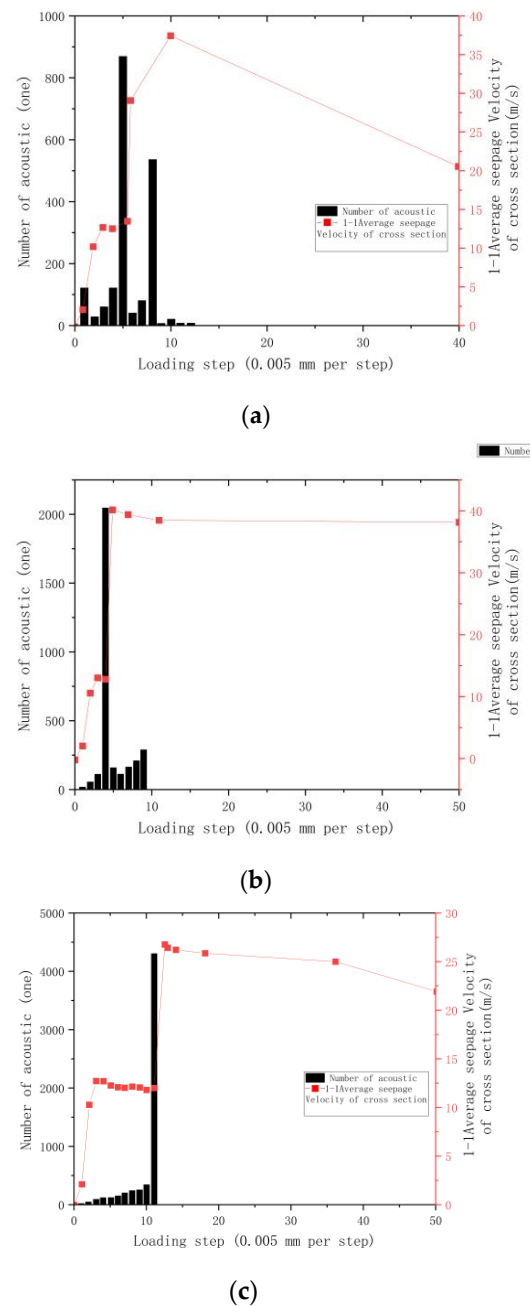


Figure 9. Numerical load step-stress-acoustic emission curve. (a) Prefabricated weak surface model. (b) Prefabricated weak zone model. (c) Complete model.

The four stages are shown in Figures 6a, 7a and 8a. With the increase in load step, the stress increased at the same time, a microfracture slowly initiated, and the permeability coefficient increased slowly from 0, which was the value at the first stage. As the load step continued to increase, the microfracture closed, and the step stage appeared, which was the second stage. After the step stage, the crack and permeability coefficient suddenly increased rapidly, which was the third stage. Then, due to the closed fracture permeability coefficient exhibiting a small decline, the fourth stage occurred.

Figures 6a and 8a indicate that the specimen slipped along the prefabricated joint surface, so the stress decreased sharply. The permeability coefficient increased sharply because the crack had penetrated. Figure 7a shows that no obvious stress drop process occurred, so the development of cracks could not be judged by the stress-strain curve. Figures 6b, 7b and 8b fully display the crack formation process, allowing our timely

understanding of where the crack extended, whether it went through, and when it went through, which were difficult to determine in the experiment. In addition, the water pressure distribution results in the process of model failure are illustrated in different colors in Figures 6c, 7c and 8c to reflect the occurrence of seepage. Red represents high water pressure, and blue represents low water pressure, that is, water permeated from top to bottom and was sealed around. These figures fully show the process of water flowing from top (high water pressure) to bottom (low water pressure) along the crack. The head pressure at the crack was the largest, and a certain water pressure distribution formed near the crack area. The area that the seepage could reach was limited due to the low permeability of limestone itself, and almost no water pressure was observed outside the crack.

The microfractures in Model 1 were concentrated near the prefabricated joints, so the width of the crack was small, and the water penetration rate was low. Loading to Step 122–1 (load step 122, step 1; when element failure occurred in each loading step, step-in-step cycle calculation was applied, but when no failure occurred in this step, the next loading step was initiated) could not fully penetrate the entire model (Figure 6c). Given that the microfractures in Model 2 (Figure 5b) were mainly distributed in the weak region, only a few microfractures occurred in the other regions, resulting in a wide seepage channel in the weak region and a high penetration rate. By Step 65–3 (Figure 7c), the water flow penetrated into almost the entire model height. The seepage velocity of the intact rock block model (Figure 5c) was relatively low because the crack formation time was long, and the microfracture had the characteristics of dispersion and disorder and was randomly distributed in the whole model. Therefore, loading at Step 18–1 (Figure 8c) did not penetrate into half of the height of the model.

Figures 6a, 7a and 8a show that the seepage velocity of Model 2 was the largest, followed by those of Models 1 and 3 (the smallest). The reason was that the joints and weak zones of Model 1 and 2 connected the high water head area at the top, and water could easily pass through this area. The weak zone of Model 2 was wider than that of Model 1, and the permeability was stronger. This is the reason why the seepage velocity of Model 2 was larger than that of Model 1. The new cracks in Model 3 did not penetrate the upper and lower interfaces, and no effective seepage channel connecting the high water head area was formed. Water could only penetrate the cracks from the high water pressure through the microfracture and then through the cracks.

For the complete model and the prefabricated weak surface model, the stress sudden drop method can be used to determine whether a model seepage channel is formed. However, this method does not allow judging whether a seepage channel is formed in the prefabricated weak zone model. The prefabricated weak zone model can only judge whether the seepage channel is formed based on the results of the water pressure distribution. Given that the results of water pressure distribution in physical experiments cannot be vividly displayed as in numerical calculation, the seepage channel must be judged through other means.

4.3. Prediction of Rock Permeability during Crack Propagation

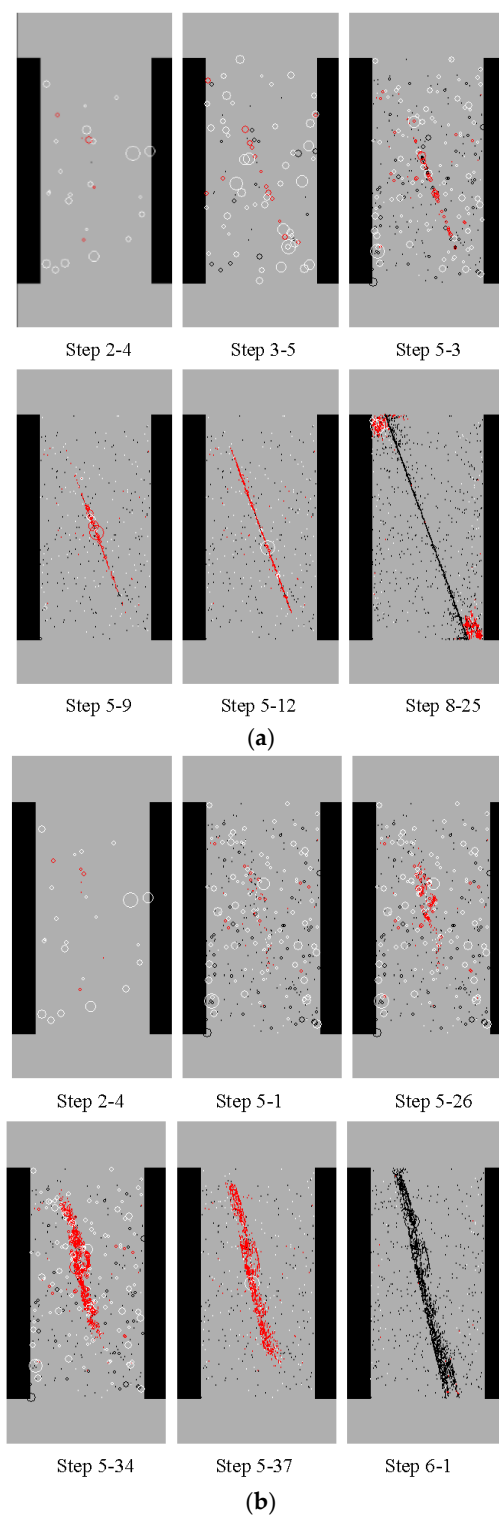
The analysis of the stress–strain–permeability curve revealed that the failure and seepage of the model could be judged by the stress drop. However, with hysteresis, passivity, and failure, predicting the catastrophic failure of the model was impossible. In fact, if the microfracture of the model is located and monitored, and crack coalescence is identified before microfracture coalescence, then crack coalescence and catastrophic seepage can be prevented effectively. When rock micro-fracture occurs under load, some strain energy is released in the form of elastic waves. These elastic waves can be monitored by the acoustic emission technology. Acoustic emission positioning technology is used to determine the location, time of occurrence, and strength of microfractures. In this way, we can analyze the mechanical behavior of the rock fracture process in terms of time, space, and strength and understand the defects of the current medium, both of which are crucial to obtain information about the precursors of the main fracture. Collection and analysis

of the data obtained through the numerical model of acoustic emission (AE) monitoring showed that AE can effectively reflect a microfracture and that dense limestone materials mainly show permeability in the cracks. Therefore, if the development of cracks can be effectively predicted, then the occurrence of seepage can be effectively controlled. The underlying specific principle has been explained in [25].

Figure 9 shows the load step–stress–acoustic emission curve of the three models. With loading, the AE number increased slowly. Before the seepage velocity increased, AE suddenly occurred, and the permeability coefficient increased significantly. The relationship curve in Figure 10 indicates that AE showed certain advantages when judging the seepage characteristics. The AE location information in Figure 10 can well reflect the occurrence and penetration of microfractures and predict the permeability characteristics. In Figure 10, a circle represents an AE event. The size of the circle refers to the relative energy of AE. The white circle represents compressive failure, the red one represents shear failure, and the black one represents a historical AE event. Under axial load, oblique cracks were produced along the direction of the prefabricated weak plane in the prefabricated weak plane model, which was predictable. This phenomenon can also be seen clearly from the AE location information in Figure 10a. At Step 2–4, the model mainly exhibited minimal pressure damage, randomly distributed throughout the model. By Step 3–5, the compressive failure was still randomly distributed in the whole model, but the red tensile failure had begun to concentrate along a certain line of the model (the direction of the prefabricated weak surface). By Step 5–3, the small tensile failures formed a shear failure zone. Nevertheless, the failure point did not penetrate the upper and lower parts of the specimen, so the water at the upper end could not penetrate into the specimen in a wide range. Seepage along the crack occurred only when the crack passed through the whole sample at Step 8–25. Model 2 was mainly destroyed along the prefabricated weak zone. Figure 10b shows the AE location information of the prefabricated weak zone model. The AE distribution of the prefabricated weak zone model was basically consistent with that of the prefabricated weak surface model. At Step 5–37, the crack penetrated, and the microfractures were mainly distributed along the prefabricated weak zone.

Comparison of Figure 10a,b showed that in the early stage of loading (Figure 10c), the microfractures of the model were randomly distributed throughout the model, and no obvious shear microfracture occurred until Step 12–30, during which some concentrated red damage points emerged in the middle. Once the macrocracks were produced, surrounding unit damage was quickly induced, especially rapid damage at both ends of the crack, and a penetrating crack formed, resulting in a shear failure zone. The failure diagram shows that the failure mode from the numerical calculation was consistent with the experimental result (Figure 4), and both showed a high-angle shear failure.

Figure 11 shows the distribution of the permeability coefficient of each element in the 1-1 section and the change with loading step during the loading process of the complete model. At Step 1, the permeability coefficient did not fluctuate much and followed an almost horizontal line. At Step 11, the permeability coefficient began to fluctuate around the horizontal line. At Step 12, a large amplitude peak emerged near the section element number of 30, which can be judged as a crack through the site. When loaded to Step 153, the fracture surface was contacted and compacted by the load, resulting in a decrease in permeability and seepage velocity at the peak position. This process is clearly reflected in the variation of seepage velocity in the 1-1 section in Figure 11.

**Figure 10.** *Cont.*

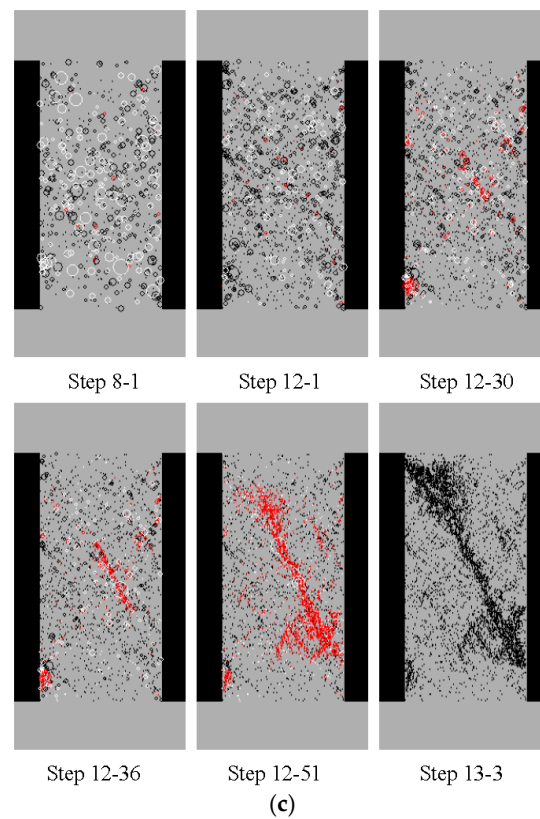


Figure 10. Numerical time distribution sequence of AE positioning in the sample loading process. (a) Acoustic emission results of Model 1's loading process. (b) Acoustic emission results of Model 2's loading process. (c) Acoustic emission results of Model 3's loading process.

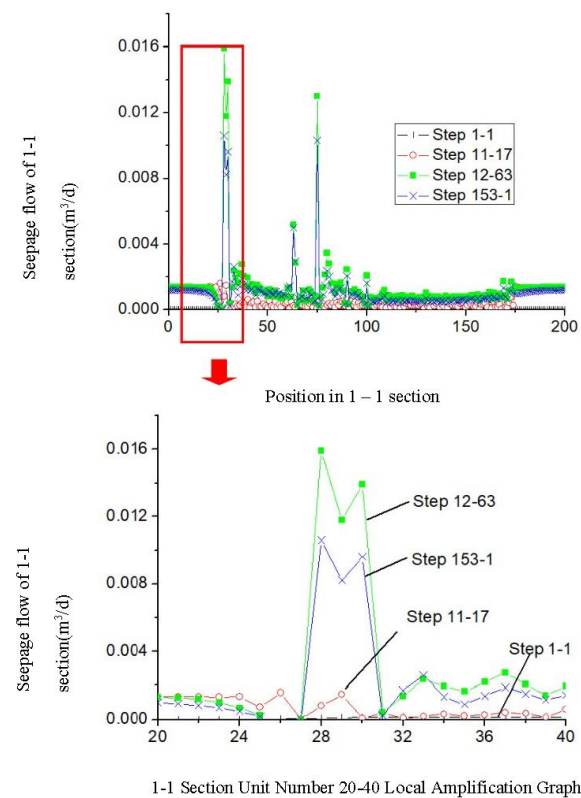


Figure 11. Numerical time distribution sequence of AE positioning in the specimen loading process.

The AE location information of the specimen loading process indicated that before the high osmotic pressure emerged, that is, before the crack went through, crack initiation underwent a process. Predicting the development direction of cracks by using the AE positioning method to monitor cracks is thus effective.

5. Discussion

In this paper, the seepage characteristics and the formation of seepage channels of limestone under high seepage pressure were studied through physical experiments and numerical simulation. Compared with previous studies, the rock permeability selected in this paper was low. Such rock seepage phenomenon is difficult to observe. Under the action of load, cracks were generated. When the cracks penetrated, the permeability increased sharply, which is extremely unfavorable to the slope safety. Finally, this paper puts forward a new idea to predict landslides by using acoustic emission to locate the position of micro cracks.

6. Conclusions

In this study, the post-peak limestone seepage test and numerical simulation were combined to study the seepage characteristics of limestone and the prediction method of seepage channel formation under high seepage pressure. The results showed that it is effective to judge the formation of the seepage channel based on the sudden stress drop for the complete model and prefabricated weak area model, but this method is invalid for the prefabricated weak area model.

In the three models in this study, the development of cracks began in the middle of the model, then developed toward both ends. At the beginning of crack initiation, no upward nor downward crack development was observed in the channel. However, as the loading continued, a crack developed toward both ends until, finally, it penetrated. Water was instantly squeezed into the seepage channel, and high osmotic pressure was generated instantaneously. This kind of sudden inflow of seepage exerts a destructive effect on slope stability and increases the difficulty of predicting catastrophic landslides with high seepage pressure.

The prediction accuracy for low-permeability jointed rock landslides can be improved to a certain extent by combining AE characteristics and seepage head changes. The AE location of microfractures in the model can reflect the location and development direction of microfractures in real time, and the seepage depth can be predicted by measuring the seepage head. If the AE location is combined with measured water head distribution results in practical engineering, then crack opening can be determined to effectively reflect and prevent crack propagation in real time. As a result, the main seepage channel will not run through, sudden seepage will not occur, and seepage pressure will not be transferred.

Author Contributions: Conceptualization, C.B. and S.T.; methodology, C.B.; software, RFPA; validation, C.B., S.T. and Y.Y.; formal analysis, A.J.; investigation, H.L.; resources, H.L.; data curation, C.B.; writing—original draft preparation, C.B.; writing—review and editing, Y.Y.; visualization, S.T.; supervision, H.L.; project administration, C.B.; funding acquisition, C.B. All authors have read and agreed to the published version of the manuscript.

Funding: NSFC-funded project (No. 51474046); National Natural Science Foundation of China—China Petroleum and Natural Gas Corporation Petrochemical Joint Fund Project (U1562103); Liaoning University Excellent Talents Support Project (LJQ2015076).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

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

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