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Research Article

A New Method of Seismic Source Parameter Estimation of a Locked-Segment Cracking Event

Bai-Cun Yang,[1] **Jian-Xin Bai**,[1] **Yong-Ting Duan**,[2,3] **and Cheng Cheng**[4,5]

[1]*School of Resources and Civil Engineering, Northeastern University, Shenyang 110819, China*
[2]*Key Laboratory of Ministry of Education on Safe Mining of Deep Metal Mines, School of Resources and Civil Engineering, Northeastern University, Shenyang 110819, China*
[3]*Key Laboratory of Liaoning Province on Deep Engineering and Intelligent Technology, Northeastern University, Shenyang 110819, China*
[4]*State Key Laboratory for Geomechanics and Deep Underground Engineering, China University of Mining and Technology, Xuzhou 221116, China*
[5]*School of Mechanics & Civil Engineering, China University of Mining and Technology, Xuzhou 221116, China*

Correspondence should be addressed to Bai-Cun Yang; yangbaicun@mail.neu.edu.cn

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Locked segments are widely present in the slip surface of large rock slopes and seismogenic faults of rock underground engineering. Each cracking occasion of the locked segment results in a seismic event. Accurate determination of the seismic source parameters of a locked-segment cracking event is crucial for the reliable evaluation of rock-mass stability associated with slopes and underground openings. The theoretical framework for calculating seismic source parameters in previous studies is mostly based on the stick-slip model, which is not applicable to describing the locked segment's damage process, and research on seismic source parameter estimation of a locked-segment cracking event is insufficient. Hence, based on the principle of energy conversion and distribution during the locked segment's damage process, we proposed an equation for the radiated seismic energy of a locked-segment cracking event. Using this equation, we established a mechanical relationship between the earthquake magnitude and the stress drop or shear strain increment (or maximum coseismic displacement) of a locked-segment cracking event. Typical case studies of rock slope and rock underground engineering showed that the proposed calculation method of seismic source parameters was reliable. In addition, this paper discusses the controversy surrounding the relationship between earthquake magnitude and stress drop. Relevant results lay a firm physical foundation to accurately calculate the seismic source parameters of a locked-segment cracking event and obtain detailed insights into the generation mechanism of the locked-segment cracking event.

1. Introduction

Many researchers [1–11] have recognized locked segments with high bearing capacity (determined both by scale and strength) and subjected to shear stress concentration, such as rock bridges, asperities, and blocks bound by faults, which are commonly found in the slip surface of large rock slopes and seismogenic faults of rock underground engineering (Figure 1). Cracking of the locked segment results in a seismic event, such as a slope-slip-induced earthquake (Figure 2) or a mining-induced earthquake [5, 10–14]. Therefore, estimating the seismic source parameters of such cracking events is essential and includes the radiated seismic energy (earthquake magnitude), stress drop, and slippage. A better understanding of these parameters will help assess rock-mass stability associated with slopes and underground openings.

The radiated seismic energy of a locked-segment cracking event, transmitted in the form of seismic waves, is a fundamental parameter when assessing the locked segment's size and source characteristics. To estimate this energy, many stud-

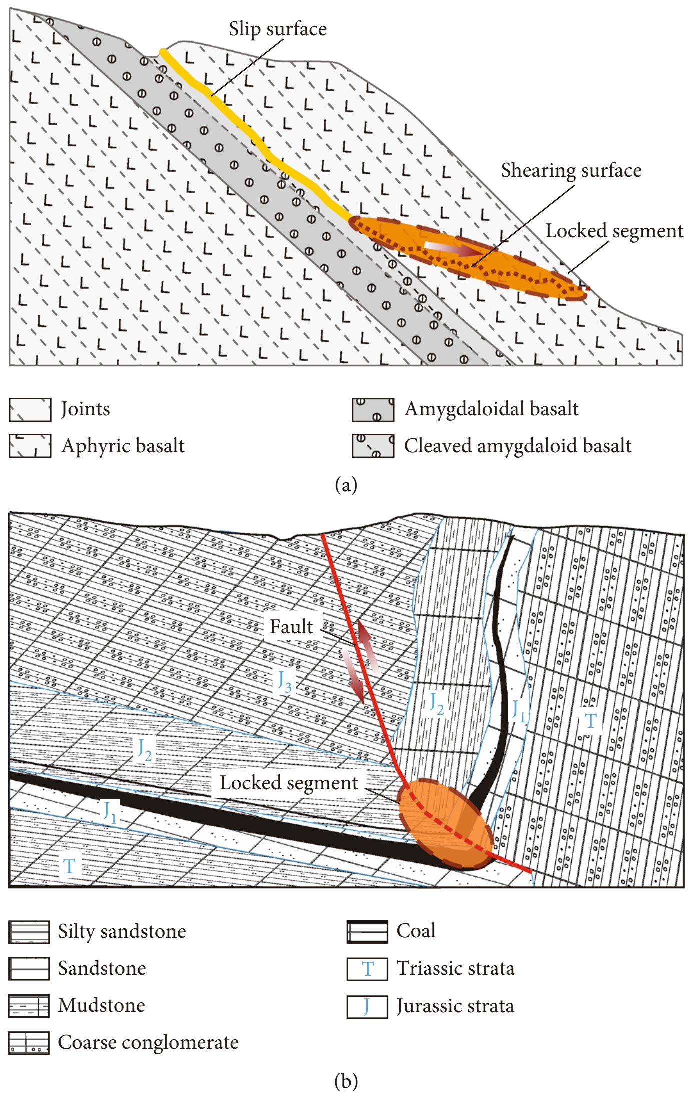

Figure 1: Conceptual model of locked segments in slip surface of rock slope (a) and seismogenic faults of rock underground engineering (b) (modified from Chen and Kong [15], Huang and Xu [16], Jiang et al. [17], and Song [18]).

ies have been conducted. For example, Savage and Wood [19] and Wyss and Molnar [20] presented an equation for the radiated seismic energy based on the theoretical framework of a stick-slip model. Kanamori [21] and Vassiliou and Kanamori [22] assumed that the average frictional stress equals the final stress to render the problem soluble. However, when the methods mentioned above were used in practical applications, especially in seismic source parameter estimation of the locked-segment cracking event, there was usually a significant error in the radiated seismic energy [13, 23]. This is due to the affected average frictional stress during the seismic rupture by many factors that cannot be treated as a constant. Moreover, the fracture surface energy produced by the cracking event is not considered in the previous methods. Rivera and Kanamori [24] presented an integral expression of radiated energy in finite faults, yet the formula is impractical due to its complex form. Anderson et al. [25] developed a self-consistent scaling model relating magnitude to surface rupture length, surface displacement, and rupture width for strike-slip faults and estimated the earthquake magnitude from the fault length and slip rate under the assumption of a constant stress drop. Zang et al. [26] obtained the seismic source parameters near the northeast margin of Qinghai-Tibet Plateau using the joint inversion method. They found that the ratio of the apparent stress to the stress drop is greater in an earthquake with a lower local magnitude, suggesting that the seismic rupture is more sufficient and the radiation energy is relatively small. As mentioned above, all the theoretical framework of these studies is based on the stick-slip model. However, some studies [4, 6, 13] show that the stick-slip model is not applicable in describing the damage evolution process of the locked segment. Unfortunately, there is little research on the seismic source parameter estimation of a locked-segment cracking event. Thus, it is crucial to propose a new method to estimate the seismic source parameters of the locked-segment cracking event.

Unlike previous studies, to accurately estimate the source parameters of a locked-segment cracking event, we focused

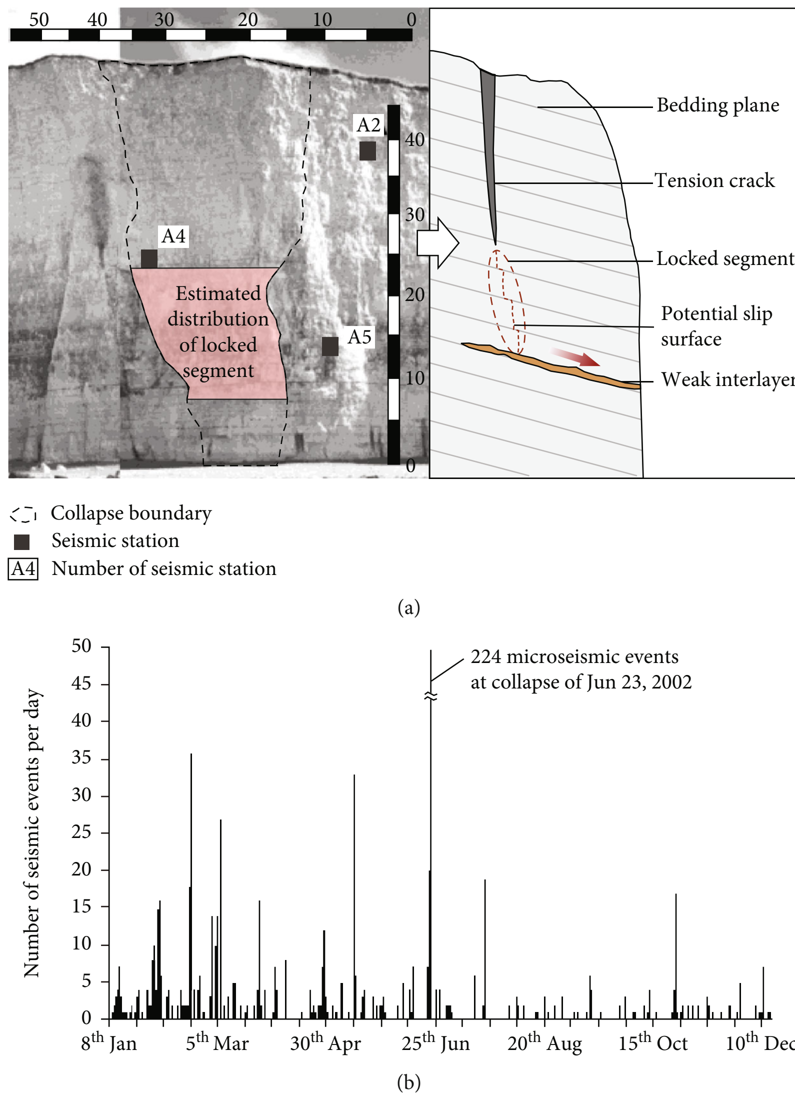

Figure 2: A rockcliff profile and its microseismic monitoring record at Mesnil-Val, Normandie, NW France (modified from Senfaute et al. [12]): (a) trailing-edge slip surface after collapse and diagram of inferred profile before the collapse; (b) microseismic time-series recorded by A4 seismic station.

on the damage evolution characteristics of the locked segment under loading. We first formulated the principle of energy conversion and distribution during the locked segment's damage process. Then, we proposed an equation for the radiated seismic energy of the locked-segment cracking event. Using this equation, we established a mechanical relationship linking the stress drop, shear strain, or maximum coseismic displacement with the earthquake magnitude for a locked-segment cracking event. Finally, we presented two typical case studies of rock slope and rock underground engineering to verify our proposed method.

2. Method for the Seismic Source Parameter Estimation

2.1. Principle of Energy Conversion and Distribution during a Locked Segment's Damage Process. Loads (such as self-weight stress, tectonic stress, and engineering disturbance) constantly provide elastic strain energy for deformation and failure of a locked segment. As the elastic strain energy stored in the locked segment accumulates to a certain extent, its damage initiates, which dissipates some elastic strain energy. When the applied stress reaches the locked segment's crack-initiation point, cracks propagate. Accompanying crack propagation is an inevitable drop in stress [13], as part of the elastic strain energy stored in the rock converts into dissipated energy, which mainly includes surface energy, friction-induced thermal energy, and radiated seismic energy (Figure 3).

According to Griffith's theory of crack propagation, crack propagation will stop when the driving force for crack propagation is equal to the crack propagation resistance. As illustrated in Figure 3, the crack starts to propagate when stress reaches point *C*, and a stress drop inevitably occurs. The mechanical effect or process of crack propagation leading to the stress drop is equivalent to the unloading of

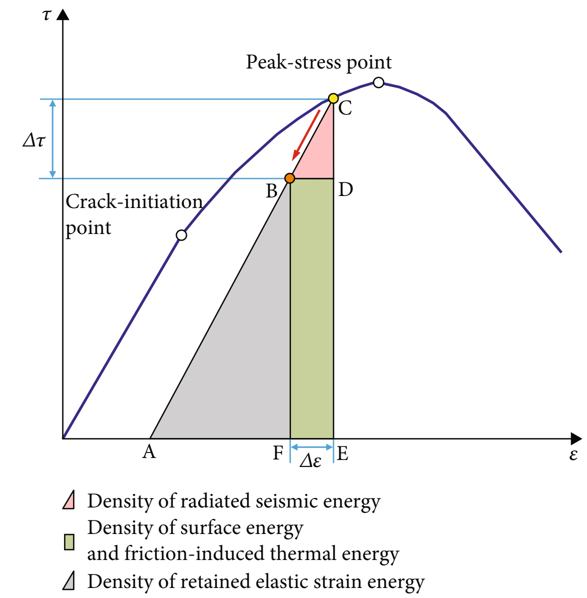

Figure 3: Conversion and distribution relationship of elastic strain energy density stored in a locked segment when a crack propagates (modified from Yang et al. [13]).

stressed rock along the CA path; when the stress drops to point B, an equilibrium between the resistance and the driving force is achieved, thereby the crack propagation is terminated. Based on the energy conservation principle, the elastic strain energy density stored in the locked segment before crack propagation ($S_{\Delta ACE}$) is equal to the sum of the elastic strain energy density ($S_{\Delta ABF}$, retained in the locked segment after crack propagation) and the dissipated energy density (S_{BCEF}, converted from the stored elastic strain energy). This S_{BCEF} is equal to the sum of the radiated seismic energy density ($S_{\Delta BCD}$) and the density of both surface energy and friction-induced thermal energy ($S_{\Delta BDEF}$).

Based on the theoretical framework mentioned above, the elastic strain energy density, dissipated energy density, and radiated seismic energy density during crack propagation can be calculated as follows [27]. The dissipated energy density during crack propagation can be calculated according to the measured stress drop (unloading stress path), initial stress before the stress drop, and final stress after the stress drop, and its value is equal to the trapezoidal area S_{BCEF} shown in Figure 3. The elastic strain energy density stored before crack propagation can be calculated according to the stress-strain curve and the measured unloading stress path, and its value is equal to the triangular area $S_{\Delta ACE}$ shown in Figure 3. The elastic strain energy density stored after crack propagation can be calculated using the difference between the elastic strain energy density stored before crack propagation and the dissipated energy density during crack propagation, which is equal to the triangular area $S_{\Delta ABF}$ shown in Figure 3. The radiated seismic energy density during crack propagation can be calculated according to the measured unloading stress path, initial stress before the stress drop, and final stress after the stress drop, and its value is equal to the triangular area $S_{\Delta BCD}$ shown in Figure 3. The calculation method of the energy conversion and distribution in a locked segment is given above, under the condition that the stress drop path is clear. The following calculation method of radiation seismic energy is proposed for the stress drop hardly obtained accurately.

2.2. Radiated Seismic Energy. Assuming that the strain in the locked segment is distributed uniformly, the unloading modulus is approximately equal to the shear elastic modulus [28, 29], and using the above-mentioned energy density relationship, we obtain the radiated seismic energy (E_r):

$$E_r = \frac{1}{2} V \Delta\tau \Delta\varepsilon = \frac{1}{2} G V \Delta\varepsilon^2 = \frac{1}{2} \frac{V \Delta\tau^2}{G}, \quad (1)$$

where V and G are the locked segment's volume and shear elastic modulus, respectively, and $\Delta\tau$ and $\Delta\varepsilon$ are the stress drop and corresponding shear (slip) strain increment, respectively.

According to Equation (1), the earthquake magnitude (radiated seismic energy) depends on the locked segment's volume, the shear elastic modulus, and stress drop or strain increment of the cracking event. As the volume and the shear elastic modulus of the same locked segment can be considered constants, the earthquake magnitude is only related to the stress drop or strain increment of the cracking event generated from the same locked segment. Compared with the previous studies [19, 22, 24], the earthquake magnitude, expressed by Equation (1), has a definite physical meaning and a simple form.

In general, a stronger locked segment corresponds to a larger shear elastic modulus [13]; therefore, the earthquake magnitude is positively correlated with the bearing capacity of the locked segment. Since the bearing capacity of a locked segment is much greater than that of a nonlocked segment (usually between the locked segment and soft medium), the earthquake magnitude of a locked-segment cracking event is generally much greater than that of a non-locked-segment cracking event. Therefore, when using the microseismic detection data to analyze the damage and fracture process of the locked segment in slope or underground engineering, the small cracking events (usually the non-locked-segment cracking events) should be excluded.

2.3. Relationships Linking Stress Drop and Shear Strain Increment or Maximum Coseismic Displacement with Earthquake Magnitude. In accordance with previous research [30–32], the relationship between earthquake magnitude (M) and the radiated seismic energy (E_r) can be expressed as

$$\lg E_r = 1.5M + C_M, \quad (2)$$

where C_M is a constant.

Substituting Equation (1) into Equation (2) yields

$$M = 1.33 \lg \Delta\tau + 0.67 \lg \frac{V}{G} - 0.67C_M - 0.2 = 1.33 \lg \Delta\tau + C_{\Delta\tau} \quad (3)$$

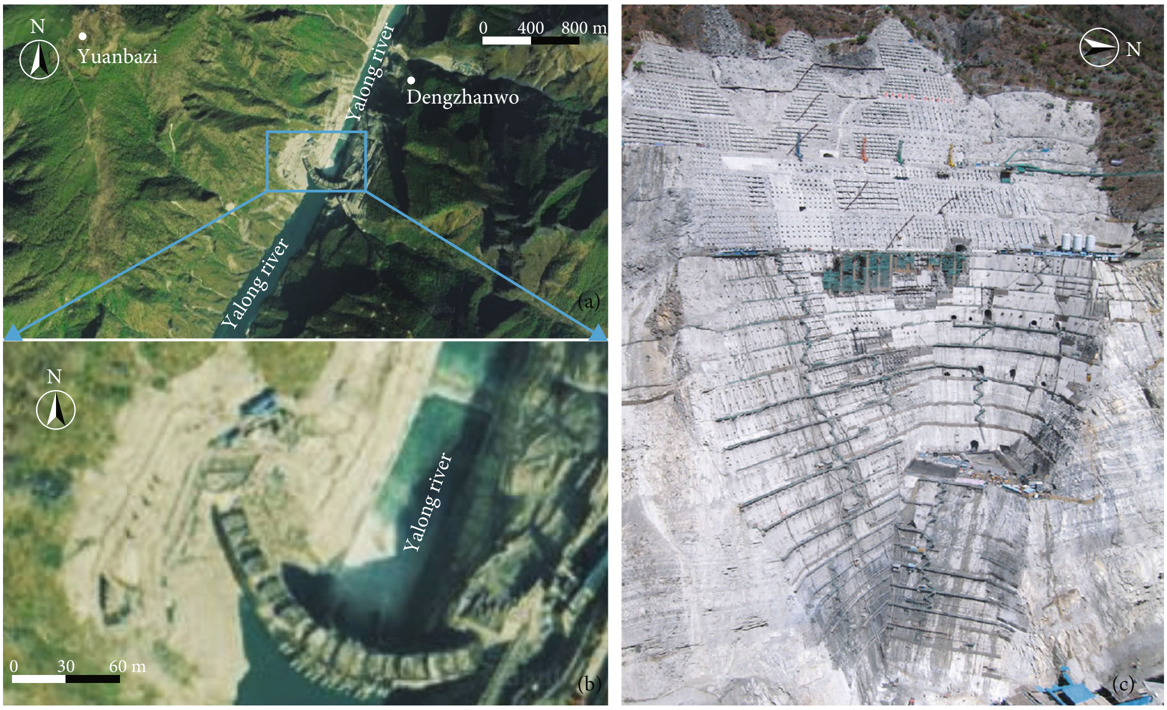

Figure 4: Overview pictures (captured from Google Earth) of the Jinping-1 dam site (a) and the left bank slope (b) and the photograph of the left bank slope after excavation (c) (modified from Xu et al. [36]).

Table 1: The source parameters of the twelve microseismic events that occurred along the key block.

Event number	Stress drop $\Delta\tau$ (Pa)	Moment magnitude M_W
1	$2.97E+04$	-3.3
2	$1.68E+05$	-2.2
3	$4.09E+05$	-1.8
4	$1.15E+05$	-2.0
5	$1.09E+05$	-2.2
6	$1.40E+05$	-1.9
7	$5.75E+05$	-1.1
8	$2.21E+05$	-1.8
9	$1.11E+05$	-2.0
10	$1.68E+05$	-2.6
11	$4.25E+05$	-1.6
12	$3.65E+05$	-1.7

or

$$M = 1.33 \lg \Delta\varepsilon + 0.67 \lg GV - 0.67 C_M - 0.2 = 1.33 \lg \Delta\varepsilon + C_{\Delta\varepsilon}, \quad (4)$$

where $C_{\Delta\tau}$ and $C_{\Delta\varepsilon}$ are two constants for the cracking events of the same locked segment.

Alternatively, by substituting shear strain increment for maximum coseismic displacement (D) in Equation (4), we can get the mechanical relationship between the earthquake magnitude and maximum coseismic displacement of a locked-segment cracking event as

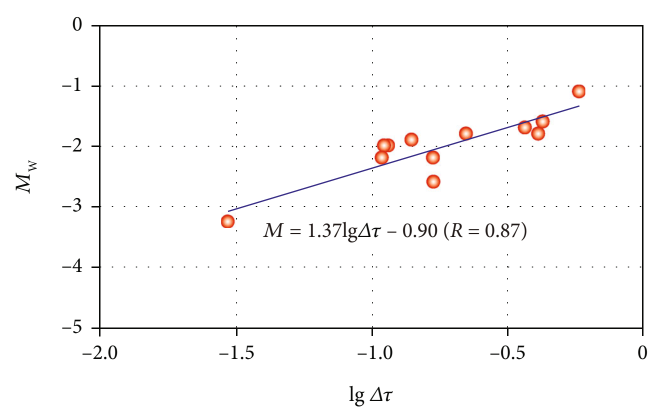

Figure 5: Relationship between the stress drop and the earthquake magnitude of the left bank slope of the Jinping-1 hydropower station. Red dots represent the twelve microseismic events that occurred along the locked segment.

$$M = \mathbf{1.33} \lg D + C_D, \quad (5)$$

where C_D is a constant. Note that when using Equations (3)–(5) to estimate seismic source parameters of a locked-segment cracking event, the various magnitudes (such as local magnitude M_L, surface-wave magnitude M_S, and moment magnitude M_W) should be transformed into a uniform scale (usually is the moment magnitude M_W). Equations (3)–(5), though similar in the form to previous empirical relations [33, 34], are established on a firm

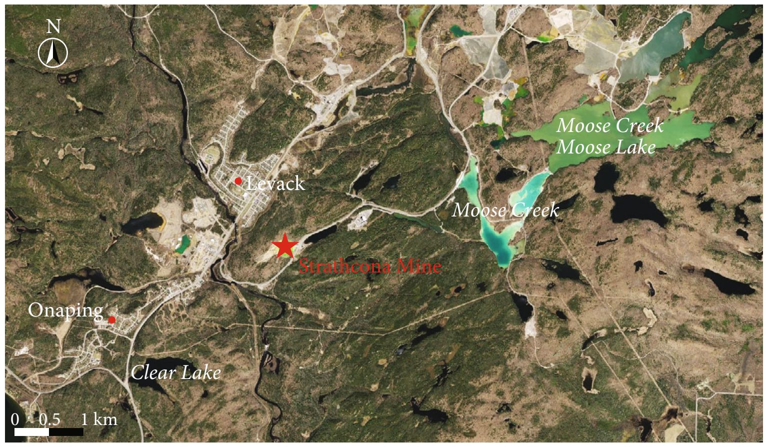

Figure 6: Overview picture of the Strathcona mine (captured from MinDat: https://www.mindat.org/).

Table 2: The source parameters of the seven mining-induced events of the Strathcona mine.

Event number	Stress drop $\Delta\tau$ (Pa)	Seismic moment M_0 (dyne·m)	Moment magnitude M_W
1	$2.1E+04$	$8.1E+19$	2.54
2	$1.4E+04$	$3.1E+19$	2.26
3	$5.0E+03$	$3.4E+18$	1.62
4	$2.0E+03$	$9.8E+17$	1.26
5	$1.0E+04$	$9.1E+18$	1.91
6	$1.2E+04$	$7.8E+19$	2.53
7	$2.2E+04$	$8.8E+19$	2.56

physical basis. In the following, we will test the reliability of the calculation method of the seismic source parameters via case studies.

3. Case Studies

3.1. Microseismic Activity on the Left Bank Slope of the Jinping-1 Hydropower Station. The Jinping-1 hydropower station is located at the sharp bend of Jinping on the Yalong River's middle reach, in Sichuan, China (Figure 4), situated within the slope transition zone from the Qinghai-Tibet Plateau to the Sichuan Basin [35]. Due to continuous excavations, 1,125 seismic events occurred at the left bank slope of the Jinping-1 hydropower station from June 2009 to May 2011 [36]. The rock mass outside the tension fissure zone and lamprophyre veins is a key block (locked segment) that controls the slope's deformation and stability [37]. Based on the measured source parameters (Table 1) of the twelve $M_W \geq -3.3$ microseismic events that occurred along the key block, a relationship between the stress drop and the earthquake magnitude (Figure 5) is fitted as

$$M = 1.37 \lg \Delta\tau - \mathbf{0.90} (\text{correlation coefficient} = 0.87). \quad (6)$$

It is seen from Figure 5 that a relatively good linear fitting result is obtained, where the slope (1.37) is close to the theoretical result of 1.33 in Equation (3). This case study demonstrates that the proposed calculation method of seismic source parameters of a locked-segment cracking event is reliable and could be used to estimate the seismic source parameters of a locked-segment cracking event in large rock slopes.

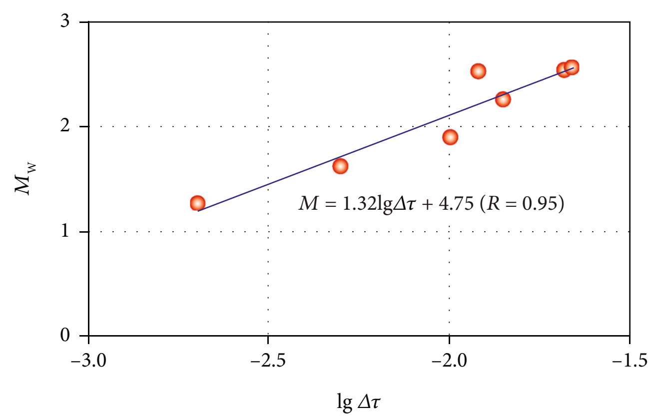

Figure 7: Relationship between the stress drop (in MPa) and the earthquake magnitude. Red dots represent seven events triggered by mining activity at the Strathcona mine.

3.2. Microseismic Activity of the Strathcona Mine. The Strathcona mine is located in the town of Levack on the North Range of the Sudbury Basin, Canada (Figure 6). In June 1988, seven mining-induced events between depths of 640 and 825 m occurred over two days in the mine [38, 39]. Data analysis and underground observation confirmed that these events were mining-induced fault-slip earthquakes [38, 40]. Based on the source parameters (Table 2) of the seven events provided by Trifu et al. [39], we plotted the relationship between the stress drop and the earthquake magnitude (Figure 7) and derived a linear fitting:

$$M = 1.32 \lg \Delta\tau + \mathbf{4.75} (\text{correlation coefficient} = 0.95). \quad (7)$$

The slope of the good linear fitting result (1.32) is very close to the theoretical result of 1.33 in Equation (3). This case study demonstrates that the proposed calculation method of seismic source parameters of a locked-segment cracking event is reliable, which could be used to estimate the seismic source parameters of a locked-segment cracking event in rock underground engineering.

4. Discussion

Whether the earthquake magnitude is related to the stress drop remains controversial and needs urgent clarification. Some scholars [41–45] believed that the earthquake magnitude is positively correlated with the stress drop. In contrast, others [46–49] held the opinion that there is no positive correlation between them. In addition, Shi et al. [50] and Jin et al. [51] accepted that the two parameters are positively correlated within a certain range of magnitudes. Based on Equation (1), the earthquake magnitude of a locked segment's cracking event is positively correlated with the stress drop if the cracking events (earthquakes) are generated from the same locked segment. It must be mentioned that the following points need to be noted in the statistical analysis of the relationship between the earthquake magnitude and the stress drop: (1) it should be distinguished whether earthquakes are the cracking events of the same locked segment, that is, the cracking events of the same locked segment is comparable using Equation (1); (2) small earthquakes are the main cracking events related to the nonlocked segment, so they should not be included in such statistical analysis.

5. Conclusions

Based on the energy conservation principle, a new method for the seismic source parameter estimation of the locked-segment cracking event was proposed, and then, it was verified by typical case studies of rock slope and rock underground engineering. The following conclusions were drawn:

(1) Based on the principle of energy conversion and distribution in the locked segment's damage process, an equation for calculating the radiated seismic energy of a locked-segment cracking event (earthquake) was proposed. It can be concluded that the earthquake magnitude is only related to the stress drop or the strain increment of cracking events generated from the same locked segment

(2) Using the equation for calculating the radiated seismic energy of a locked-segment cracking event, the mechanical relationships of the earthquake magnitude and the stress drop, and the earthquake magnitude and the shear strain increment (or maximum coseismic displacement) of a locked-segment cracking event were established

(3) The proposed calculation method of seismic source parameters is validated using the measured data of the stress drop and the earthquake magnitude from two typical engineering cases. The results show that this method is reliable and can be widely used in rock slope and rock underground engineering

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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