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Research Article

Effects of Geometrical Parameters on Stress Wave Propagation across the Rough Joint

Chen Xin [1,2] Tan Wenhui, [1,2] and Wang Peng [3]

[1] *Beijing Key Laboratory of Urban Underground Space Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[2] *Department of Civil Engineering, University of Science and Technology Beijing, Beijing 100083, China*
[3] *PAN-CHINA Construction Group Co., Ltd, Beijing 100070, China*

Correspondence should be addressed to Chen Xin; xin_chenustb@163.com

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The contact surface of the rough joint has geometrical parameters as the joint matching coefficient (JMC) and the distribution pattern of the contact segments. The specimen used in the modified SHPB test got the artificial joint by sawing some notches on the surface contacted to the output bar. Different assemblies of the notches formed various contact areas and distribution patterns. Using the modified SHPB tests data, the altered thin-layer interface model was used to analyze the effects of geometrical parameters on one-dimensional stress wave transmission and energy dissipation across a single rough joint. It revealed that the transmission coefficient decreased with the diminution of JMC, and it increased with the scattered distribution pattern as the similar trend for each JMC set. As for the energy coefficients, with the decrease of JMC, the transmission energy coefficient reduced sharply, but it increased very slowly with the reflection energy coefficient and irreversible energy coefficient. It revealed that the JMC of 0.5 was the critical point of the energy dissipation. More energy transmitted across the joint rather than reflecting back and dissipating, when JMC > 0.5. Nevertheless, the irreversible energy coefficient was much larger than the transmission and reflection coefficients, when JMC < 0.5.

1. Introduction

Due to the existence of joints, fractures, faults, and so on, rock masses have properties such as discontinuity, anisotropy, and nonlinearity [1, 2]. Rock dynamics has applications in earthquakes, mining, energy, environmental, and civil engineering, when dynamic loads are encountered [3]. Earthquake, rockburst, and other disasters are scientific issues about stress wave propagation in jointed rock masses [4]. Formed the discontinuous interfaces in rock masses, joints have significant effects on stress wave propagation. It has been one of the research focuses in rock mechanics and rock engineering in recent years.

The surface topography of the joint demonstrates its spatial geometrical attribute, which is the key factor affecting the deformation of the rock mass. Only the dynamical models with surface topography parameters could overall illustrate the actual mechanical behavior of the rock mass. Fractal description of the joint asperity, relationship between JRC and fractal dimension, and the effect of fractal dimension on shear strength and friction angle of joints were discussed [5]. Tatone et al. developed a roughness evaluation methodology for 2D roughness profiles to objectively quantify JRC [6]. Rasouli et al. presented a new parameter for quantitative roughness determination based on the distribution of unit normal vectors to a rock profile [7]. Zhang et al. proposed a new method for accurate JRC estimation [8]. Li and Huang developed numerous empirical equations to estimate the joint roughness coefficient (JRC) of a rock fracture based on its fractal dimension (D) [9]. Park and Song found a numerical method to determine the contact areas of a rock joint under normal and shear loads

[10]. Zheng and Qi found that all mathematical relationships of surface inclination of surfaces dipping opposite to shear direction with JRC satisfy the power law equation (11).

It has been generally recognized that joints would result in the attenuation of the amplitude and velocity of the stress wave, and the attenuation of the amplitude could react the properties of the jointed rock mass better [12, 13]. Perino et al. reviewed and compared theoretical methods of the displacement discontinuity model and the equivalent medium method, and considerations about the advantages and disadvantages of these methods were given [14]. Li et al. presented an analytical and experimental study on a longitudinal wave (P-wave) transmission normally across a filled rock joint [15]. Li et al. proposed an equivalent viscoelastic medium model to analyze longitudinal wave propagation through discontinuous media with parallel joints [16]. Park and Song established a joint surface model which enabled quantitative evaluation of the steepness of contact areas, as well as their location and size [17]. Gong et al. provided a reference method to determine sample size for actual test conditions [18]. Huang et al. conducted experiments to study the relationship between the transmission ratio (TR) and normal stress, joint roughness, joint number, and frequency of incident waves, respectively, when ultrasonic waves pass across a rock mass with one joint and multiple parallel joints oriented normally [19]. Wu and Zhao revealed that the attenuation factor in a filled fracture increases with higher water content from an air-dry state to a saturated state [20]. Wei et al. proposed a set of systematic experimental methods to research the influence of discontinuity roughness on strength and deformation of discontinuity [21].

Zhao proposed a joint matching coefficient (JMC) based on the percentage of joint surface area in contact as an independent joint surface geometrical parameter [22]. Chen et al. studied the effects of JMC and spatial geometries of the joint on wave transmission by the modified SHPB experiment [23]. Li et al. modeled the fracture as a thin-layer interface by two smooth surfaces separated by square column asperities with different heights, and the wave propagation equation is established by analyzing the interaction between a stress wave and the rough fracture [24]. In this study, geometrical parameters refer to JMC and the notches quantity of the artificial joint, which represent the contact area ratio and the distribution pattern of the joint, respectively. Combing the above research findings, this study input the test parameters and incident wave of the modified SHPB tests into the altered thin-layer interface model, and the effects of geometrical parameters of the joint on wave transmission and energy dissipation were analyzed.

2. Theoretical Analysis

Regarded as the one-dimensional P-wave propagating across the elastic joint with rough surface, effects of the geometrical parameters of the modified SHPB experiment could be analyzed based on the thin-layer interface model altered with JMC, as shown in Figure 1.

At time t_i, the relation of the velocity of the right-running wave before the jth interface v_r, j (t), the velocity of the right-running wave after the jth interface v_r, j (t), the velocity of the left-running wave before the jth interface $v^-(t)$, and the velocity of the left-running wave after the jth interface $v^+(t)$ can be expressed as

$$\begin{bmatrix} v_{r,j}^{+}(t) \\ v_{l,j}^{-}(t) \end{bmatrix} = m^{-1} \cdot n \cdot \begin{bmatrix} v_{r,j}^{-}(t) \\ v_{l,j}^{+}(t) \end{bmatrix}, \tag{1}$$

where m and n are the matrix parameters,

$$\begin{aligned} m &= \begin{bmatrix} 1 & 1 \\ \dfrac{S_j^+}{S_j^-} & -1 \end{bmatrix}, \\ n &= \begin{bmatrix} 1 & 1 \\ 1 & -\dfrac{s_j^+}{s_j^-} \end{bmatrix}. \end{aligned} \tag{2}$$

At the nominal contact surface S' of the joint, where $j = 0$, the incident wave $v_I(t)$ is

$$v_I(t) = v_{r,0}^{-}(t). \tag{3}$$

The reflected wave $v_R(t)$ is

$$v_R(t) = v_{l,0}^{-}(t), \tag{4}$$

$$\frac{S_0^+}{S_0^-} = \text{JMC}. \tag{5}$$

At the contact surfaces S/O (surface S is of the input side and surface O is of the output side, respectively, as shown in Figure 1(b)), where $j = N$, the transmitted wave $v_T(t)$ is

$$v_T(t) = v_{r,N}^{+}(t), \tag{6}$$

$$\frac{S_N^+}{S_N^-} = \text{JMC}^{-1}. \tag{7}$$

Then, transmission energy coefficient e_T and the reflection energy coefficient e_R of the joint can be calculated, respectively, as

$$e_T = \frac{W_T(t_0)}{W_I(t_0)} = \frac{\int_0^t v_T^2(t)\,dt}{\int_0^t v_I^2(t)\,dt}, \tag{8}$$

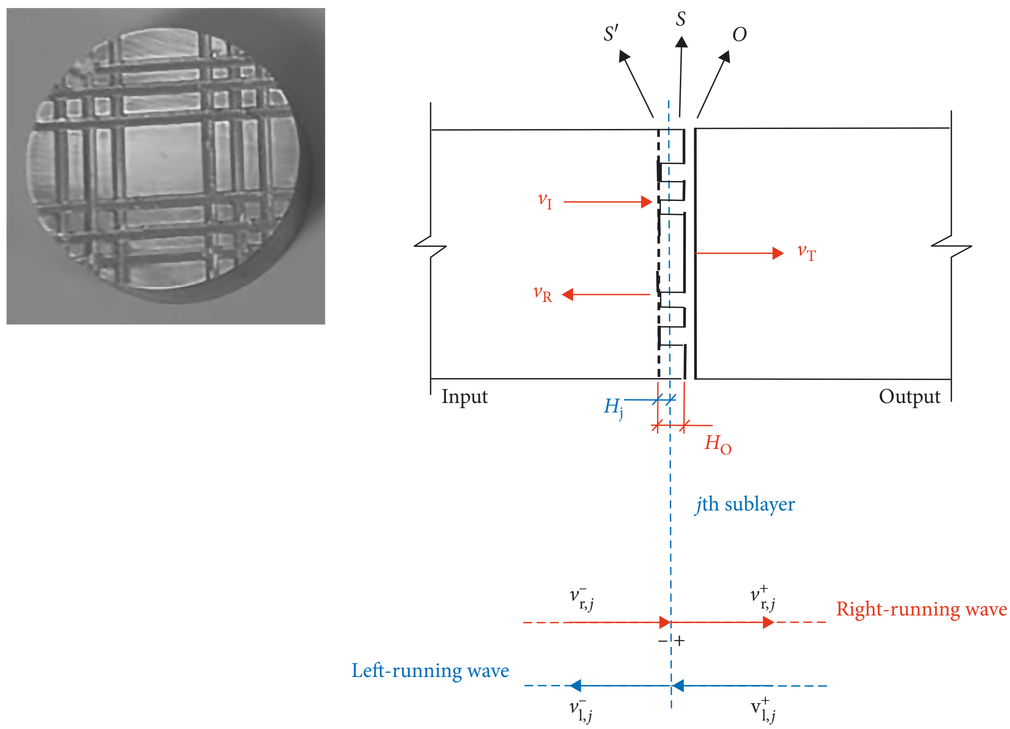
$$e_R = \frac{W_R(t_0)}{W_I(t_0)} = \frac{\int_0^t v_R^2(t)\,dt}{\int_0^t v_I^2(t)\,dt}. \tag{9}$$

Thus, the irreversible energy coefficient e_J of the joint can be calculated as

$$e_J = 1 - e_T - e_R. \tag{10}$$

3. Effects of Geometrical Parameters of the Joint

3.1. Essential Parameters. As for the modified SHPB experiment [23], the apparatus consisted of a loading bar, an



(a) (b)

Figure 1: P-wave propagates through a rough joint. (a) An artificial rough surface of a specimen in the modified SHPB tests. (b) P-wave separation when propagating across the joint.

input pressure bar, an output pressure bar, and a specimen between the pressure bars. All bars have the same diameter, as well as the specimens. The physical parameters of the aluminum specimens are shown in Table 1.

Tables 2–5 show the geometrical parameters of the specimens in 4 sets. As shown in Table 2, specimens #1-1 and #1-2 in #Set 1 have a JMC about 0.81, but with different quantities of notches which refer to different distribution patterns of the notches. With bigger quantity of the notches, the distribution pattern of the notches is more scattered. Whereas, the distribution pattern of the notches is lumped with less quantity of the notches. Hence, the quantity of the notches could denote contact pattern of the jointed surface as scattered or lumped. #Set 2, #Set 3, and #Set 4 have the same situation, that is, specimens in each set have the nearly equal JMC but distribution patterns varied from scattered to lumped.

The test data were recorded based on the Gen3i platform. Then, the data processing method was adopted to obtain the incident wave and reflected wave at the nominal contact surface S'. According to Equations (1)–(7), the transmitted wave at the contact surfaces S/O could be acquired. Therefore, the transmission energy coefficient, reflection energy coefficient, and irreversible energy coefficient could be got by Equations (8)–(10) respectively.

3.2. Effect on Transmission Coefficients. Figure 2 demonstrates the relation between the quantity of the notches and transmission coefficients under different JMC sets. It is obvious that the transmission coefficient declined as JMC decreased. For each JMC set, the relation of transmission coefficient and the quantity of notches has the similar trend, which could be fitted by the allometric function:

$$y = a \cdot x^b, \tag{11}$$

where the parameters are listed in Table 6.

As shown in Figure 2, the transmission coefficient was relatively higher, as the quantity of notches increased, while the transmission coefficient was relatively lower, as the quantity of notches decreased. It indicated that more waves transmitted across the joint when the distribution pattern of the joint was scattered, and less waves transmitted through when the distribution pattern of the joint was lumped. It revealed that relatively scattered distribution of the joint surface could result in relatively higher transmission effect, and relatively lumped distribution of the joint surface could result in relatively lower transmission effect. Thus, it demonstrated the relation between the geometrical parameters and the transmission coefficients.

3.3. Effect on Energy Dissipation. According to Equations (8) and (9), the transmission and reflection energy coefficients could be obtained, respectively, and the irreversible energy coefficient could be obtained by Equation (10). Figure 3 shows the relation of JMC with the 3 above energy coefficients. When JMC is 0.81, the transmission energy coefficient is about 0.8, while the reflection energy coefficient is near 0, and the irreversible energy coefficient is about 0.2. It expresses that

Table 1: Physical parameters of the aluminum specimens.

Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio	Diameter of the cross section (mm)	Depth of the joint (mm)
2,700	70	0.33	40	1

Table 2: Geometrical parameters of the specimens: #Set 1.

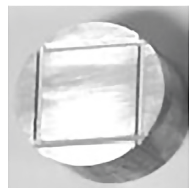
JMC	0.81	
	0.82	0.81
Specimen no.	#1-1	#1-2
Quantity of notches	4	1
Distribution patterns		

Table 3: Geometrical parameters of the specimens: #Set 2.

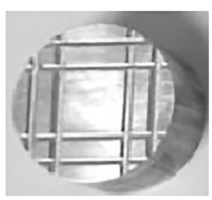
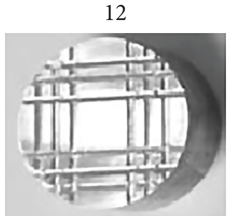
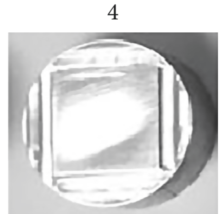
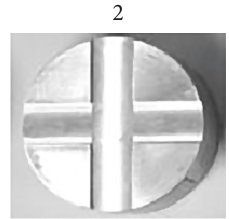
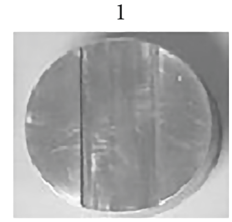
JMC		0.64	
	0.64	0.65	0.65
Specimen no.	#2-1	#2-2	#2-3
Quantity of notches	8	4	1
Distribution patterns			

Table 4: Geometrical parameters of the specimens: #Set 3.

JMC		0.49		
	0.47	0.49	0.50	0.50
Specimen no.	#3-1	#3-2	#3-3	#3-4
Quantity of notches	12	4	2	1
Distribution patterns				

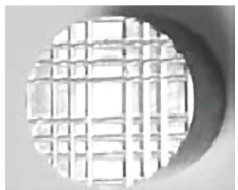
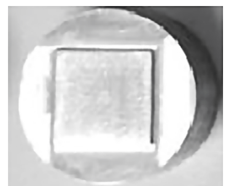
energy transmitted mostly without any reflection, but dissipated by permanent deformation partly, under a JMC of 0.81. With the decrease of JMC, the transmission energy coefficient decreases sharply, but the reflection and irreversible energy coefficients increase slowly. The fitted curves in Figure 3, respectively, could be expressed as

$$y = m \cdot x^2 + n \cdot x + l, \quad (12)$$

where the parameters are in Table 7.

It could be noted that the transmission energy coefficient equals to the irreversible energy coefficient with a JMC of 0.5. This denotes that the energies of transmission and dissipation are equivalence, when the joint surface has half of the surface area in contact. The irreversible energy coefficient continues to increase when JMC reduces. When JMC is less than 0.5, the irreversible energy coefficient is larger than the transmission energy coefficient. Hence, more energy dissipates by the permanent deformation rather than transmission when less than half of the surface is in contact.

Table 5: Geometrical parameters of the specimens: #Set 4.

JMC	0.36			
	0.37	0.35	0.36	0.36
Specimen no.	#4-1	#4-2	#4-3	#4-4
Quantity of notches	16	4	2	1
Distribution patterns				

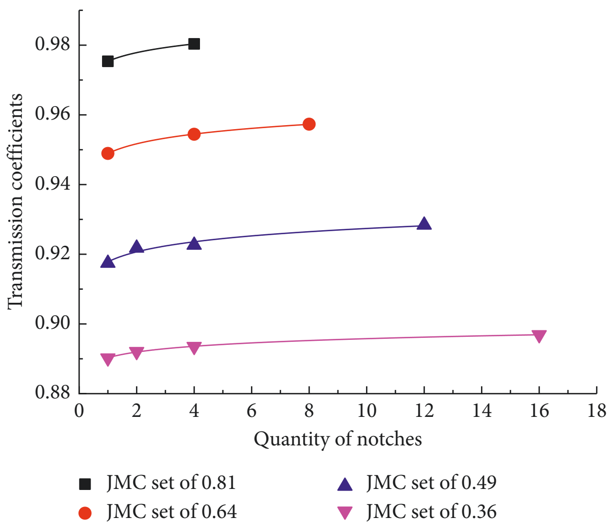


Figure 2: Relations of the geometrical parameters and transmission coefficients.

Table 6: Parameters of the fitted curves (T-distribution pattern).

Parameters	JMC set			
	0.81	0.64	0.49	0.36
a	0.97536	0.94891	0.91781	0.89029
b	0.00368	0.00423	0.00451	0.00267

When JMC reduces to 0.36, the irreversible energy coefficient is around 0.5, and the energy coefficients of transmission and reflection are approximately equal. It demonstrates that almost half of the incident energy dissipated when JMC is 0.36.

Table 7: Parameters of the fitted curves (energy coefficients: JMC).

Curves of	Parameters		
	m	n	l
e_T	−0.07524	1.24669	−0.15927
e_R	0.96141	−1.58772	0.66732
e_J	−0.88624	0.34111	0.49193

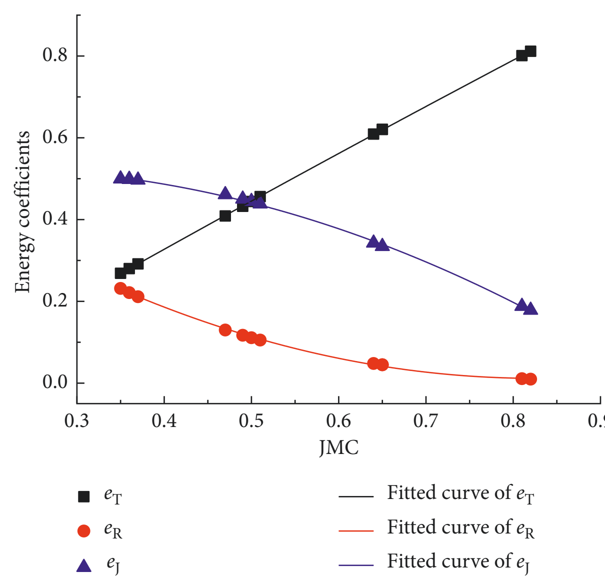


Figure 3: Relations of JMCs with e_J, e_R, and e_T.

4. Discussions

The altered thin-layer interface model could be used on the analysis of modified SHPB experiment, which had taken geometrical parameters of the joint into account. According to the calculation results, comparisons were made among various artificial jointed specimens with diverse JMCs and notches quantities. The transmission coefficient decreased with the diminution of JMC, and it also decreased with the diminution of notch quantity with the similar trend for each JMC set. It illustrated that both JMC and distribution pattern have obvious influence on stress wave transmission effect. As for the energy coefficients, with the decrease of JMC, the transmission energy coefficient reduced sharply from about 0.8 to 0.2, but reflection and irreversible energy coefficient increased very slowly with only 20% and 30%, respectively. It revealed that JMC affected the energy dissipation when stress wave propagated across the rough joint. With more than half of the surface area in contact, more energy transmitted rather than dissipated by the permanent deformation. On the contrary, more energy dissipated rather than transmitted with less than half of the surface area in contact. It demonstrated that the JMC of 0.5 is the critical point which affects the energy dissipation.

5. Conclusions

This paper studied the geometrical parameters of the joint, including JMC and the quantity of notches, which represent contact area ratio and the distribution pattern of the joint. The altered thin-layer interface model with JMC could be used to analyze one-dimensional stress wave propagation across the elastic joint with rough surface.

It has been revealed that geometrical parameters have significant influence on one-dimensional wave transmission and energy dissipation of the joint.

(1) As JMC reduced, both transmission coefficient and transmission energy coefficient decreased sharply by around 60%, while the reflection energy coefficient and irreversible energy coefficient increased slowly by about 20%–30%.

(2) JMC-0.5 has been discovered as the critical point that affected the energy dissipation. At this point, the transmission energy coefficient equaled to the irreversible energy coefficient. When JMC > 0.5, that is more than half of the surface in contact, energy had mostly transmitted through the joint, rarely reflected back, and the rest dissipated by permanent deformation. Inversely, when JMC < 0.5, that is less than half of the surface in contact, energy had dissipated more than transmitted and reflected increasingly.

(3) The transmission coefficient varied accordingly to distribution pattern of the joint with the similar trend under the same JMC. For each JMC set, transmission coefficient was relatively higher when the distribution pattern was scattered, and it decreased with the lumped distribution pattern.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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