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Research Article

A New Method for Determination of Joint Roughness Coefficient of Rock Joints

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The joint roughness coefficient (JRC) of rock joints has the characteristic of scale effect. JRC measured on small-size exposed rock joints should be evaluated by JRC scale effect in order to obtain the JRC of actual-scale rock joints, since field rock joints are hardly fully exposed or well saved. Based on the validity analysis of JRC scale effect, concepts of rate of JRC scale effect and effective length of JRC scale effect were proposed. Then, a graphic method for determination of the effective length of JRC scale effect was established. Study results show that the JRC of actual-scale rock joints can be obtained through a fractal model of JRC scale effect according to the statistically measured results of the JRC of small-size partial exposed rock joints and by the selection of fractal dimension of JRC scale effect and the determination of effective length of JRC scale effect.

1. Introduction

Joint roughness coefficient (JRC) is a vital parameter of the JRC-JCS model for estimation of shear strength of rock joints [1–5]. The JRC will decrease with an increase in sampling length due to JRC scale effect [6–8].

Field investigations show that it is usually hard to measure the JRC of actual-scale rock joints directly because the field rock joints are hardly fully exposed or well saved. The estimation of the JRC of actual-scale rock joints by statistically measured results of the small-scale JRC of partial exposed rock joints is critical to the reliability of the shear strength of rock joints empirically estimated by the JRC-JCS model.

Based on the analysis on quantities of rock joints through joint model test, Barton and Bandis [2] proposed a modified curve of JRC scale effect (see Figure 1) and a modified formula defined as

$$\mathrm{JRC}_n \approx \mathrm{JRC}_0 \left[\frac{L_n}{L_0}\right]^{-0.02\mathrm{JRC}_0}, \tag{1}$$

where JRC_n is the JRC value of rock joints with sampling length L_n and JRC_0 is the JRC value of standard-size joints (the sampling length is L_0, i.e., 10 cm).

Du et al. [9] have statistically measured the JRC values of 1023 profile curves on SSE group joints from Xiaolangdi by the use of the profilograph and roughness ruler and got the regularity of the decrease characteristic of JRC with an increase in sampling length (see Figure 2).

In this paper, a new method is introduced to study the estimation of the JRC of actual-scale rock joints by statistically measured results of the small-scale JRC of partial exposed rock joints through the analysis of JRC scale effect of rock joints. A fractal model of JRC scale effect was established. The physical meaning of the fractal dimension of JRC scale effect was defined. A method to determine the effective length of JRC scale effect was proposed based on the study of the effectiveness of JRC scale effect.

2. Fractal Dimension of JRC Scale Effect

According to (1) and the regularity of JRC scale effect in Figures 1 and 2, the fractal expression of JRC scale effect can be obtained:

$$\mathrm{JRC}_n = \mathrm{JRC}_0 \left[\frac{L_n}{L_0}\right]^{-D}, \tag{2}$$

where D is the fractal dimension of JRC scale effect, which defines the velocity rate of JRC_n decreases with an increase in sampling length L_n.

TABLE 1: Fractal dimension of JRC scale effect of tonalite joint J_{1-1}.

Direction/°	L_n/cm	JRC	D_n	Direction/°	L_n/cm	JRC	D_n
Trend (0)	10	10.35	0.0000	Strike (90)	10	11.90	0.0000
	20	8.23	0.3307		20	7.11	0.7431
	30	6.13	0.4769		30	5.65	0.6781
	40	5.20	0.4966		40	4.75	0.6625
	50	4.78	0.4800		50	4.00	0.6774
	60	4.48	0.4674		60	3.58	0.6705
	70	4.58	0.4190		70	3.38	0.6469
	80	4.25	0.4281		80	3.05	0.6598
	90	4.05	0.4271		90	3.00	0.6273
	100	3.78	0.4374		100	2.80	0.6284
Oblique (45)	10	13.83	0.0000	Oblique (135)	10	11.10	0.0000
	20	7.93	0.8025		20	7.60	0.5465
	30	5.70	0.8070		30	5.80	0.5910
	40	5.15	0.7126		40	4.65	0.6277
	50	4.23	0.7360		50	4.00	0.6341
	60	3.50	0.7670		60	3.58	0.6317
	70	3.23	0.7474		70	3.30	0.6234
	80	2.88	0.7546		80	3.28	0.5863
	90	3.00	0.6957		90	2.98	0.5986
	100	2.78	0.6968		100	2.95	0.5755

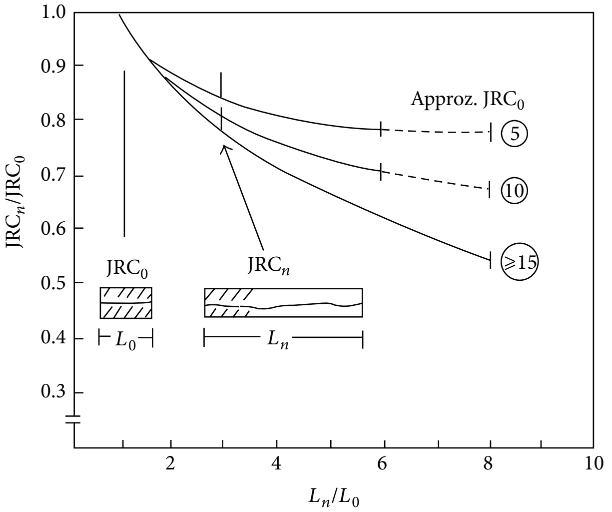


FIGURE 1: Scale effect related to JRC$_0$ [2].

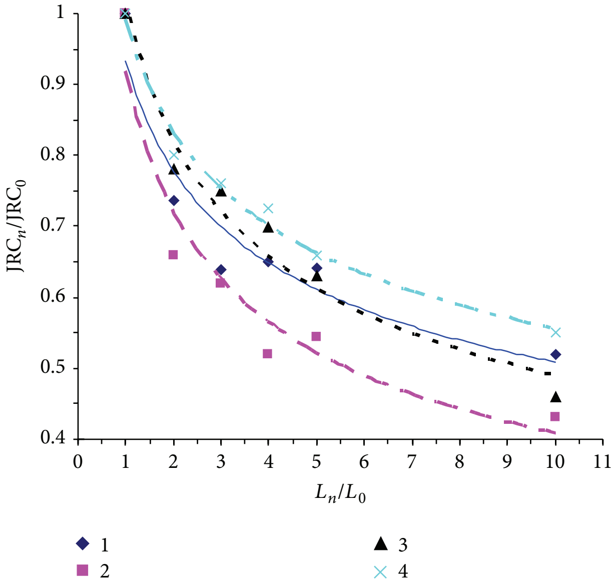


FIGURE 2: JRC scale effect of SSE group joint in Xiaolangdi. (1) Calcareous packsand along joint strike direction (160°), (2) calcareous packsand along joint trend direction (250°), (3) silty clay rock along joint strike direction (160°), and (4) silty clay rock along joint trend direction (250°).

Statistically measured results show that the fractal dimension of JRC scale effect is comparatively stable. D_n, calculated from the fractal model of JRC scale effect according to the statistically measured results of JRC$_n$ of random sampling length along the same direction of rock joints in the same wall rock, distributes over a stable interval (see Table 1). From Table 1, it can be seen that the fractal dimension along the tonalite joint (J_{1-1}) trend direction ranges from 0.3307 to 0.4966, with mean value of 0.4404; the range of fractal dimension along 45° direction is 0.6957–0.8070, and mean value is 0.7466; the range of fractal dimension along the strike direction is 0.6273–0.7431, and mean value is 0.6656; the range of fractal dimension along 135° direction is 0.5465–0.6341, and mean value is 0.6016. This means that the fractal dimension of JRC scale effect (D_{30}) converted by the JRC measurement results of small-size joint is the same as the fractal dimension of JRC scale effect (D_{100}) converted by the JRC measurement results of large-size joint. D_{100} and

TABLE 2: Fractal dimension of JRC scale effect of typical rock joints.

Joint wall rock	Joint type	D_{30}
Magmatic rock		
Coarse-grained granite	Joint	0.3458
Fine-grained granite	Joint	0.3752
Coarse-grained diorite	Joint	0.3165
Dacite-porphyrite	Joint	0.3877
Fluorite dike rock	Joint	0.3500
Basalt	Joint	0.4883
Sedimentary rock		
Rudaceous grit	Joint	0.2578
Arkosic sandstone	Joint	0.1698
Siltstone	Ripple bedding	0.2850
Siltstone	Joint	0.4234
Calcilutite	Joint	0.4758
Calcareous packsand	Joint	0.5093
Nodule clay rock	Joint	0.2662
Calcareous mudstone	Ripple bedding	0.3563
Calcareous mudstone	Joint	0.2578
Volcanic debris rock		
Volcanic breccia	Joint	0.2746
Fusion tuff	Joint	0.4234
Crystal tuff	Joint	0.2788
Metamorphic rock		
Carbonaceous slate	Foliation	0.2012
Phyllite rock	Phyllite	0.4150
Plagioclase hornblendite	Joint	0.3500

D_{30} signify 100 mm and 30 mm joint sample size. Therefore, the fractal dimension of JRC scale effect can be directly determined according to the JRC statistical measurement results of small-size rock joints. In engineering applications, the value of D_{30} is usually used to analyze the JRC scale effect in order to facilitate the statistical measurement of the JRC.

Considering the difference of JRC scale effect of rock joints with different wall rock, fractal dimension of JRC scale effect of typical rock joints was converted by the fractal model of JRC scale effect according to the statistically measured results from JRC_{10} and JRC_{30} of 13529 profile curves of 21 different wall rock joints (see Table 2).

3. Effective Length of JRC Scale Effects

In order to discuss the effectiveness of JRC scale effect of rock joints, the sensitivity of JRC_n on the sampling length L_n was analyzed with constant $JRC_0 = 12.4$ and $D = 0.7009$. From Figure 3, it can be seen that when sampling length L_n is smaller than a certain value, JRC_n decreases dramatically with an increase in sampling length L_n, indicating significant JRC scale effect. While the sampling length L_n is larger than the certain value, JRC_n decreases very slowly with the increase of sampling length L_n; that is, the JRC scale effect is insignificant. The sampling length corresponding to shift from significant to insignificant JRC scale effect is named effective length of JRC scale effect, defined as L_n^*. In other words, only within the length of L_n^* will the influence of JRC scale effect of rock joints be significant.

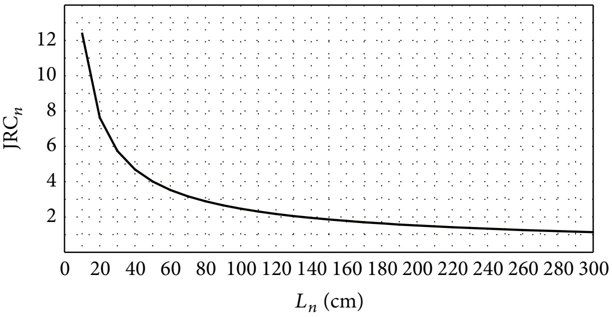


FIGURE 3: Relationship between sampling length L_n and JRC_0.

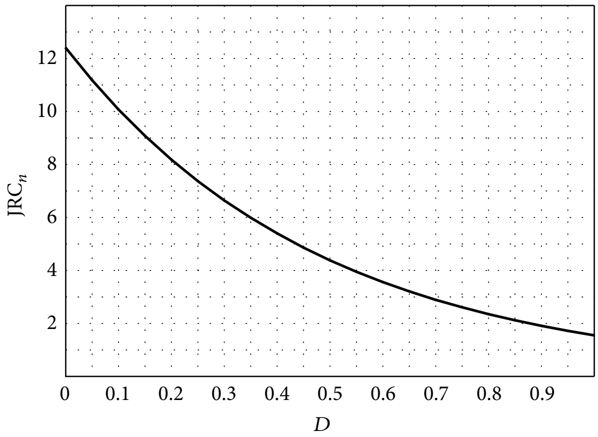


FIGURE 4: Plot of JRC_n versus D.

The sensitivity analysis between JRC_n and fractal dimension of JRC scale effect D is shown in Figure 4 when $JRC_0 = 12.40$ and $L_n = 80$ cm. It can be seen that JRC_n is very sensitive to the value of fractal dimension of JRC scale effect D.

According to the fractal model of JRC scale effect (see (2)), the fractal dimension D can be defined as

$$D = \frac{\lg\left[JRC_n/JRC_0\right]}{1 - \lg\left(L_n\right)}. \tag{3}$$

The relationship curve between D and $\lg(L_n)$ calculated by (3) is shown in Figure 5 when $JRC_0 = 12.40$ and $JRC_{300} = 1.14$. From Figure 5, it can be seen that the change of fractal dimension of JRC scale effect is obviously affected by the value of sampling length L_n of rock joints.

From the aforesaid analyses, it is clear that the change of fractal dimension of JRC scale effect is very sensitive to JRC and effective length of JRC scale effect, which can be used to determine the effective length of JRC scale effect L_n^*.

TABLE 3: D_{30} of SSE group joint of Xiaolangdi.

Joint wall rock	Direction	$L_n = 10$ cm		$L_n = 30$ cm		D_{30}
		Sample	JRC_{10}	Sample	JRC_{30}	
Calcareous packsand	Strike	35	8.61	34	5.50	0.4079
	Trend	31	12.12	30	7.43	0.4454
Calcareous nodule clay rock	Strike	88	15.83	84	11.86	0.2628
	Trend	82	20.48	77	15.46	0.2560

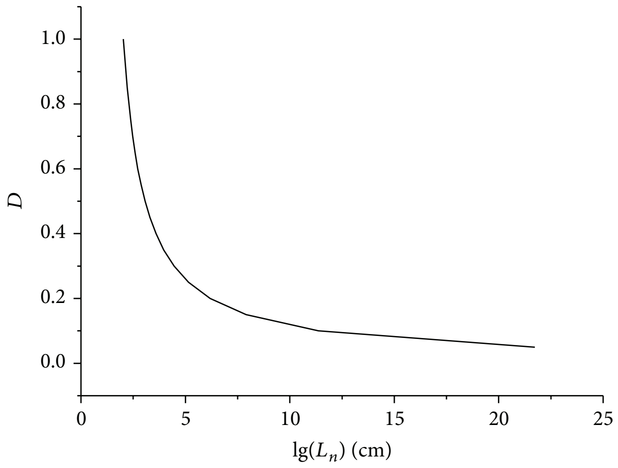


FIGURE 5: Relationship curve of $D - \lg(L_n)$.

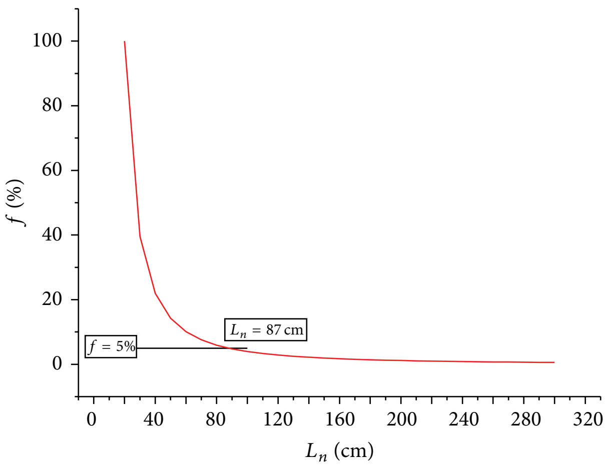


FIGURE 6: Relationship curve of L_n-f.

4. Graphic Method for Determination of Effective Length of JRC Scale Effect

Define f_n as the coefficient of JRC scale effect when sampling length is L_n:

$$f_n = \frac{\mathrm{JRC}_n - \mathrm{JRC}_{n-10}}{L_n - L_{n-10}}, \quad (4)$$

where JRC_n is the JRC of rock joints when sampling length is L_n; JRC_{n-10} is the JRC of rock joints when sampling length is L_{n-10}, $n = 20, 30, 40, 50, \ldots$.

Then, the coefficient of JRC scale effect when sampling length is 20 cm can be expressed as

$$f_{20} = \frac{\mathrm{JRC}_{20} - \mathrm{JRC}_{10}}{L_{20} - L_{10}} = \frac{\mathrm{JRC}_{20} - \mathrm{JRC}_{0}}{L_{20} - L_{0}}. \quad (5)$$

Let $f = f_n / f_{20}$ as the relative coefficient of JRC scale effect; then

$$f = \frac{(\mathrm{JRC}_n - \mathrm{JRC}_{n-10}) / (L_n - L_{n-10})}{(\mathrm{JRC}_{20} - \mathrm{JRC}_{0}) / (L_n - L_0)}. \quad (6)$$

Substituting (2) into (6) enables (7) to be determined:

$$f = \frac{(0.1L_n)^{-D} - (0.1L_n - 1)^{-D}}{2^{-D} - 1}. \quad (7)$$

According to (7), the relationship curve between L_n and f can be plotted (see Figure 6). From the figure, it can be found that the initial point whereas the relative coefficient of JRC scale effect f starts to increase with the sampling length L_n is $f = 5\%$. From error criterion, it can be known that JRC scale effect is insignificant when $f \leq 5\%$. Then, the value of the effective length of JRC scale effects L_n^* can be determined.

On the surface of the partial exposed rock joints, JRC_{10} and JRC_{30} of profile curves with sampling length of 10 cm and 30 cm can be statistically measured. Then, the fractal dimension of JRC scale effect can be calculated by the fractal model of JRC scale effect. Substituting the fractal dimension of JRC scale effect into (7), the relationship curve between L_n and f can be obtained (see Figure 6). The sampling length corresponding to $f = 5\%$ on L_n-f relationship curve is the effective length of JRC scale effect L_n^*. If the value calculated by the graphic method is between L_n and L_{n+10}, then let $L_n^* = L_n$ (e.g., $L_n^* = 80$ cm in Figure 6).

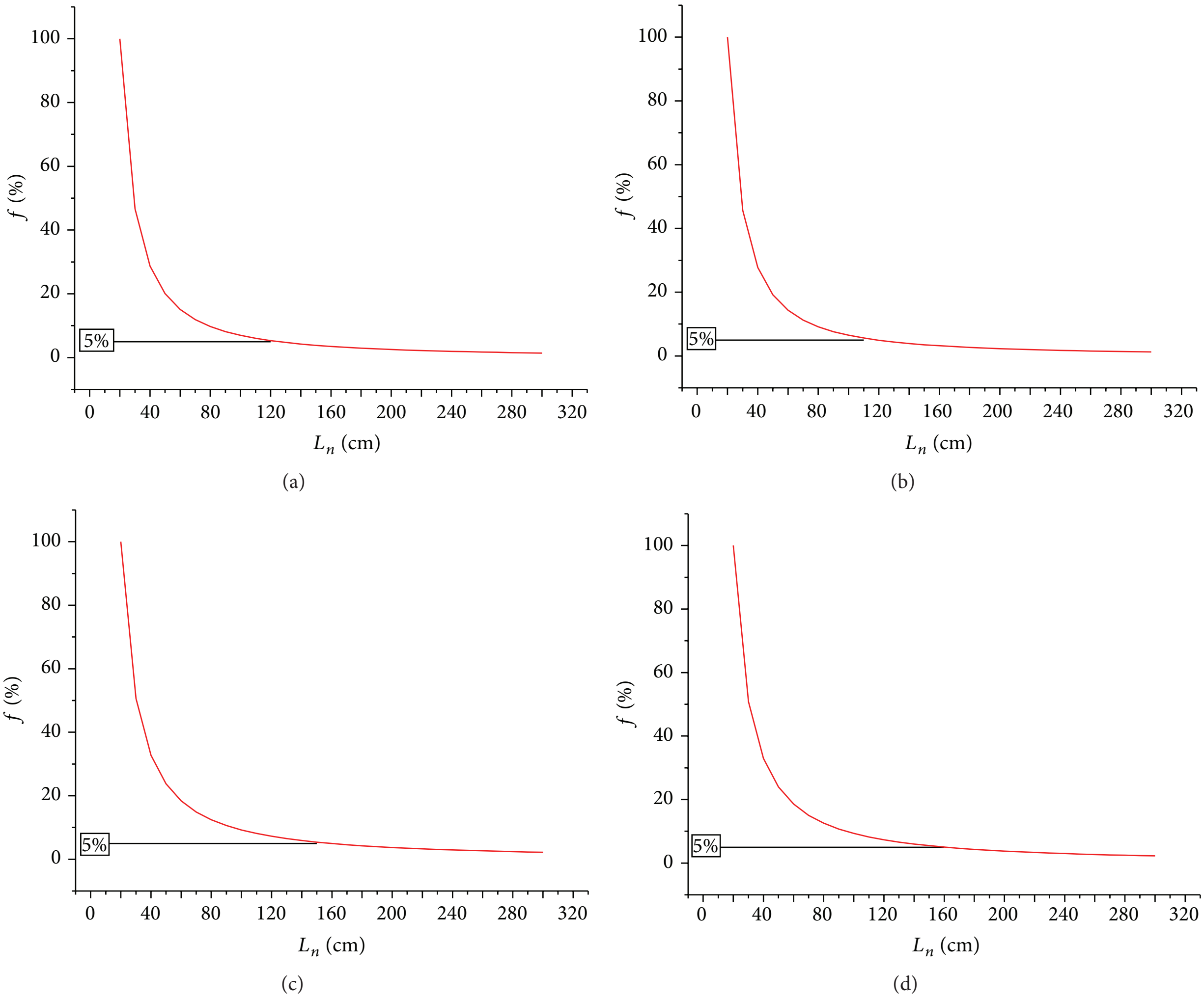
Conclusively, the fractal model of JRC scale effect (see (2)) can be used to estimate the JRC of actual-scale rock joints through the statistically measured JRC of small-size rock joints and to determine the fractal dimension of JRC scale effect and the effective length of JRC scale effect.

5. Case Study

Statistically measured JRC_{10} and JRC_{30} of 387 profile curves of SSE group joint of the west side slope rock of Xiaolangdi reservoir [10] and the values of D_{30} converted by the fractal model of JRC scale effect are listed in Table 3. According

Table 4: JRC of actual-scale SSE group joint of Xiaolangdi.

Joint wall rock	Direction	JRC_0	$L_n{}^*$/cm	D_{30}	JRC_n
Calcareous packsand	Strike	8.61	120	0.4079	3.12
	Trend	12.12	110	0.4454	4.17
Calcareous nodule clay rock	Strike	15.83	150	0.2628	7.77
	Trend	20.48	160	0.2560	10.07



(a)

(b)

(c)

(d)

Figure 7: Relationship curves of L_n-f of SSE group joint of Xiaolangdi. (a) Calcareous packsand along joint strike direction, (b) calcareous packsand along joint trend direction, (c) calcareous nodule clay rock along joint strike direction, and (d) calcareous nodule clay rock along joint trend direction.

to Table 3, relationship curves of L_n-f of calcareous packsand and calcareous nodule clay rock along the joint trend direction and strike direction can be plotted (see Figure 7). From Figure 7, it can be calculated that the effective length of JRC scale effect L_n^* of calcareous packsand along the joint trend direction and strike direction is 120 cm and 110 cm, respectively; and the effective length of JRC scale effect L_n^* of calcareous nodule clay rock along the joint trend direction and strike direction is 150 cm and 160 cm, respectively. Figure 7 shows that the effective length of JRC scale effect L_n^* decreases with an increase in the fractal dimension of JRC scale effect.

According to the effective length of JRC scale effect L_n^* calculated by the graphic method, the actual-scale joint roughness coefficients JRC_n of calcareous packsand and calcareous nodule clay rock along the joint trend direction and strike direction estimated by the fractal model of JRC scale effect are listed in Table 4. JRC_n in Table 4 is used in the empirical estimation of shear strength with the JRC-JCS model, which contains the scale effect and has wide application (because the JRC is obtained by directional statistical measurement). Thus, the joint shear strength parameters obtained by empirical estimation can be directly used to evaluate the stability of the rock.

6. Conclusions

Hence, our conclusions are as follows:

(1) Joint roughness coefficient of rock joints has the characteristic of scale effect. The sensitivity analysis of JRC_n to the sampling length L_n shows that JRC_n decreases dramatically with an increase in sampling length L_n when the sampling length L_n is smaller than a certain value; when the sampling length L_n is larger than the certain value, JRC_n decreases very slowly with an increase in sampling length L_n. This eigenvalue of JRC scale effect is named the effective length of JRC scale effect. Only within the length of L_n^* will the influence of JRC scale effect be significant. The sensitivity analysis of the relative coefficient of JRC scale effect f to the sampling length L_n shows that the sampling length corresponding to $f = 5\%$ of L_n-f relationship curve is the effective length of JRC scale effect, L_n^*.

(2) The sensitivity analysis of the fractal dimension of JRC scale effect D to the sampling length L_n shows that the change of D strongly affects the value of L_n. Therefore, the fractal dimension of JRC scale effect can be used to determine the effective length of JRC scale effect, L_n^*. The case study shows that the effective length of JRC scale effect L_n^* decreases with an increase in the fractal dimension of JRC scale effect.

(3) The procedures of the graphic method to determine the effective length of JRC scale effect are as follows. Firstly, JRC_{10} and JRC_{30} are measured through the statistically measured profile curves with sampling length of 10 cm and 30 cm on the surface of rock joints. Secondly, the fractal dimension of JRC scale effects D_{30} is determined by the fractal model of JRC scale effect. Thirdly, substituting the fractal dimension into the relative coefficient of JRC scale effect formula (see (7)), the relationship curve of L_n-f can be plotted. Finally, the sampling length corresponding to $f = 5\%$ in L_n-f relationship curve is the effective length of JRC scale effect, L_n^* (if the value calculated by graphic method is between L_n and L_{n+10}, then let $L_n^* = L_n$).

(4) Field investigations show that the field rock joints are hardly fully exposed or well saved. The graphic method in some terms solves the problem by promoting the utilization of the fractal model of JRC scale effect. Using this method, the JRC of actual-scale rock joints can be determined by the fractal model of JRC scale effects through the statistically measured JRC of small-size and partial exposed rock joints.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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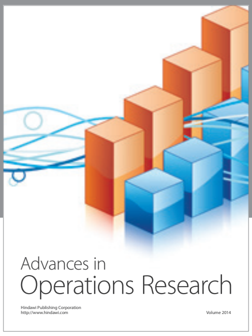
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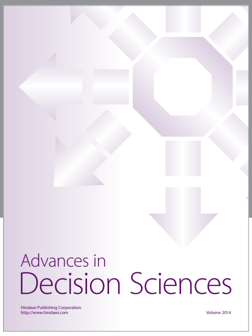
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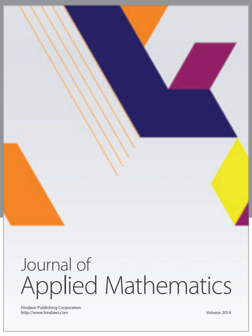
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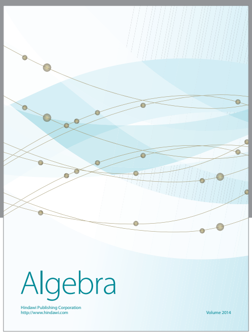
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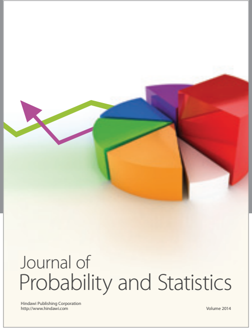
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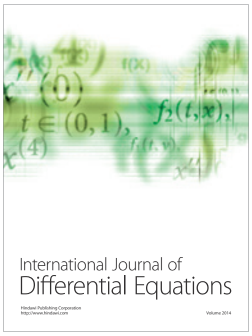
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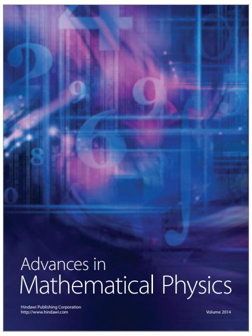
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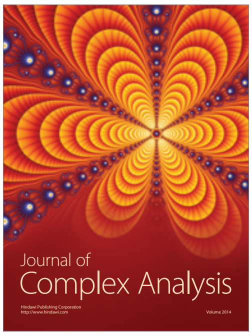
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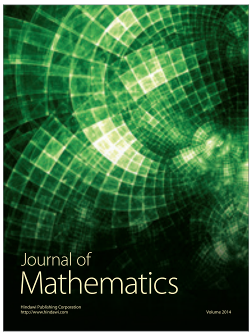
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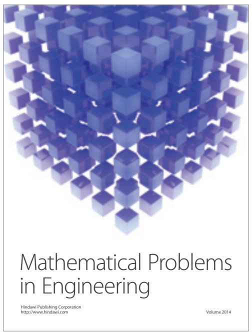
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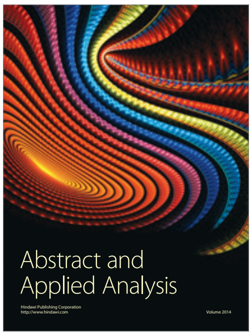
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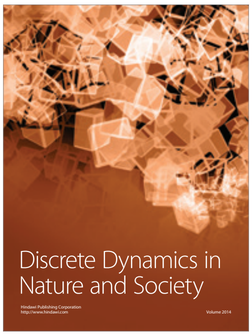
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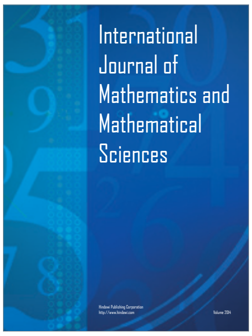
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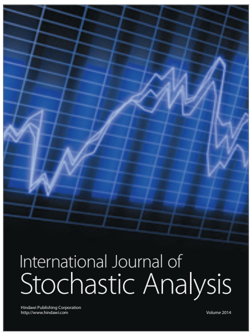
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