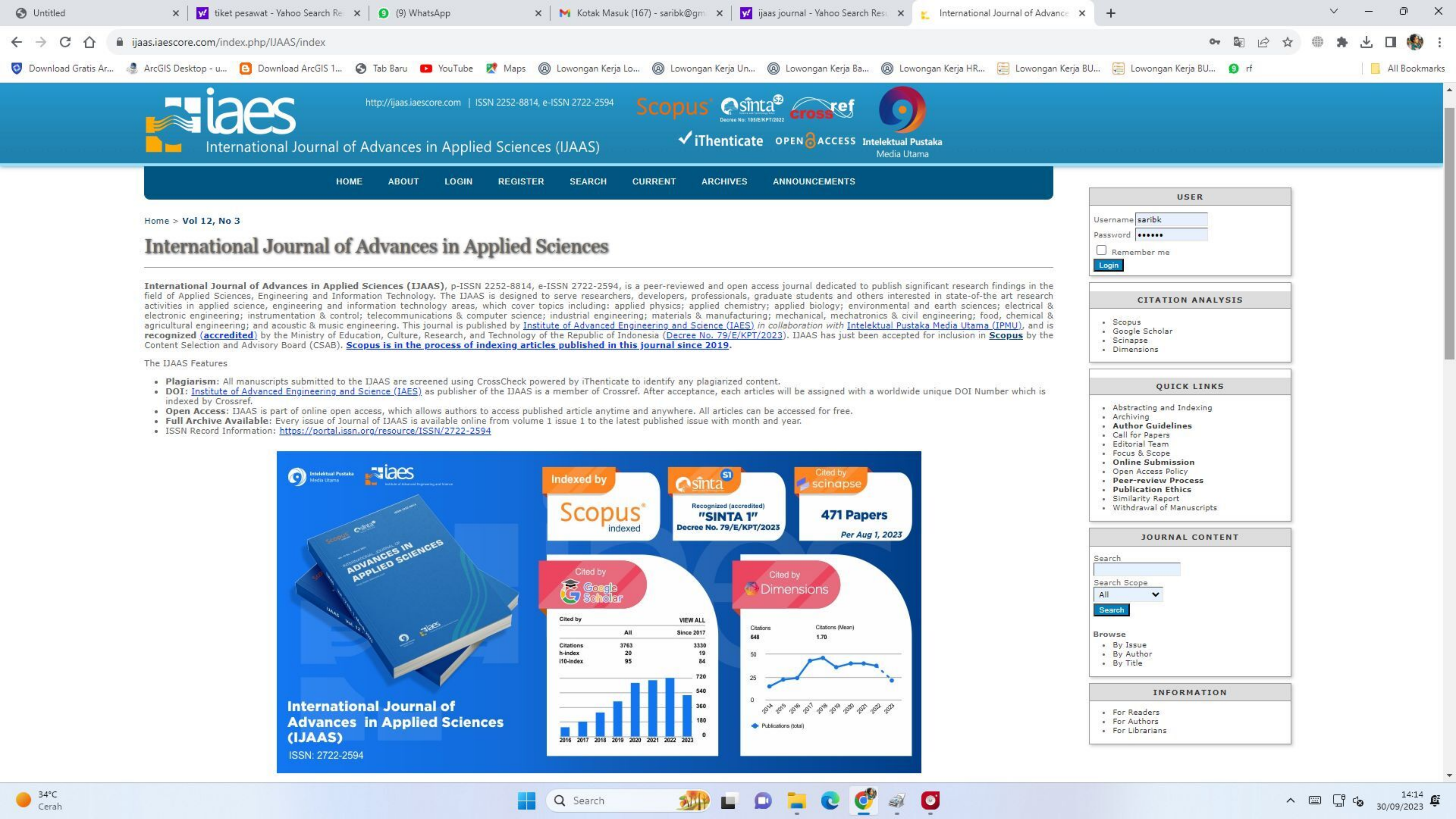

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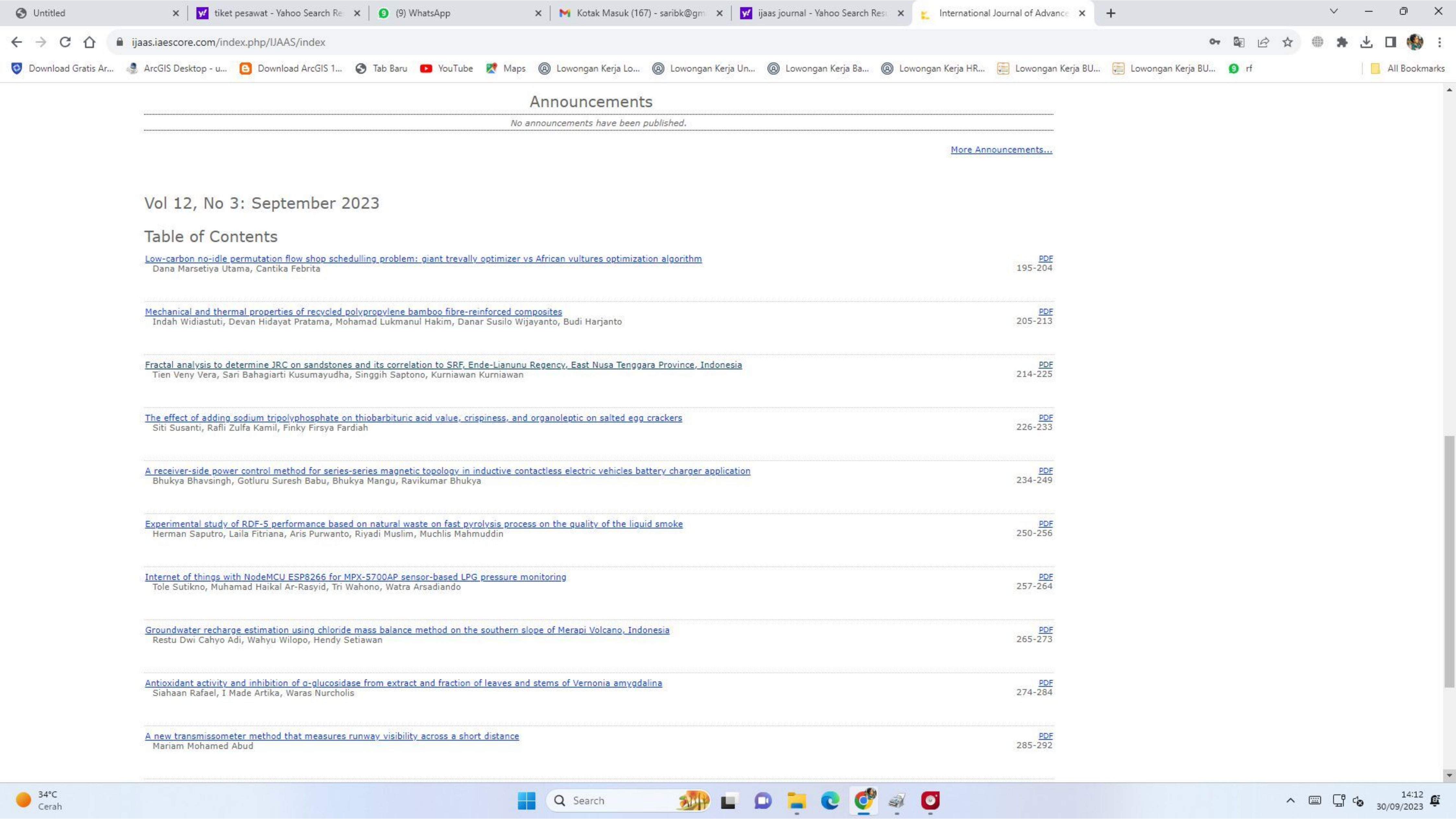

Announcements

No announcements have been published.

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Fractal analysis to determine JRC on sandstones and its correlation to SRF, Ende-Lianunu Regency, East Nusa Tenggara Province, Indonesia

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ABSTRACT

The study area is located in Ende-Lianunu Regency, East Nusa Tenggara Province, Indonesia, with mountainous and hilly morphology, and is part of the Kiro Formation which is composed of tuffaceous sandstones. Discontinuities in the sandstone are in the form of bedding planes and joints, which affect the mechanical properties of the rock mass, reduce its strength, and affect slope stability. The discontinuity condition that affects mechanical behavior is surface roughness. This research aims to define the fractal dimension value of surface roughness using a box-counting method, joint roughness coefficient (JRC), and simulate the strength reduction factor (SRF) value on slopes that have a certain JRC. The fractal dimension of fine-grained samples = 1.0010 and coarse-grained = 1.0056. The average JRC value is 6.25 (Range 4-6). Simulation at JRC 0-20, gives different SRF values. On slopes with JRC = 0, the critical SRF = 1.35. If JRC = 20, the critical SRF = 1.47. It can be inferred, that the fractal dimension of the roughness of the sliding plane correlates with JRC and SRF. As the fractal dimension value increases, so do the JRC and SRF values, resulting in more stable slope conditions.

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1. INTRODUCTION

Sandstone is a sedimentary rock consisting of sand-sized granules or the result of compaction of sediment in the form of loose material. In sandstones, the discontinuities that generally develop are bedding planes and joints, these have a considerable impact on the mechanical behavior of the rock masses, which reduces its strength [1]. The most important discontinuity properties are orientation, planarity, asperity, roughness, and rock wall strength [2]. The surface roughness of the discontinuity plane affects the forces, amendment, and fluid flow properties of a rock. The roughness of the discontinuity has the potential to affect shear forces, especially in the case of interlocking blocks [3]. The key factor in calculating the confining shear strength of a rock mass is the joint roughness coefficient (JRC).

From profile geometries like fractal analysis, many researchers have conducted experiments in estimating the JRC value for a surface [4]–[7] or statistical [8], [9]. Tse and Cruden [10] identified eight different statistical parameters, Z2 (average square root of the tangent of slope angle along profile), and the structure-function shows a significant correlation with the JRC value. Since Mandelbrot [11] introduced fractal geometry, numerous researchers have attempted to utilize it to characterize the roughness of rock surfaces. Many researchers have agreed that the brittle profile of rocks in nature can be thought of as fractal curves and the concept of fractals has proven to be a very useful way of describing the statistics of naturally occurring geometries [11]. Important developments in rock mechanics theory over the last few years have been based on fractal geometry and damage mechanics [12]. As is known, a network of cracks in rocks can be categorized as fractal objects [13]. Conversely, the fragility of rocks at all scales, from the micro-scale, microcracks, to the continental scale, mega faults [14], [15], can give rise to fractal structures, so that fractal analysis can be applied to the field of rock mechanics [16]. The fractal dimension can be computed using various methods. These include divider, box count, variogram, spectral and roughness length [17]. Furthermore, Lee *et al*. [4] also found a coincidence between JRC and D, such that coarser profiles with increased JRC have higher D values. In addition, Seidel and Haberfield [18] and Kulatilake *et al*. [19] also produced similar trends between JRC and D. Sanei *et al.* [7], used Barton's empirical equation to assess rock shear strength and the JRC profile to obtain the JRC-D relationship by comparing the results with previous studies.

Since its introduction by Barton and Choubey [20], JRC has been widely used in rock slope stability assessment. JRC can be assessed by simply matching the roughness of the discontinuity with the roughness profile value. Kim *et al*. [21], analyzed the effect of JRC variations on slope stability using the universal distinct element code (UDEC) and concluded that as the JRC value increases, the slope safety factor also increases. To assess the effect of JRC on slope stability and slope collapse mechanisms, we used numerical analysis with the finite element method, a numerical method that uses the concept of differential equations that considers the stress-strain relationship in the material. With the finite element method, the model will be analyzed by first being divided into small parts called elements.

In this regard, the study area includes the Ende-Lianunu Regency, East Nusa Tenggara Province, Indonesia. This area is located on a hilly morphology with steep to very steep slopes along the edge of the cross-provincial road which is a strategic route connecting the Ende and Maumere regions [22]. The research area is included in the geological map of Ende sheet, East Nusa Tenggara [23], shown in Figure 1. This area is part of the Kiro Formation (Tmk) which is composed of sandstone, tuff, and tuffaceous sandstone, brownish and eroded. The formation is well layered with dips between 10-35°. The formation is of Early-Middle Miocene age with an onshore depositional environment. Sandstones in the study area contain discontinuities and have the potential for landslides.

This paper addresses what is important about the fractal characteristics of the joint roughness of sandstones in the study area and their correlation with the strength reduction factor. Thus, the objectives of this study include computing the fractal dimension values and determining JRC, and SRF values on slopes showing JRC using numerical analysis, the finite element method.

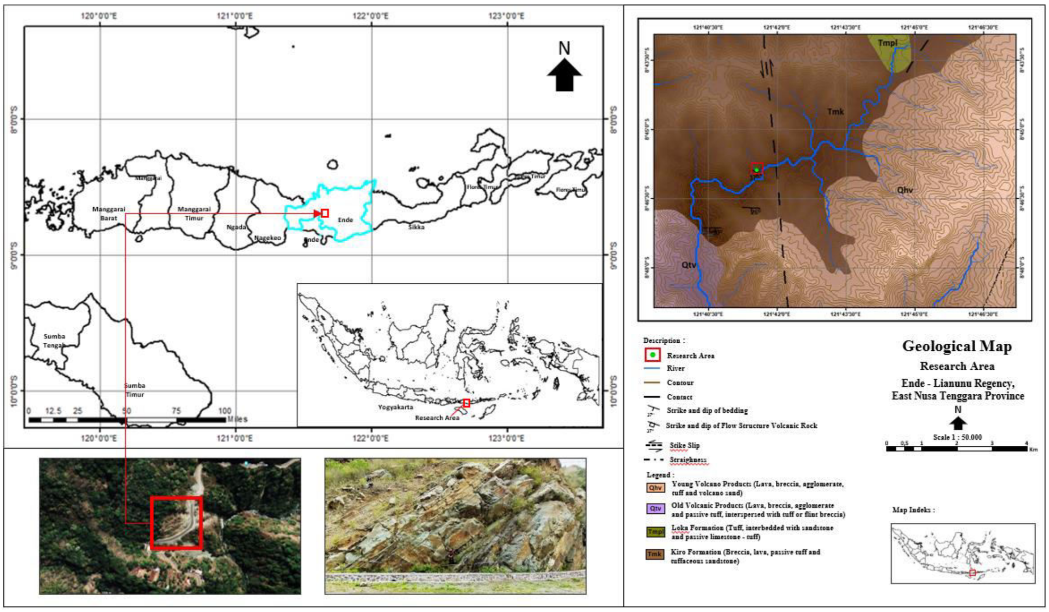


Figure 1. Geological map of the study area, Ende and Maumere regions and Kiro Formation (Tmk) [22], [23]

2. RESEARCH METHOD

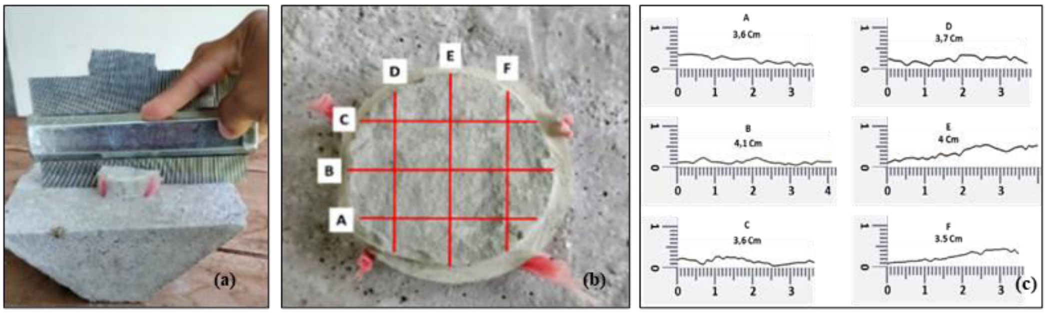
Direct-shear tests were executed to obtain the cohesion (c) and internal friction angle (Ø) of peak and residual rock core samples. The core specimens were subjected to a direct shear test using the Indotest portable shear box RN 140 test apparatus, by using pressure gauges and dial gauges, load-shear and displacement-shear can be measured. Generally, direct-shear testing is performed according to recommended shear-strength determination methods [24]. Direct-shear tests have been performed on 5 samples of rock. Physical and mechanical tests carried out on the sampled rock are shown in Table 1.

Table 1. Physical and mechanical test results

Physical and mechanical tests	Unit	Value
Natural water content	(%)	0.82-2.75
Saturated density (Υ sat)	(g/cm^3)	2.470-1.714
Uniaxial compressive strength	MPa	32.23-70.83
Cohessi (c)	MPa	0.06-1.05
Internal Friction Angle	°	26.57-41.99

2.1. Surface roughness measurement

Rock surface roughness measurements were carried out using the Barton Comb, a measuring instrument for the evaluation of the surface roughness of rock samples, see Figure 2 [25]. This simple device allows a very thin steel needle to be placed perfectly on the surface of the sample being tested, thus obtaining a rock surface profile. The width of the tested sample surface varied from 3.2 to 4.5 cm. Surface roughness was measured using a Barton comb on five rock samples with six surface measurements shown in Figures 2(a) and (b). In one sample, six (A, B, C D, E, and F) surface profiles were obtained using the grid method, to get surface roughness accuracy. The results of the measurement are then photographed and converted to raster data by digitizing the photos using Corel Draw software. The following are the results of the rock surface profile digitization, see Figure 2(c).



(a) (b) (c)

Figure 2. Rock surface roughness measurements using (a) Barton comb, (b) Grid method on the rock surface after shear test, and (c) Digitizing photos using Corel Draw software [23]

2.2. Fractal dimension

In this study, the fractal dimension of joint roughness is calculated by the box-counting method using a small rectangle of boxes as a counting reference. Profiles and contours resulting from horizontal slices of the surface are measured. Select a box size (r) and calculate the number of boxes (N) needed to cover the entire profile or contour. This is repeated for a series of boxes of different sizes [17].

$$D = \lim_{r \to \infty} \frac{\log Nr\ (F)}{-\log r} \tag{1}$$

Where the number of squares covering the fractal set is represented by Nr(F), (F) r is the length of each side of the box. Then the correlation between the number of squares and the square size (l) is plotted on a log-log graph. The fractal dimension D can be obtained by calculating the slope of the plot, see Figure 3.

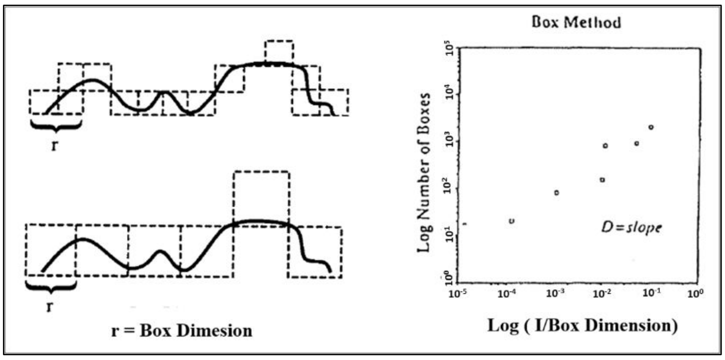


Figure 3. Box-counting method [23] [23]

2.3. Joint roughness coefficient

Hoek [26] points out that the shear strength and stability of excavations in rock masses are influenced by surface roughness. Roughness is a profile or surface shape defined by discontinuity surface irregularity relative to a reference plane [27]. The roughness of joint surfaces is a crucial parameter that affects the mechanical behavior of rock masses [28], [29]. The Barton-Bandis constitutive model offers a truthful representation of rock joint behavior observed in laboratory experiments. These include nonlinearities in normal and shear characteristics, dynamic behavior under repeated loading, removal of asperity during shear transference, and scale-related effects [30]. JRC was introduced by Barton to characterize the surface roughness of the joint [20] 10 roughness profiles and coefficients are assigned on a 0-20 scale to represent different degrees of smoothness, as shown in Figure 4.

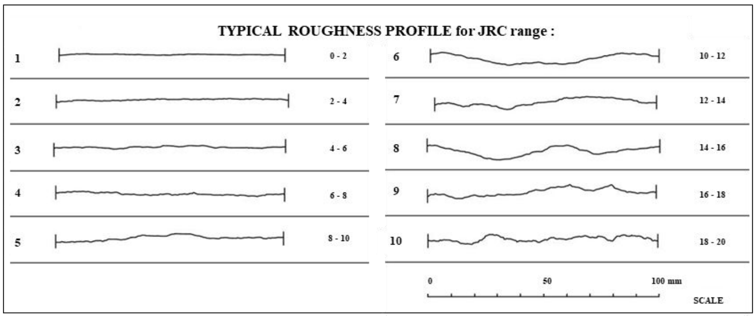


Figure 4. Roughness profiles and defined coefficients ranging from 0-20 [20] [20]

Correlation between fractal dimension and JRC has been established by several previous researchers using empirical statistical equations as a function of dimension, including i) The relationship study used Barton's empirical equation to assess the shear strength of rocks with laboratory tests on more than 30 samples from Bakhtiary Dam and JRC profiles to obtain the JRC-D correlation by comparing the results with previous studies [7]. The resulting equation for the correlation between JRC and D is (2),

$$JRC = -37580D2 + 77018D - 39438 \tag{2}$$

and ii) The surface roughness of the joint becomes an essential factor in the analysis of the displacement and failure of the rock mass along the discontinuity [4]. Objectively, the fractal dimension is a method of measuring the roughness profile of discontinuities. The following is an empirical equation for the relation between the fractal dimension and the JRC value:

$$JRC = -0.87804 + 37.7844(D - 1/0.015) - 16.9304(D - 1/0.015)^2 \tag{3}$$

Based on 10 standard JRC profiles from Barton and Choubey [20], Lee *et al*. [4] calculated the fractal dimension with the results shown in Table 2. The correlation between the fractal dimension value and surface roughness (JRC), means that the roughness increases as the fractal dimension increases.

Table 2. Calculation of fractal dimension for JRC determination [4]

JRC range	Fractal dimension	JRC range	Fractal dimension
0-2	1.000446	10-12	1.005641
2-4	1.001687	12-14	1.007109
4-6	1.002805	14-16	1.008055
6-8	1.003974	16-18	1.009584
8-10	1.004413	18-20	1.013435

2.4. Shear strength of discontinuous

By studying the performance of rock joints, researchers suggested equating as (4) [20], [31].

$$\tau = \sigma_n \tan\left(\emptyset_b + JRC\ log_{10}\left(\frac{JCS}{\sigma_n}\right)\right) \tag{4}$$

The JCS value is the joint wall compressive strength. Later in 1977, Barton and Choubey conducted direct shear test experiments on one hundred and thirty samples of weathered calcified rock, the equation became (5) [20].

$$\tau = \sigma_n \tan\,(\emptyset_r + JRC\ log_{10}\left(\frac{JCS}{\sigma_n}\right)) \tag{5}$$

The value of the residual internal friction angle (∅r) can be estimated from (6).

$$\emptyset_r = (\emptyset_b - 20) + 20\left(\frac{r}{R}\right) \tag{6}$$

Where r is the rebound Schmidt number of the wet and weathered fracture and R is the same for the non-weathered dry fracture, JRC is defined as the degree of roughness of a joint surface, the compressive strength of the joint wall (JCS) is the maximum compressive stress that a joint can withstand when subjected to axial loading, the residual friction angle ($\emptyset r$) is the angle between the plane of the joint and the shear plane after shearing has occurred. These equations are part of the Barton-Bandis criteria for the assessment of the strength and deformability of calcified rock [4].

2.5. JRC scale effect correction

The JRC exhibits a characteristic scale effect. When measured on exposed rock, the JRC value is smaller than that of an actual scale rock joint, as the latter often has less exposure. Hence, it needs to be corrected for the scale effect to obtain accurate JRC values. Barton and Bandis [25] discovered that roughness depends on scale. Small-scale roughness affects short joint lengths while large-scale roughness affects long joint lengths, see Figure 5. By introducing an empirically derived scale correction from JRC:

$$JRCn = JRC0\left(\frac{Ln}{L0}\right)^{-0.02\,JRC0} \tag{7}$$

Where JRC_n is the roughness coefficient of sliding contact surface for discontinuities with length L_n, JRC_0 is the roughness coefficient of sliding contact surface for a discontinuity whose length is L_0; L_0 is equal to 100 mm.

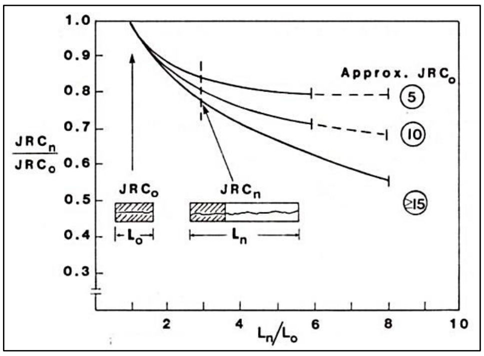


Figure 5. JRC_0 scale effect correction was performed to obtain the JRC of the rocks at the actual scale [25]

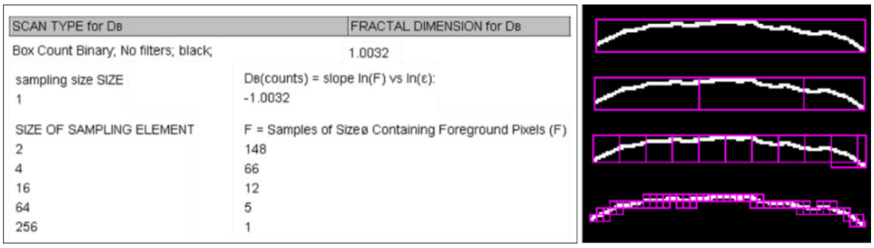
2.6. Finite element method

The finite element method is a numerical method that uses a differential concept that takes into account the stress-strain relationship in the material. In the finite element method, the model to be analyzed is divided into small parts called elements. Each nodal point will form a series that as a whole approximates the shape of the original model. Each nodal point can describe the amount of displacement and stress in each element. Slope stability rating (SSR) is a concept where the shear strength of a rock mass is reduced by a factor called SRF. This SRF value expresses the safety factor of a rock mass [1]. Arif [2] explains that is a method of analyzing slope stability that progressively reduces the shear strength of the material until an avalanche or collapse mechanism forms on the slope. The Factor of Safety equals the SRF at the exact moment of collapse [2].

3. RESULTS AND DISCUSSION

3.1. Fractal analysis

The calculation of fractal dimension uses ImageJ FracLac software, an image analysis software written in Java which was developed by Wayne Rasband of the National Institutes of Health in Bethesda, Maryland [32]. ImageJ FracLac objectively analyses the complexity, heterogeneity, and multiple binary measures of digital images. Extracting patterns from various types of images and converting them into binary digital images for analysis with FracLac is a straightforward process. The input data used are images of the surface of the rock that have been digitized in BMP, JPG, or GIF format. The following is an example of the results of the calculation of the fractal dimension in Section S1-B and the graph of Log r against Log N(F) which can be seen in Figure 6.



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SCAN TYPE for DB                              FRACTAL DIMENSION for DB
Box Count Binary; No filters; black;          1.0032

sampling size SIZE           DB(counts) = slope ln(F) vs ln(ε):
1                            -1.0032

SIZE OF SAMPLING ELEMENT     F = Samples of Sizeø Containing Foreground Pixels (F)
2                            148
4                            66
16                           12
64                           5
256                          1
```

Figure 6. Calculation of fractal dimension in section S1-B using FracLac for ImageJ software

For fractal dimension calculation values, samples S3 and S5 are sandstones with fine grains that have low fractal dimension values of 1.0010 and 1.0017. Samples S1 and S4 are sandstones with medium grain size that have fractal dimension values of 1.0037 and 1.0028 and sample S2 is a tuff sandstone with coarse grain size that has the highest fractal dimension value of 1.0056. The larger the grain size, the rougher the rock surface profile. It can be concluded that high fractal dimension values will be owned by materials with coarse grain size, but it does not apply to materials with uniform grain shape [33]. The fractal dimension provides a distinct quantitative approach to describe surface roughness that can be characterized qualitatively. Table 3 shows the results of the following fractal dimension calculations.

Table 3. Fractal dimension calculation results

Sample	Lithology	Grain size	Fractal dimension						
			Section						Average
			A	B	C	D	E	F	
S1	Sandstone	Medium	1.0035	1.0032	1.0038	1.0039	1.0032	1.0043	1.0037
S2	Tuffaceous Sandstone	Coarse	1.0054	1.0055	1.0058	1.0047	1.0054	1.0065	1.0056
S3	Sandstone	Fine	1.0015	1.0012	1.0008	1.0008	1.0004	1.0015	1.0010
S4	Sandstone	Medium	1.0031	1.0022	1.0029	1.0024	1.0026	1.0035	1.0028
S5	Sandstone	Fine	1.0016	1.0022	1.0012	1.0021	1.0013	1.0015	1.0017

3.2. Correlation between fractal dimension and JRC

The laboratory analysis provides the rock shear strength value. Equation (4) calculates the JRC value, which is provided in Tables 4 and 5. Comparison of fractal dimension results and JRC values using (3) is closest to the JRC value calculated by the researcher's laboratory. While (2) has the lowest JRC value compared to the others. The fractal dimension value becomes the multiplying factor of the equation to calculate the JRC value, where both present the roughness profile of the rock surface.

Table 4. Calculation results of rock shear strength against JRC value

Sample	τ (MPa)	σn (MPa)	$Ø_r$ (°)	UCS (MPa)	UCS/σn	Log 10 (UCS/σn)	JRC
S1	0.26	0.49	14.04	35.38	71.77	1.85	7.55
S2	0.52	0.64	19.29	32.23	50.00	1.70	11.40
S3	0.37	0.69	24.23	70.83	103.18	2.01	1.92
S4	0.48	0.69	24.23	31.5	45.89	1.66	6.60
S5	0.63	0.81	30.96	60.98	75.28	1.87	3.80

Table 5. JRC value calculation resume

Sample	Fractal dimension	JRC from laboratory	JRC from equation previous researcher	
			Equation (2)	Equation (3)
S1	1.0037	7.55	6.28	7.31
S2	1.0055	11.40	9.15	10.78
S3	1.0010	1.92	1.88	1.64
S4	1.0028	6.60	4.88	5.55
S5	1.0019	3.80	2.96	3.07
Average	1.0030	6.25	5.03	5.67

3.3. Scale effect correction

To be able to determine the JRC value of the scaled rock joint, it is necessary to correct for the JRC scaling effect. From the results of the calculation of the empirically derived JRC scale effect correction using (7). The power trendline equation of the JRC_n/JRC_0 value against Ln/L_0 is obtained (8).

$$\mathrm{JRC}_n/JRC_0 = L_n/L_0{}^{-0.05} \tag{8}$$

Figure 7 shows there is a difference in the coefficient in the above equation with (7). The simulation was made using JRC_0 values of 5, 10, and 15, resulting in a rank coefficient value of -0.02. In this study, the JRC_0 values used are 2, 4, 7, 8, and 12 so that the rank coefficient value of -0.05 is obtained. Based on the graph of the JRC_n/JRC_0 value against Ln/L_0 above, it can be concluded that the higher the L_n/L_0 value, the lower the JRC_n/JRC_0 value, meaning that the longer the profile scale, the lower the roughness coefficient value.

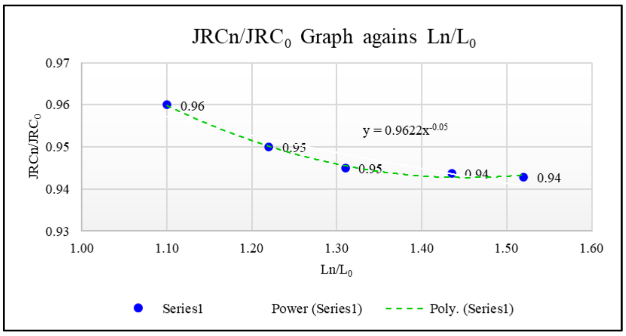
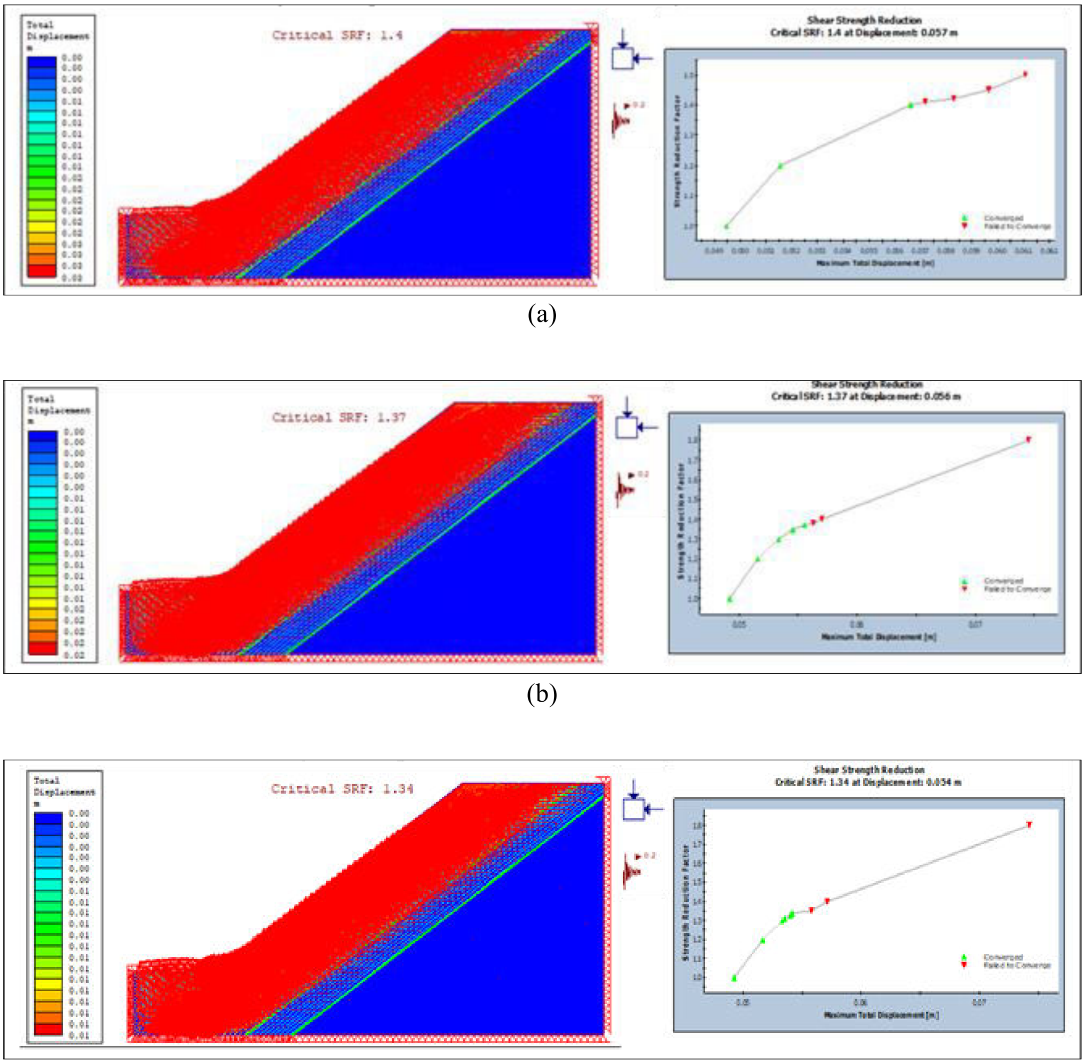


Figure 7. Graph of JRC_n/JRC_0 value against Ln/L_0, showing the higher the Ln/L_0 value, the lower the JRC_n/JRC_0 value

3.4. Numerical analysis based on JRC value

Slope modeling is carried out for further safety factor analysis using the finite element method with RS2 software, shown in Figures 8(a)-(c). The dimensions of the slope are described according to the actual conditions in the field, with a slope height of 40 m and a slope slope of 37°. The slope's unfavorable condition is due to the sandstone layer dipping in the same direction as the slope, which causes the slope in the study area to have the potential for planar type landslides, which is a rock slide that occurs along a sliding plane that is considered to be flat. The slide plane can be a fault plane, a joint, or a rock layer plane.



(a)

(b)

(c)

Figure 8. Numerical analysis using finite element method using RS2 software based on, (a) JRC from laboratory calculation, (b) Lee *et al.* [4], and (c) Sanei *et al.* [7]

Figures 8(a)-(c) above show that the JRC value based on the laboratory value of 1.4 gives the highest SRF value. The SRF values obtained from (3) [4] and (2) [7], were 1.37, and 1.34 respectively. Table 6 shows a tabulation of numerical analysis results based on JRC laboratory calculations, (2) and (3).

Table 6. Numerical analysis results based on JRC from laboratory, (2) and (3)

No.	JRC calculation	SRF	Displacement (m)
1	Laboratory	1.40	0.057
2	Equation 3	1.37	0.056
3	Equation 2	1.34	0.054

3.5. Numerical analysis based on simulated JRC value

Numerical analysis based on simulation of JRC values of 0 to 20, obtained varying SRF values. Table 7 displays the analysis results. Results of numerical analysis based on simulation of JRC values 0 to 20, obtained SRF values vary. In the simulation of the JRC value of 0, which means that the slope conditions are not affected by the JRC, the SRF value of 1.35 is obtained at a displacement: of 0.055 m. While the slope with the largest JRC influence (JRC = 20) has an SRF of 1.47 at displacement: 0.054 m. Everything is in a stable condition because it is above the FoS>1.1. JRC affects the SRF value because it represents the variation of rock surface roughness. A rough rock surface will make the material have high shear strength due to interlocking between grains. As a result, the increase in maximum displacement will be slow and gradual, with the shear strength of the material decreasing gradually until failure occurs and the critical point of the SRF is reached. Increasing the JRC value corresponds to an increase in the roughness of the rock surface and the SRF value of the slope. The relationship between JRC, fractal dimension, and SRF is shown in Figure 9.

Table 7. Results of numerical analysis based on simulated JRC values

JRC	Fractal Dimension	*SRF*	JRC	Fractal dimension	*SRF*
0	1	1.35	11	1.005027	1.42
1	1.000223	1.36	12	1.005641	1.42
2	1.000446	1.37	13	1.006375	1.43
3	1.000843	1.37	14	1.007109	1.44
4	1.001687	1.38	15	1.007582	1.44
5	1.002246	1.38	16	1.008055	1.44
6	1.002805	1.38	17	1.008819	1.45
7	1.003389	1.39	18	1.009584	1.46
8	1.003974	1.4	19	1.011509	1.46
9	1.004193	1.42	20	1.013435	1.47
10	1.004413	1.42			

Reading the graph of the relation between the value of the fractal dimension, JRC, and SRF, see Figure 9, it can be seen that the red dotted line intersects the blue (Fractal dimension vs. SRF) and brown (Fractal dimension vs. JRC) lines, where the x-axis (JRC) is 14, the fractal dimension value will be read on the y-axis (fractal dimension) of 1.0071, and on the y-axis (SRF) the SRF value of 1.44 is obtained. The graph above shows The relation between the value of the fractal dimension to JRC and SRF, where the higher the fractal dimension value, the higher the JRC and SRF values so the more stable the slope conditions because roughness is influenced by the size of the grain material that holds each other or interlock. The JRC parameter is only one of the parameters that affect the stability condition of a slope, there are others such as whole rock strength, rock quality designation, discontinuity field spacing, discontinuity conditions (persistence, aperture, infilling, and degree of weathering) and groundwater conditions.

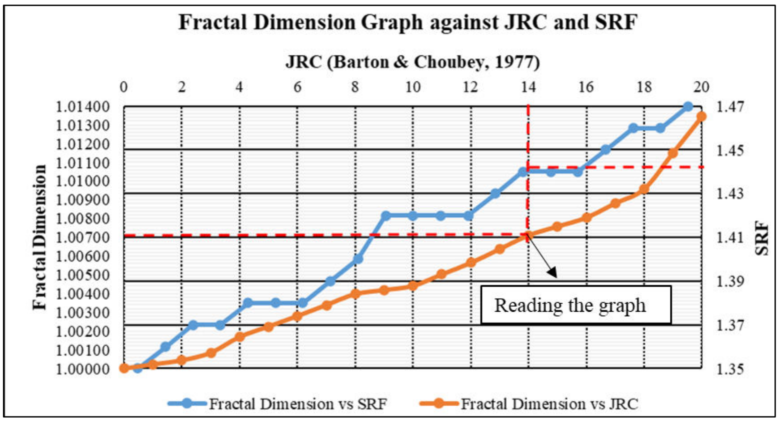


Figure 9. A graph comparing the fractal dimension with JRC and SRF values reveals an increase in JRC and SRF values with higher values of fractal dimension

4. CONCLUSION

From the research results we can conclude, first, the average JRC value in the study area is 6.25, with a range of 4-6. The five types of sandstone in the study area show that fractal dimension, grain size, JRC, and rock shear strength have a positive correlation. Higher fractal dimension values result in coarser grain size and higher JRC and rock shear strength values which affect slope stability. Second, from the fractal analysis of the roughness, and after analysis based on the JRC value in the range 0-20, there is a relationship between JRC, fractal dimension value, and SRF that has a positive correlation, the higher the value of the fractal dimension, the higher the values of JRC and SRF, and therefore the more stable the slope conditions.

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