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Study of the crack extension about splitting grouting based on fracture mechanics[1]

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Abstract. The extended geometric shape of soil crack is an important factor in the strengthening design of split grouting, but the occurrence and development of soil split grouting is difficult to be visualized. This paper studies the cracks form of splitting grouting, establishment of the failure criterion and determination method of crack from the point of fracture mechanics. In order to establish the finite element model of crack extension we employed ABAQUS software together with engineering parameters of soil reinforcement from Lanzhou New Area fast road project K1 + 662.053. We also analyzed the crack length and effect of split grouting pressure and the impact of soil physical and mechanical properties. This research report demonstrates that when calculating split grouting pressure we should take the impact of crack extension length and soil strength parameters into major consideration. Crack length is affected dramatically by grouting pressure in which it shrinks non-linearly as the crack length increases.

Key words. Loess, split grouting, crack length, fracture mechanics, extension (propagation) behavior, effective paths.

1. Introduction

Grouting technology is a very professional academic branch of geotechnical engineering which has a good effect in improving the engineering geological conditions. Fracturing grouting is the exploitation of slurry pressure to promote the expansion of soil cracks, which changes the original structure of soil. And through the filling of the slurry it should also eliminate the soil of the overhead space, eliminate the collapsibility of soil, and, finally, to achieve the purpose of reinforcement [1]–[3]. Due to

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the conspicuous soil thickness in the Loess Plateau region, utilizing grouting method to reinforce the building of settlements has become an effective mean of technology. However, most of the engineering design is blindness, and the selection of grouting parameters often depends on subjective experience. In addition, the research on the expansion behavior theory of the slurry in the soil body is very slow during the grouting.

It is very necessary to study the fracturing grouting crack propagation distance, which has a close connection with the effect of grouting reinforcement. The hydraulic fracturing process usually refers to the soil or rock mass that they produce crevice under high liquid pressure [4]. This theory is not only the theoretical basis of treatment engineering seepage control, but it is also the key method to solve the underground grouting engineering. The stress intensity factor is an important parameter to characterize the fracture of material, and it is one of the most important factors for solving various kinds of cracks of fracture mechanics [5]. In order to develop a calculation method for the fractured rock mass fracturing grouting pressure, Zou et al. adapted a strength criterion of nonlinear Hoek-Brown in fracture mechanics, and established the type II and mixed mode cracks of fracturing grouting pressure calculation method in the fractured rock mass, which introduces the hydraulic fracturing theory and fracture mechanics method into the theory of fracturing grouting [4]. Aiming at the plane strain of tunnel, plane model study of elastic stage of composite soil after split grouting was studied; on the basis of the study of the existing split diffusion model and area equivalent principle, a two dimensional simplified equivalent unit model of the composite soil after split grouting was put forward. Based on the theory of homogenization, the equivalent elastic parameters of the two dimensional simplified model were derived by the principle of deformation coordination [3]. Based on the Bingham constitutive model, a single plate crack slurry transport equation was established under the condition of constant pressure grouting [10]. However, most of studies were based on special rock conditions, and it was difficult to better explain the strengthening mechanism of split grouting in collapsible loess area of large thickness.

To research the criterion and determination method, a finite element model of crack extension was established by using ABAQUS software and combining Lanzhou New Area fast road project K1 + 662.053 engineering parameters of soil reinforcement. Some aspects of soil were also analyzed, such as the crack length, effect of split grouting pressure, and impact of physical and mechanical properties. It provides guidance and references for the engineering practice of split grouting in the large thickness of the west of China.

2. Fracturing mechanics analysis of fracturing pressure

2.1. Griffith crack assumption

The substance of fracturing grouting is to use high pressure grouting process, based on injecting cement or chemical agent. Then the grout puts additional compressive stress to the surrounding soil and the soil produces shear fracture and fracture failure. According to the theory of Griffith crack [5], fracture is not the two part along the interface of crystal breaking, but the result of the soil mass crack extension under the pressure grout in the process of grouting soil.

In this paper, the substance of the loess in the process of fracturing grouting cracks under the uniform internal pressure was simplified for the elliptical hole process Griffith crack under the uniform internal pressure. As shown in Fig. 1, we assume that the soil in the distance is not subjected to force, and affects the distributed pressure p on the elliptical hole L evenly. Then, according to elastic theory, the boundary conditions are as follows [5]:

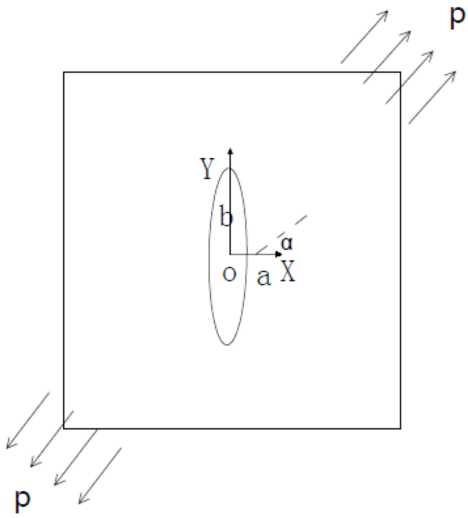

Fig. 1. Stress distribution in fracture model

$$\text{for } \sqrt{x^2+y^2} \to \infty : \ \sigma_{ij} = 0\,. \tag{1}$$

For $(x+y) \in L$ there holds

$$\left.\begin{aligned} \sigma_{xx}\cos(n,x) + \sigma_{xy}\cos(n,y) &= -p\cos(n,x)\,, \\ \sigma_{xy}\cos(n,x) + \sigma_{yy}\cos(n,y) &= -p\cos(n,y)\,. \end{aligned}\right\} \tag{2}$$

Here, $\cos(n,x)$ and $\cos(n,y)$ express any point outward normal direction of direction cosine. Symbol n expresses the the unit outward normal to the point.

According to fracture mechanics theory, the hole side stress can be obtained using the formula

$$\begin{aligned} &(\sigma_{\varphi\varphi})_{\rho=1} = p\tfrac{1-3m^2+2m\cos 2\varphi}{1+m^2-2m\cos 2\varphi}\,, \\ &(\sigma_{\rho\rho})_{\rho=1} = -p\,, \end{aligned} \tag{3}$$

where $m = (a-b)/(a+b)$.

The maximum normal stress is

$$\left.\sigma_{\max} = (\sigma_{\varphi\varphi})_{\substack{\rho=1\\ \varphi=0,\pi}} = (\sigma_{yy})_{\substack{x=\pm a\\ y=0}} = p\frac{1+3m}{1-m} = p(-1+2\frac{a}{b})\right\}. \quad (4)$$

Comparing the formula (3) and (4), the radius of curvature $\rho_0 \to 0$ at the top of the elliptic semi-major axis, internal pressure of elliptical hole and stretching of maximum normal stress of elliptic hole are almost the same. At the same time, the elliptic hole is transformed into a Griffith crack when $b = 0$.

2.2. Establishment of fracturing crack failure criteria

Stress distribution within the crack is composed of two parts when fracturing grouting, namely the original ground stress and pore fluid pressure. As stipulated in fracture mechanics, tensile stress is positive and pressure stress is negative, while the plus-minus sign is just contrary in soil mechanics [4]. To simplify the calculation, this paper considers the compressive stress positive. Then, the soil mass crack fracture mechanics analysis model diagram is shown in Fig. 2. Assuming that the soil is homogeneous and isotropic, according to the linear elastic theory of semi-infinite medium, the shear failure criterion satisfies Mohr–Coulomb criterion.

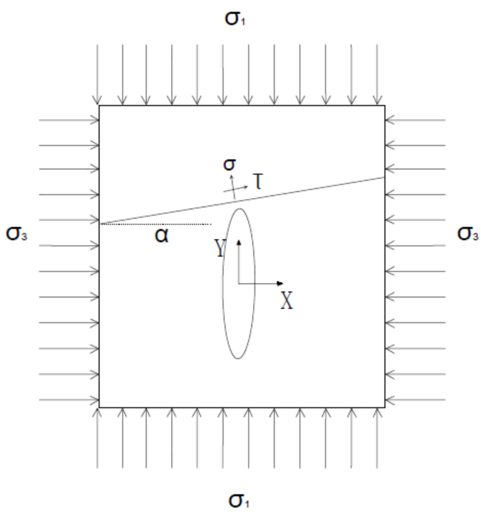

Fig. 2. Soil mass crack fracture mechanics analysis model diagram

The criterion expression is

$$\tau = C + \sigma_{\mathrm{n}} \tan\varphi\,, \quad (5)$$

$$\tau = \frac{\sigma_1 - \sigma_3}{2} \sin 2\alpha\,, \tag{6}$$

$$\sigma_{\rm n} = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos 2\alpha\,. \tag{7}$$

The symbols τ and $\sigma_{\rm n}$ represent the shear stress and normal stress on the surface of the shear failure, respectively; symbol α shows the shear failure plane method and the maximum principal stress direction angle, φ and C show the internal friction angle and cohesive force of soil, respectively.

According to the principle of Terzaghi effective stress, the pore pressure of soil shear failure occurs and can be expressed as

$$p_1 = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos 2\sigma - \frac{\left(\frac{\sigma 1 - \sigma_3}{2} \sin 2\alpha\right)}{\tan\varphi}\,. \tag{8}$$

In accordance with the above analysis, the serous fracturing surface usually occurs in the stress on the surface of least resistance. So we can see that once the normal stress on the surface of the shear fracture is equal to zero, cracks begin to expand, and the pore pressure is

$$p_2 = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos 2\sigma\,. \tag{9}$$

2.3. Fracturing grouting discriminant methods of crack extension

When fracturing grouting loess conforms to the rule of fracture mechanics of the propagation of the crack (namely during crack propagation), the end of each point stress intensity factor is equal to the critical stress intensity factor of the loess [5]. Fracture criterion of crack propagation is then as follows

$$K_{\rm I} = K_{\rm IC}\,. \tag{10}$$

The symbol $K_{\rm I}$ is the crack extension criterion which is the stress intensity factor of crack, while $K_{\rm IC}$ is the fracture toughness. Among them:

$$K_{\rm I} = \frac{p\sqrt{\pi}}{E(k)} \left(\frac{b}{a}\right)^{\frac{1}{2}} (a^2 \sin^2\varphi + b^2 \cos^2\varphi)^{\frac{1}{4}}\,. \tag{11}$$

The formula $E(k)$ is the second type of complete elliptic integrals, namely

$$E(k) = \int_0^{\frac{\pi}{2}} \left(1 - k^2 \sin^2\alpha\right)^{\frac{1}{2}} \,{\rm d}\alpha\,, \tag{12}$$

where

$$k^2 = \frac{a^2 - b^2}{a^2}\,. \tag{13}$$

The length and width of the crack are equal when assuming that the crack front is infinitely small, namely $a = b$. The elliptical crack becomes a disc crack at this time and

$$E(k) = \frac{\pi}{2}\,. \tag{14}$$

Then a simplified formula can be obtained and at any point the stress intensity factor of homogeneous internal pressure along the elliptic crack front is

$$K_{\mathrm{I}} = \frac{2p\sqrt{a}}{\sqrt{\pi}}\,. \tag{15}$$

3. Model analysis

3.1. Project summary

The fast road project K1 + 662.053 is a section of engineering in Lanzhou new district, Formations for the top are loess, gravel layer and the bedrock. According to the field condition, the design of grouting depth is 5. m, the undisturbed loess under SEM microscopic structure is as shown in Fig. 3, undisturbed loess mechanics performances are shown in Table 1.

Table 1. Mechanical properties of intact loess

The moisture content ω (%)	Void ratio e	Modulus of elasticity E (GPa)	Poisson ratio μ	Cohesive force C (kPa)	Angle of internal friction φ (°)
20.3	1.10	20	0.3	32	26

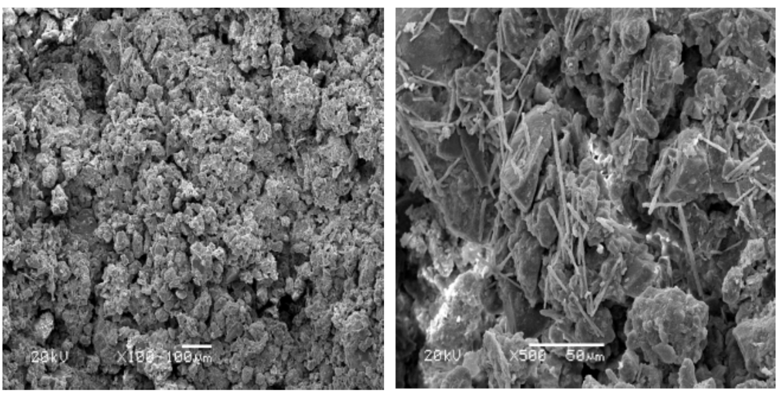

Fig. 3. Microstructure of undisturbed loess SEM: left–100 times magnified, right–500 times magnified

3.2. Model building

The grouting process of crack propagation was simulated by the finite element software ABAQUS. The stress intensity factor of the calculation unit can be calculated by the analysis of the stress and serous pore pressure values of the model, and whether the crack will extend can be evaluated by the criteria proposed in this paper. The model area is shown in Fig. 4.

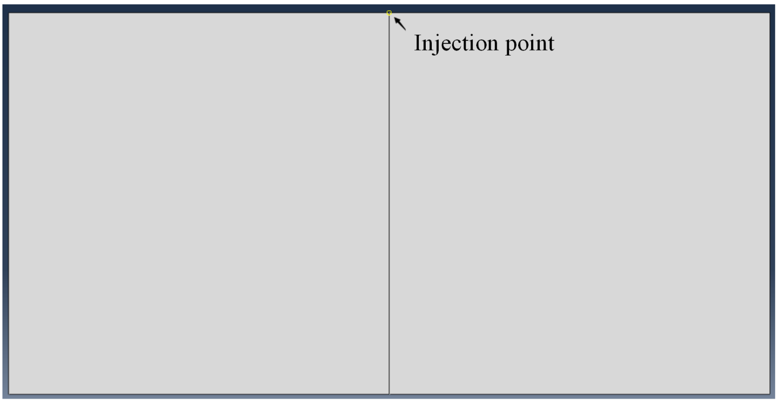

Fig. 4. Crack growth demonstration model

The parameters were selected in the following way: the fracture toughness of the loess is taken $K_{\mathrm{IC}} = 2.7\,\mathrm{MN/m^{3/2}}$ and the fracture energy in the shear mode is 54.7 J. Cohesive unit selection is COH2D4, other materials selection is CPS4R, the field test process can be determined using this method of the stability of the loess soil structure by analysis the calculation results. The analysis of fracture-initiation pressure and fracture morphology belongs one of the key technologies of fracture grouting. According to the changes of stress path in different times, the damage of the element can be analyzed, and the crack propagation in different periods can be obtained. The element boundary taken as a "Path" is shown in Fig. 5, the calculation path being conducted from the bottom up.

3.3. Data analysis

According to the changes of stress path in different times, the damage of the element can be analyzed, and the crack propagation in different periods can be obtained [11–12]. The calculation results of stress path are shown in Fig. 6.

In Fig. 6, we can see that the maximum value of S11 at the lowest end of the path is less than 2.7 MPa when time $t = 0.075\,\mathrm{s}$, and the interface did not appear failure behavior. The S11 at the lowest end of the path achieved the damage value of 2.7 MPa when time $t = 0.1143\,\mathrm{s}$,and the lower end of the unit began started to damage at this time. When time $t = 0.1720\,\mathrm{s}$, the path at the bottom of the interface is declining S11 value of damaging the original point. The value is not zero, which indicates that the damage value D does not reach 1 yet, although destruction was

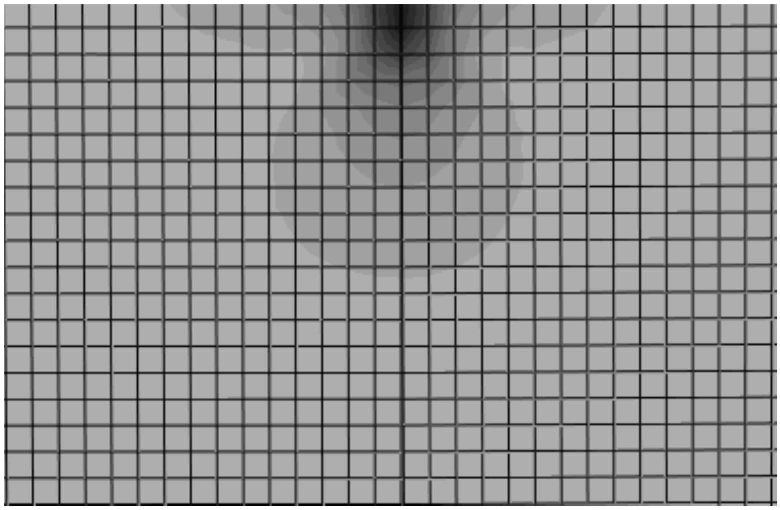

Fig. 5. Calculated interface path diagram

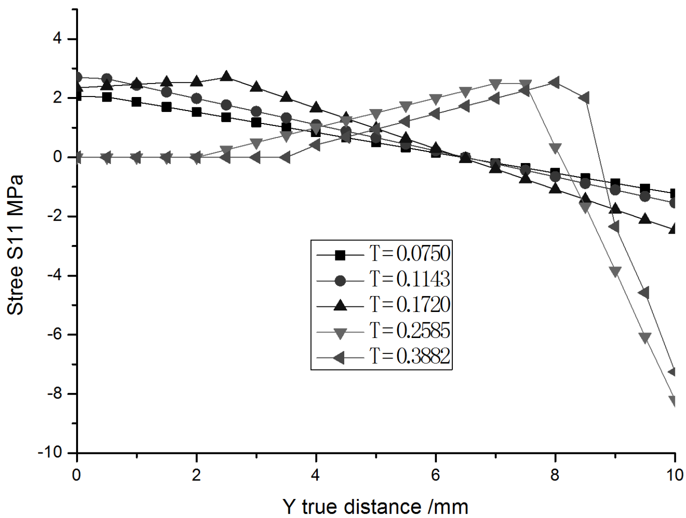

Fig. 6. Path diagram of calculation results

conducted here. The interface crack tip continues to spread along the path. When time $t = 0.2585\,\mathrm{s}$, one can see several S11 values on the top of the patch and bottom is zero. It is showed that the damage value of these units has reached 1, and it means a complete failure state. When time $t = 0.3882\,\mathrm{s}$, the failure units continues to increase, and crack continues to propagate along the path.

By analyzing the pressure of different periods, it is found that the damage of the unit is advancing slowly with time and the failure unit is increasing slowly. At the same time, the expansion of the crack also expands slowly with the increase of the failure unit, which shows that the stress intensity factor of the crack is greater than the stress intensity factor of the unit. With the expansion of the crack, the stress intensity of the crack gradually becomes smaller and smaller until it is less than the stress intensity factor of the element.

Cracks of soils are expanded through grout pressure in fracturing grouting to change the original structure of the soils. Overhead inter-spaces of the soils are removed through filling grouts, thus removing collapsibility of the soils and reaching consolidation [9]. The curves of crack length and grouting pressure are as shown in Fig. 7.

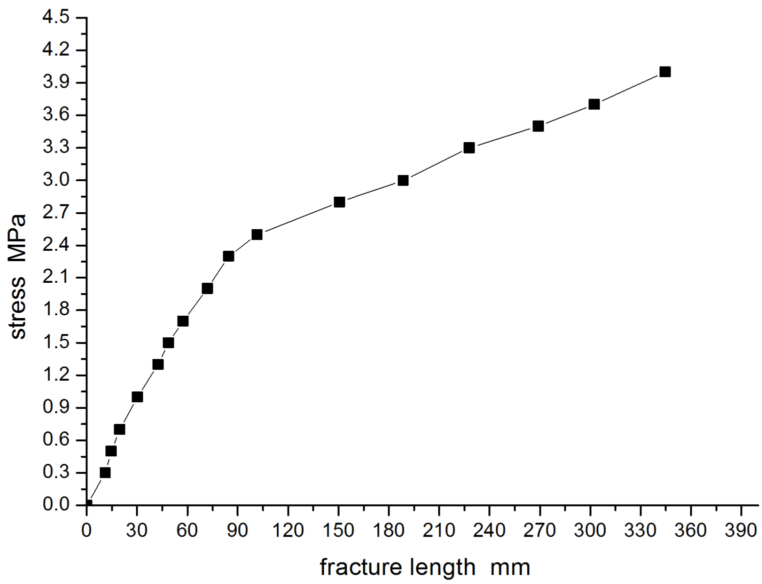

Fig. 7. Curves of crack length and grouting pressure

One can see in Fig. 7 that the crack length is affected by grouting pressure significantly; with the crack length increasing, the grouting pressure presents a nonlinear increase curve. At the same time, the nonlinear extension of the crack length indicates that the structural integrity of the local loess is better; the reason is that only the integral loess soil can form a long crack length. On the contrary, if the crack length changes not obviously with the increase of grouting pressure, it means that the structure integrity of the loess is not completed and may be damaged. In addition, the tension stress and shear stress that the slurry in the extension process in soil needs to overcome, increases with the increase of the crack length. Therefore, from Fig. 8 we can see that grouting pressure increases with the increase of the crack length.

Fracturing grouting cracks extension is not only related to the grouting construction technology, but also to the in situ stress and physical and mechanical properties of soil [6]. As one of two important parameters of the rock (soil) mass, internal friction angle is a shear strength index and an essential parameter of engineering design [7]. Internal friction angle of the soil reflects the frictional characteristics. Influence of internal friction angle of the soil on grouts flowing in the cracks is remarkable during fracture grouting.

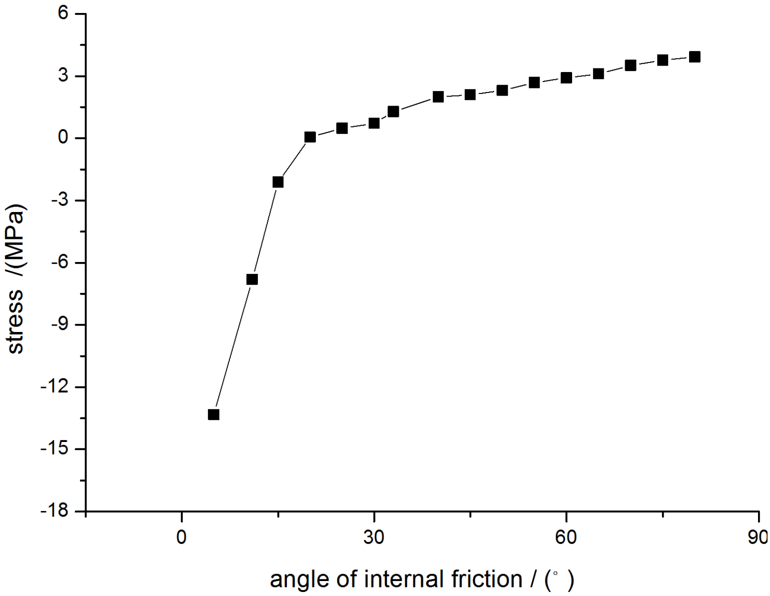

Fig. 8. Relationship between grouting pressure and internal friction angle

Based on literature [13], shear strengths of rock and soil material consist of two parts. However, the cohesion reaches its peak when in small deformation, while the friction can only give full play upon occurring rather large deformation. As a result, the cohesion displays fragility of the rock and soil, while the internal friction demonstrates plastic property. A curve of grouting pressure changing along with the variation of the internal friction angle is shown in Fig. 8. We can see from Fig. that gradually increasing grouting pressure is required with the increasing internal friction angle of the soil. As the destructive process of the rock and soil is just the process of the friction gradually play its role, the larger the internal friction angle of the soil; Grouting pressure shall overcome the strength of the soil, leading to the greater resistance of flowing grouts. Thus, the greater grouting pressure is required.

3.4. Test analysis

In the process of the actual test, fracturing grouting soil mass crack propagation can be analyzed by the change of displacement of soil. Because the test zone of fracture form is more complex, it is difficult to evaluate the results by statistics tools. So we selected the test section which is more representative from a few viewpoints. The measured crack extension data are shown in Table 2.

Table 2. The test results of crack propagation

Number	Soil depth/m	Grouting pressure/MPa	Fracture length/m	Delay on highly/m	Decurrently height/m
Test 1#	4	0.9	0.31	0.031	0.029
Test 2#	4	0.9	0.33	0.027	0.025
Test 3#	4	0.9	0.32	0.030	0.026
Test 4#	4	0.7	0.25	0.024	0.021
Test 5#	4	0.7	0.24	0.022	0.025
Test 6#	4	0.7	0.25	0.021	0.020

According to the test of 1–6 reinforced soil monitoring data (Table 2), after the splitting, crack propagation in 0.24 m–0.32 m decreases with depth. For the soil under the different pressure of fracture, simulation results and experimental data are basically identical. Meanwhile, under low pressure, the diffusion distance is smaller, but near the injection pipe, the soil displacement is larger. Therefore, we can deduce that under low pressure, slurry long time in a bubble form, to compaction of soils, soil under the high pressure is given priority to with splitting, slurry flow far away. And fracture general trend of present along the split face next fracturing, rarely possible secondary splitting.

In Table 2, the soil mass crack propagation length is closely related to the ductility ratio and soil mass stress state, and the ratio measurement with the soil circle size a linear relationship between principal stress ratios. It also verifies the splitting cracks in the smallest little the conclusion of extending direction of principal stress plane

Microstructure analysis (see Fig. 3) found that soil structure differs from between space distributions. Lead to split face uncertainty guide, make each time grouting grout to different, cause of fracture of surrounding soils in the local discreteness. It also demonstrates the soil particle cementing with structural, and the expansion of crack is weak cementation with fracture.

In this paper, the studied object is loess medium. The grouting crack simulation results of tested soil layer under different pressure are basically consistent. The results show that the crack propagation of split grouting is consistent with the Griffith crack theory in fracture mechanics.

4. Conclusion

1. Based on the fracture mechanics, the crack forms, failure criterion and determination method of the crack expansion in splitting grouting process were studied and crack propagation model in Loess Area was established.

2. Through the model analysis, it is concluded that the crack growth is controlled by the fracture factor. The stress intensity factor of the computational element can be calculated according to the crustal stress and pore pressure, and through the decision criterion it is possible to evaluate whether the crack is extended.

3. The crack expansion of split grouting is not only related to the grouting construction technology, but also related to the crustal stress and the physical and mechanical properties of soil. The effect of crack length by grouting pressure is particularly significant, also the regularity of crack length illustrates the stability of the soil structure. Using this method can determine the stability of loess soil structure in the field tests, and provides a theoretical guidance for the follow-up field reinforcement design.

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