Acta Technica *62* (2017), No. 5B, 161–168

Numerical study on one dimensional cement-based fracture grouting in weathered granite based on FEM

WANG Hongbo[2], ZHANG Qingsong[2], LIU Rentai[2,3], ZHENG Zhuo[2], JIANG Peng[2]

Abstract. A numerical model of one dimensional fracture grouting in sediment is proposed based on Finite Element Method and solid-fluid coupling theory. The injected grout and the sediment are treated as a continuum as a whole, in which the stresses and strains are averaged over a certain representative volume. Fracture propagation process was successfully simulated and variation of fracture length and width at different times was acquired. Results show that: For a constant injection rate condition, the length of the fracture increases with time in an almost linear trend. The width of the fracture is comparatively large around the inlet and reduces along the advancing direction. The maximum deformation occurs near the inlet on both the upper and lower side of the fracture. The grouting pressure increases linearly with time at first and then decreases slowly until it reaches a constant value. As the elastic modules of the sediment increases, the initiation pressure becomes larger, And the gap between the fracture initiation pressure and the propagating pressure also increases, which means it is harder for the sediment to be fractured.

Key words. Fracture grouting, fluid-solid coupling, dinite element method, numerical simulation.

1. Introduction

Fracture grouting has been used as an effective method for ground improvement during construction of geotechnical project, which effectively improves the mechanical property of the sediment and provide sufficient strength for excavation[1–3]. For sediments with a lower strength than intact rock, such as weathered granite, the fracturing behavior is greatly influenced by the permeability. With the permeability

---

[1] Acknowledgement - This work is support by the national key research and development plan of China (2016YFC0801600)

[2] Workshop 1 - Geotechnical and Structural Engineering Research Center, Shandong University, Jinan, 250061, China

[3] Corresponding author: LIU Rentai; e-mail: `1205961129@qq.com`

increasing, the flow patterns of the grout changes through three phases: fracture grouting, fracture-permeation grouting and permeation grouting. During the grouting process, grout materials are injected into the ground. The sediment is fractured due to grouting pressure. Then, the grout spreads to further distance as the fracture propagates. The pressure at which fracture occurs is called initiation pressure, which depends on the properties of the sediment, such as the Poisson's ratio of the sediment, the initial circumferential tress, and the degree of saturation and consolidation. As the grout advances, pressure loss increases due to viscous force of the grout and the resistance on the interface between grout and the sediment. Thus, the injection pressure should be increased in order to keep grout advancing. The grout process ceases when the grout reaches the boundary of target reinforcement area or the injection pressure reaches its upper limit value.

In recent years, a series of empirical and theoretical models has been proposed for estimating the initiation pressure, pressure loss, and the length and thickness of the fracture [4–8]. However, due to the complicated interaction mechanism between grout suspension and sediment, the validation and the application conditions of these models still need to investigate. Moreover, the process of fracture propagation can hardly be observed directly, and the information of the fracture shape and pressure variation is acquired usually by indirect measurements. With the development of computing technology, it is convenient to study complicated scientific problems using numerical methods. Thus, a number of numerical simulations have been carried out for better understanding the grout fracturing mechanism, such as the crack initiation and grout vein propagation process [9–14]. The numerical methods provide a direct understanding of the grout advancing process.

In this study, a numerical model of one dimensional fracture grouting in sediment is proposed based on Finite Element Method and solid-fluid coupling theory. The injected grout and the sediment are treated as a continuum as a whole, in which the stresses and strains are averaged over a certain representative volume. The fractured area of the sediment, which is occupied by the injected grout, is characterized by changing the physical and mechanical properties. Fracture propagation process was successfully simulated and variation of fracture length and width at different times was acquired.

2. NUMERICAL MODEL OF FRACTURE GROUTING

2.1. Fundamental mechanism of fracture grouting

Generally, solid material is fractured when the tensile stress at the fracture tip exceeds the tensile strength. The stress distribution during fracture grouting process is shown in Fig. 1. The original stress field is represented by the black arrows, composed of minimum principal stress in vertical direction and maximum principal stress in horizontal direction. Before grouting, the sediment is in a compressive state. Then, as the grout is injected, the sediment is fractured and the stress field is changed. At the interface between grout and the sediment, the sediment is compressed by the grout pressure and the fracture width keeps increasing. At the fracture tip, the sediment is in a tensile condition. The fracture propagates when the grout pressure is sufficient to break the bonding force of the sediment. From fracture tip to infinity along horizontal direction, the stress state changes from tensile to compressive and level off to the minimum principal stress.

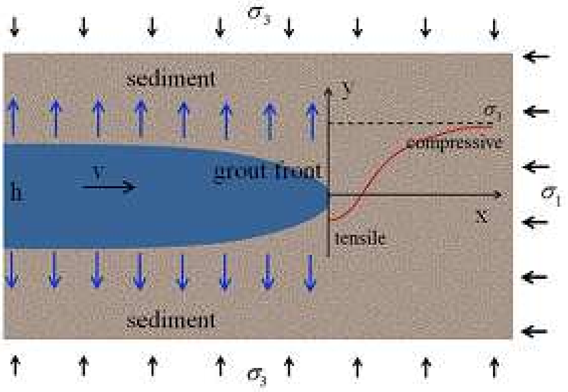

Fig. 1. Stress distribution in the sediment during fracture grouting process

The physical and mechanical property of sediment is significantly influenced by the influence of surrounding condition, such as crustal stress and groundwater. The permeability and mechanical characteristics can change greatly during fracture grouting process. In this model, the failure of sediment caused by grout fracturing is regarded as a total loss of integrity or formation of yield area with strain softening response.

The grout advancing process and the flowing of the pore water in sediment is described by Darcy's law. The flow is driven by gradients in the hydraulic potential field of the grout suspension. According to Darcy's law, the net flux across a face of porous surface is expressed as:

Where u is the velocity of grout, is the density of grout, p is grout pressure, K is permeability of the medium, is grout viscosity, g is gravitational acceleration, and D is vertical coordinate.

The continuity equation for the grout is expressed as:

Where is the porosity, and is a mass source term. Porosity is defined as the fraction of the control volume that is occupied by pores.

The relationship between the storage coefficient and porosity is expressed as:

Inserting Eq. 1 and Eq. 3 into Eq. 2 produces the generalized governing equation:

3. Fracturing process

According to Touhidi-Baghini, permeability can be expressed as a function of the initial state of permeability, porosity and volumetric strain:

Here, K_0 and are initial permeability and porosity, is the volumetric strain. B is an empirical coefficient, and is set as 2 in the following calculation.

4. Sediment deformation

The stress-strain relationship of the medium with the influence of fluid pressure is expressed as:

Here, is the Cauchy stress tensor, is the strain tensor, is the Biot-Willis coefficient, C is the elasticity matrix.

5. Numerical model set up

A numerical model for fracture grouting has been established based on the finite element method. The dimension of the calculation domain is set as a rectangular with a height of 1m and a width of 1.5m. A normal load of 0.4MPa and is applied on the upper and lower side of the domain, and a normal load of 0.6MPa is applied on the right side, which represents crustal stress environment. The grout is injected in the middle of the left side with a length of 0.04m. An inflow velocity of 0.1m/s is applied directly at the inlet, which represents a constant flow rate condition. The water pressure on the left and right side is also 0.2MPa.

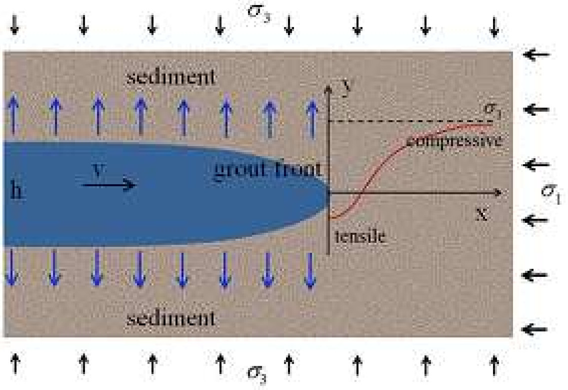

Fig. 2. Numerical model and boundary conditions

The calculation parameters which are used in the numerical model are listed in table 1.

Table 1. Calculation parameters in the numerical model

Initial permeability	K_0	m^2	6e-12	Grout viscosity	μ	Pa·s	1.5
Initial porosity	ϕ_0	-	0.46	Biot coefficient	α_B	-	1
Elastic modulus	E	MPa	37	Grout density	ρ	kg/m^3	1500
Poisson's ratio	v	-	0.25	Inlet velocity	v_0	m/s	0.1

6. calculation Results

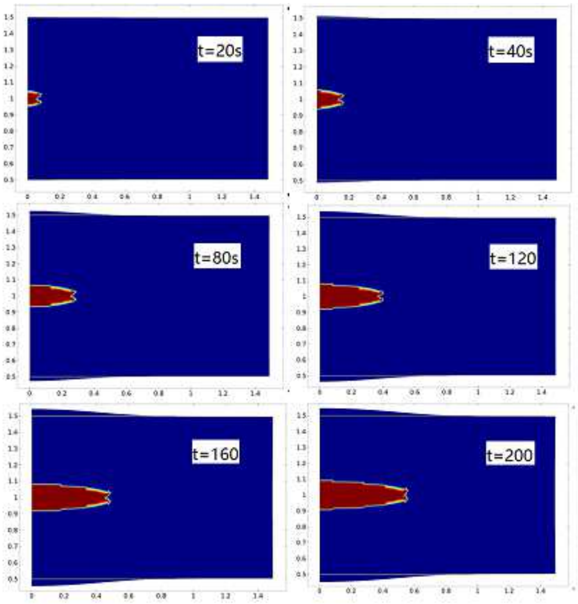

Fig. 3. Variation of the fracture shape according to different grouting time

Fig. 3 shows the variation of the fracture shape at different times. As can be seen, as grouting time increases, the length and the width of the fracture keep growing. The length of the fracture increases with time in an almost linear trend. The width of the fracture is comparatively large around the inlet and reduces along the advancing direction. During grouting process, the displacement field changes significantly. The sediment deforms mainly along the vertical direction. As the grout width increase, the sediment expands towards upper and lower side. The deformation is large around the inlet and becomes smaller in further place. Moreover, the influenced area of deformation is larger than the grout fractures. At grouting time of 200s, the fracture length reached 0.6m, while the influenced area reached 0.8m.

Fig. 4 shows the vertical deformation of the sediment at different grouting times. Since identical conditions are set on the upper and the lower sides of the domain, the deformation of the sediments is symmetrical along the horizontal center line of the domain. As can be seen, as grouting time increases, the deformation of the sediment keeps growing. The deformation field is greatly changed after the sediment is fractured while it remains unchanged ahead of the fracture tip. The maximum deformation occurs near the inlet on both the upper and lower side of the fracture. At grouting time of 40s, the maximum deformation is about 0.03m while it exceeds 0.054m at grouting time of 160s.

Fig. 5 shows the variation of grouting pressure according to grouting time with different elastic modules of sediment. As can be seen, the variation of the grouting

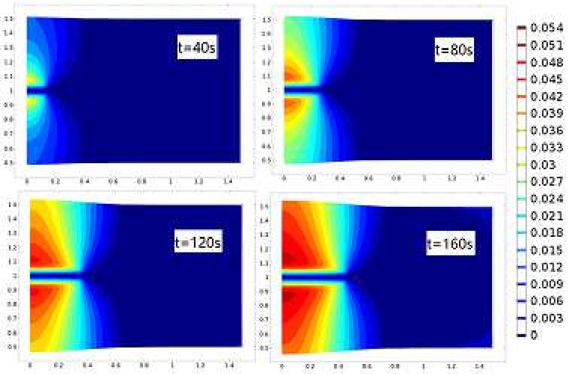

Fig. 4. Vertical deformation of the sediment according to different grouting times

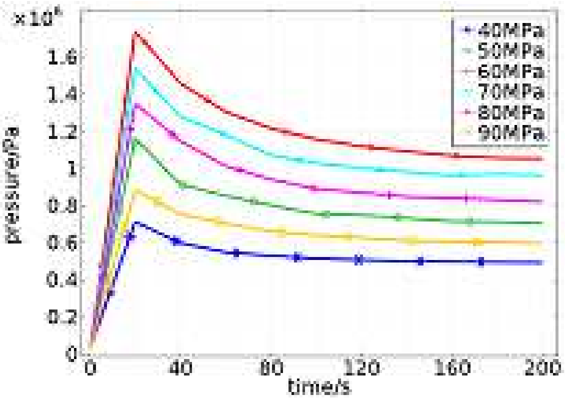

Fig. 5. Variation of grouting pressure with different elastic modules of sediment

pressure is divided into two phases. The grouting pressure increases linearly with time at first and then decreases slowly until it reaches a constant value. The maximum grouting pressure occurs at the turning point of the two phases with grouting time of about 20s, which represents the fracture initiation pressure. During the first phase, the grout is injected due to compression of the sediment. As the injected volume of the grout grow, the stress at the interface between the sediment and the grout increase. When the stress reaches the fracture initiation pressure, the sediment is fractured. Afterwards the fracture keeps propagating as the subsequent grout is injected.

The fracture initiation pressure is mainly influenced by the elastic modules of the sediment. As the elastic modules of the sediment increases, the initiation pressure becomes larger, which means it is harder for the sediment to be fractured. The pressure for fracture propagating also increases. For the sediment with elastic modules of 40MPa, the fracture initiation pressure is about 0.7Mpa and the fracture propagating pressure is about 0.5MPa. For the sediment with elastic modules of 90MPa, the fracture initiation pressure is almost 1.8Mpa and the fracture propagating pressure is more than 1.1MPa. It is also shown that the gap between the fracture initiation pressure and the propagating pressure also increases. As the elastic modules increases from 40MPa to 90MPa, the gap between the fracture initiation pressure and the propagating pressure increases from 0.2MPa to 0.7MPa.

7. Conclusions

In this study, a numerical model of one dimensional fracture grouting in sediment is proposed based on Finite Element Method and solid-fluid coupling theory. Fracture propagation process was successfully simulated and variation of fracture length and width at different times was acquired. The main conclusions are as follows:

For a constant injection rate condition, the length of the fracture increases with time in an almost linear trend. The width of the fracture is comparatively large around the inlet and reduces along the advancing direction. The sediment deforms mainly along the vertical direction. The deformation is large around the inlet and becomes smaller in further place and the influenced area of deformation is larger than the grout fractures.

The deformation field is greatly changed after the sediment is fractured while it remains unchanged ahead of the fracture tip. The maximum deformation occurs near the inlet on both the upper and lower side of the fracture. At grouting time of 40s, the maximum deformation is about 0.03m while it exceeds 0.054m at grouting time of 160s.

The variation of the grouting pressure is divided into two phases. The grouting pressure increases linearly with time at first and then decreases slowly until it reaches a constant value. As the elastic modules of the sediment increases, the initiation pressure becomes larger, And the gap between the fracture initiation pressure and the propagating pressure also increases, which means it is harder for the sediment to be fractured.

References

[1] Y. D. Wu, Y. W. Ju, Q. L. Hou, J. N. Pan, Y. Zhang: *Filed test of comprehensive treatment method for high pressure dynamic grouting.* Journal of China Coal Society *35* (2010), No. 08, 1314–1318.

[2] R. Wen: *Spreading model of grouting in rock mass fissures based on time-dependent behavior of viscosity of cement-based grouts.* Chinese Journal of Rock Mechanics and Engineering *24* (2005), No. 15, 2709–2714.

[3] W. X. Wang, W. H. Sui, B. Faybishenko, W. T. Stringfellow: *Permeability variations within mining-induced fractured rock mass and its influence on groundwater inrush.* Environmental Earth Sciences *75* (2016), No. 4, 326.

[4] J. W. Yun, J. J. Park, Y. S. Kwon, B. K. Kim, I. M. Lee: *Cement-Based Fracture Grouting Phenomenon of Weathered Granite Soil.* Ksce Journal of Civil Engineering *21* (2016), No. 1, 1–11.

[5] L. Shu, W. J. ZHANG, Q. S. ZHANG: *Research on advantage-fracture grouting mechanism and controlled grouting method in water-rich fault zone.* Rock and Soil Mechanics *35* (2014), No. 3, 744–752.

[6] T. L. CHEN, L. Y. ZHANG, ZD. L. HANG: *An FEM/VOF hybrid formulation for fracture grouting modeling.* Computers and Geotechnics *58* (2014) 14–27.

[7] L. PENG, Q. S. ZHANG, X. ZHANG: *Analysis of fracture grouting mechanism based on model test.* Rock and Soil Mechanics *35* (2014), No. 11, 3221–3230.

[8] Z. J. ZOU, W. TONG, H. LUO, X. WANG: *Mechanism of fracture grouting for fractured rock based on failure criterion.* Journal of Central South University (Science and Technology) *44* (2013), No. 7, 2889–2896.

[9] Y. YAO, L. LIU, L. M. KEER: *Pore pressure cohesive zone modeling of hydraulic fracture in quasi-brittle rocks.* Mechanics of Materials *83* (2015) 17–29.

[10] WISSER. C, AUGARDE. C. E, BURD. H. J: *Numerical modelling of compensation grouting above shallow tunnels.* Int J Numer Anal Meth Geomech *29* (2005) 443–71.

[11] YANG. M. J, YUE. Z. Q, LEE. P. K. K, SU. B: *Tham LG. Prediction of grout penetration in fractured rocks by numerical simulation.* Can Geotech J *39* (2002), No. 6, 1384–1394.

[12] TANG. C. A, THAM. L. G, LEE. P. K. K, YANG. T. H, LI. L. C: *Coupled analysis of flow, stress and damage (FSD) in rock failure.* Int J Rock Mech Min Sci *39* (2002), No. 4, 477–489.

[13] Y. GOU, L. ZHOU, X. ZHAO, Z. HOU, P. WERE: *Numerical study on hydraulic fracturing in different types of georeservoirs with consideration of H 2 M-coupled leak-off effects.* Environmental Earth Sciences *73* (2015), No. 10, 6019–6034.

[14] P. WANG, X. B. MAO, J. B. LIN, C. Z. DU: *Study of the borehole hydraulic fracturing and the principle of gas seepage in the coal seam.* Proc Earth Planet Sci *1* (2009), No. 1, 1561–1573.

Received November 16, 2017