An Experimental Research on Crack Propagation Regularity During Fracture Grouting

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Abstract. A new grouting model test device has been developed to model the fracture grouting process and improve understanding of the crack propagation regularity during grouting. It was concluded that the propagation process of crack is not one-time formed but undergoes the sequential mode of "expansion, stagnation, re-expansion, re-stagnation" after fracture initiation. The smaller the grouting pressure is, the longer the stagnation time is, and the smaller the crack propagation velocity is. The crack width increases rapidly when the crack tip stagnates or the expansion speed is small. Research results can help achieve better grouting aims and realize grouting safety in practice

Keywords: Crack propagation, fracture grouting, model test.

1. Introduction

Fracture grouting has been widely applied in geotechnical engineering in order to enhance bearing capacity and reduce permeability of soils. However, the fracture propagation of fracture grouting developed in soils remains difficult to be directly observed, and the regularity of crack growth inside soil is not clear yet.

The wide application of fracture grouting has inspired researchers to deeply study the fracture mechanism via experimental, theoretical and numerical approaches. Experimental investigations have been presented to characterize the mechanisms related to the initiation pressure and growth of fractures stimulated from vertical or horizontal wells [1]. Some researchers investigated the bleeding phenomenon and possible fracture geometries in fracture grouting[2]. Zhang [3] divided the fracture process into three stages: grout ball, first fracture surface and following fracture surface. Scholars obtained the corresponding relationship equation between grouting pressure and diffusion radius about Newtonian fluid [4], Bingham fluid [5] and exponential fluid [6] based on the narrow plate model. A conceptual, analytical model was developed to describe the fracture grouting process in sand [7]. Numerical tool has become a good option for gaining insight into the fracturing process. However, some unrealistic simplifications and assumptions are generally made in theoretical and numerical studies. On the other hand, the fracture propagation process, such as step mode, variation of crack propagation velocity and crack width evolution during grouting, still needs to be well investigated.
In this paper, a new test device of grouting model has been developed to study crack propagation occurred during fracture grouting in clay. We analyzed the step mode of crack propagation and studied the regularity of grouting pressure on crack propagation velocity and crack width.

2. Model setup

2.1. Test system

A grouting device that consists of an air compressor, a storage tank, a three-dimensional test box, a real-time video recording system, and a grouting pipeline was designed, as shown in Fig. 1. The three-dimensional test box with internal dimensions 2m × 0.5m × 0.5m (length × width × height) was used to model fracture grouting process. The clay in the test box was filled up to 0.30 m height and compacted evenly. The grouting hole is located 15cm above the bottom and 20cm from the left side of the box. We can record the crack propagation process through a transparent organic glass plate which used to cover on clay and make it evenly stressed.

2.2. Test conditions

The purpose in the test is to observe the extension of single crack instead of multiple cracks. Hence, a 1mm wide thin crack prefabricated in the longitudinal center line of the soil, and then the soil is loaded and consolidated for 12 hours when the crack in the soil has almost healed but still a weak plane. So that the fracture will propagate preferentially in one direction. Silty clay from Beijing area is selected for this test. The mechanical properties of silty clay is listed in Table 1.

| Soil      | Density /g/cm³ | Elastic Modulus /MPa | Cohesion /kPa | Friction angle /° |
|-----------|----------------|----------------------|--------------|------------------|
| Silty clay| 1.8            | 10.6                 | 25.0         | 20.5             |

The grout material is a kind of carboxymethyl cellulose sodium (CMC) solution with a viscosity of 0.8 Pa·s. To display a better visualization, a small quantity of black ink is also added to the solution. The grouting pressures supplied by air compressor in the test are 0.01MPa, 0.02MPa, 0.03MPa, 0.04MPa, 0.05MPa, and 0.06MPa. Three sets of tests were carried on under each grouting pressure.

A real-time video recording system was used to record the crack propagation process, tip position and crack width during the fracture grouting under different grouting pressures. Results of the model test

2.3. Crack propagation step mode

The crack propagation process during fracture grouting under different grouting pressures has common stepping mode. Although the propagation velocity and crack width are very different. Fig. 2
is the test diagram of the crack propagation process when the grouting pressure is 0.04 MPa. From the figure, we can understand the stepping mode of crack propagation.

After the initial fracturing of soil, the expansion speed is very fast, and the crack tip has expanded to 19 cm at 45 s. In this period, the crack is very slender, and the expansion of crack tip is much faster than the increase in crack width. The energy of the grout in this stage is mainly used to fracture the soil in front of the crack tip. As the grouting continued, the tip of the crack reached 29 cm at 83 s. At this stage, the crack tip expansion speed decreases while the rear crack width increases. However, the crack tip forward expansion still dominates. Between 83 s and 122 s, the crack tip stagnates while there is a significant increase in the width of the entire crack from the vicinity of the grouting hole to the crack tip. At this stage, crack tip stagnates, and the increase in crack width dominates. The crack tip expanded forward rapidly again after a short stagnation and reached to 33 cm within 122 s to 135 s. During 135 s to 160 s, the crack tip expanded to 36 cm, but the velocity dropped significantly. At the 160-180 s stage, the crack tip stagnated again, and the crack width increased quickly.

**Figure 2.** Crack propagation of fracture grouting

Crack propagation regularities under other pressures are similar to Figure 2. It was concluded that the propagation process of crack undergoes the sequential step mode of "expansion, stagnation, re-expansion, re-stagnation" after fracture initiation and the crack is not one-time formed. As the grouting time continues, the stagnation time becomes longer and longer. The crack tip propagation and the increase of crack width exist and compete at the same time. The crack width increases significantly when the crack tip stagnates.

**Figure 3.** Crack propagation radius and grouting pressure relationship  
**Figure 4.** Position of crack tip and time under different grouting pressure
2.4. Grouting pressure and crack tip propagation
The grouting pressure has a significant effect on the crack propagation radius and propagation process. We can see from Fig. 3 that as the grouting pressure increases, the propagation radius of the crack increases.

Figure 4 shows the curves of fracture tip position vs. time at different grouting pressures. We can find that the crack tip position expands stepwise over time, and the smaller the pressure is the longer the "platform" time is. During the "platform" period, the crack tip stagnates, and it takes a long time to split forward and expand if the grouting pressure is small. As the grouting pressure increases, the tip stagnation time decreases and the switching frequency increases between stagnation and expansion.

2.5. Influence of grouting pressure on crack propagation velocity
The crack propagation velocity was calculated by recording the position of the crack tip at different time interval. The relationships between crack propagation velocity and time under different grouting pressures are shown in Figure 5.

The crack propagation velocity and time curve is not smooth, indicating that the speed does not decrease monotonically but fluctuates. There are several speed peaks and troughs in the fracture process, which represents the rapid expansion and stagnation of crack tip at this stage.

The smaller the grouting pressure is, the longer the crack tip stagnation time is (0.02MPa). The larger the grouting pressure is, the shorter the crack stagnation time is, and the more frequent the expansion and stagnation convert (0.03MPa). As grouting pressure continues to increase, there is almost no stagnation, but there are still velocity fluctuations in crack propagation (0.06MPa). We can find that the crack propagation velocity gradually decreases overall, because of the pressure drop along the crack. At the beginning of grouting, the speed declined fastest, indicating that the pressure drop near the grouting hole was fastest.

![Graphs showing crack propagation velocity under different grouting pressures](a) 0.02MPa, (b) 0.03MPa, (c) 0.06MPa

**Figure 5.** Crack propagation velocity under different grouting pressure
We also got the average velocity of crack propagation velocity under different pressures by dividing the expansion distance by the total time. With the increase of grouting pressure, the average propagation velocity of crack increases continuously. Once the grouting pressure reaches a certain level, the propagation velocity increases dramatically (See Figure 6). In engineering practice, grout gushing and other geological disasters are easier to occur when the grouting pressure is too high especially when there is a risk of groundwater inflow in the engineering environment. Therefore, the grouting pressure must be properly controlled during the fracture grouting process.

![Figure 6. Average propagation velocity under different grouting pressure](image1)

![Figure 7. Crack width distribution and grouting pressure](image2)

2.6. Crack width
Crack width is also an important indicator for the evaluation of the effect of fracture grouting. In the experiment, we recorded the crack width at different locations under different grouting pressures (See Figure 7). The crack width decreases with increasing distance from the grouting hole, especially near the crack tip. The final crack width at the same location increases as the grouting pressure increases.

3. Conclusion
The model text leads to the following conclusions:

The crack is not one-time formed, but experienced a sequential mode of "initiation, expansion, stagnation, re-expansion, re-stagnation"; the crack tip propagation and the increase of crack width exist and compete at the same time during fracture grouting; Crack propagation velocity shows a fluctuating change rather than a monotonous decrease; crack width gradually decreases with distance from grouting hole. These findings are essential in improving the theoretical understanding and numerical simulation of fracture grouting.

Acknowledgments
This work was supported by National Key R&D Plan (Grant No. 2017YFC0805400).

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