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An experimental study of crack propagation regularity monitored in fracture grouting in clay

A new grouting model test device has been developed to model the fracture grouting process in clay soil. The objective of this model test is to improve understanding of this process and to study the crack propagation regularity. The results can be used to assess the parameters that control the fracture process, especially grouting pressure. This paper presents a model test to study the stepping mode of crack propagation and links the grouting pressure to the crack propagation velocity and crack width. It is 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 is the stagnation time, and the smaller is the crack propagation velocity. 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 realizes grouting safety in practice.

Keywords: Fracture grouting, model test, crack propagation velocity, crack width, clay soil

1. Introduction

Hydraulic fracturing, which is mainly applied to rock formations in deep ground, is of great interest in both academic and industrial fields. Fracture grouting is one of the popular applications in soils. It has been widely applied in geotechnical engineering in order to enhance bearing capacity and reduce permeability of soils. The fracture propagation period is the crucial stage to realize the grouting purpose. 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 in geotechnical engineering 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[2,3] and possible fracture geometries[4] in fracture grouting. Zhang[5] divided the fracture process into three stages: grout ball, first fracture surface and following fracture surface.

Significant contributions have also been made to understand the mathematical physics of the fluid-driven problem by using rigorous and complex analysis in elastic media. Scholars obtained the corresponding relationship equation between grouting pressure and diffusion radius about Newtonian fluid[6], Bingham fluid[7] and exponential fluid[8] based on the narrow plate model. A conceptual, analytical model is developed to describe the fracture grouting process in sand[9].

With the rapid development of computer science, numerical tool has become a good option for gaining insight into the fracturing process. The methods include finite element method[10,11], extended finite element method[12], boundary element method[13], discrete element method[14], displacement discontinuity method[15] etc.

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 set up

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 is designed, as is shown in Fig. 1. The three-dimensional test box with internal

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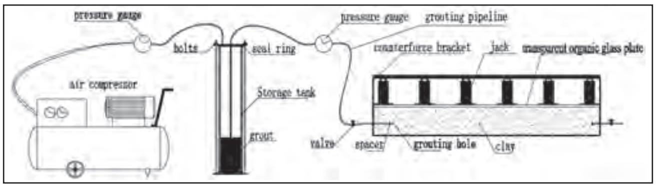
dimensions of 2m × 0.5m × 0.5m (length × width × height) are used to model fracture grouting process. The clay in the test box is filled up to 0.30m height and compacted evenly. The grouting hole is located 15cm above the bottom and 20cm from the left side of the box. We can record the crack propagation process through a transparent organic glass plate which is used to cover on clay and made it evenly stressed. Eight jacks are evenly arranged on the glass plate to impose vertical loads to limit the displacement.



(a) Schematic Drawing

air compressor storage tank test box

(b) Physical Device

Fig. 1. Grouting system of model test

2.2. Test conditions

Fracturing surface initiates from small principal stress surface. That is, if there is a relatively weak interface existing around crack initiation area in the soil, the crack will preferentially propagate through this surface. Our 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 centerline of the soil, and then the soil is loaded and consolidated for 12 hours when the crack in the soil is 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.

Table 1. Parameters of soil

Soil	Density (g/cm^3)	Elastic modulus (MPa)	Cohesion (kPa)	Friction angle (°)
Silty clay	1.8	10.6	25.0	20.5

The grout material is a kind of carboxy methyl 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 are carried on under each grouting pressure.

A real-time video recording system is used to record the crack propagation process, tip position and crack width during the fracture grouting under different grouting pressures. The crack propagation velocity can be calculated through the position of the crack tip at different times.

3. Results of the model test

3.1. 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 19cm at 45s. 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 29cm at 83s. At this stage, the crack tip expansion speed decreases while the rear crack width increases. However, the crack tip forward expansion still dominates.

Between 83s and 122s, 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 33cm within 122s to 135s. During 135s to 160s, the crack tip continues to expand to 36cm, but the velocity drops significantly. At the 160-180s stage, the crack tip stagnated again, and the crack width increases quickly.

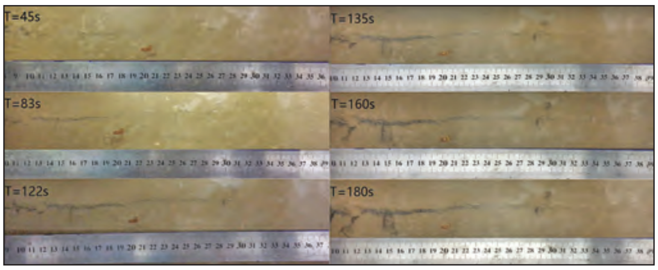


Fig. 2: Crack propagation of fracture grouting

Crack propagation regularities under other pressures are similar to Fig. 2. It is 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.

3.2. 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.

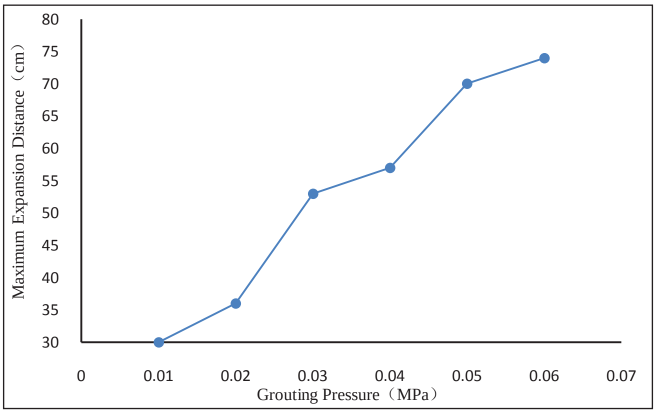


Fig. 3: Crack propagation radius and grouting pressure relationship

Fig. 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 is the ‘platform’ time. 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. As the grouting pressure continues to increase, the stagnation of the tip almost disappears, and the entire crack propagation is almost continuous.

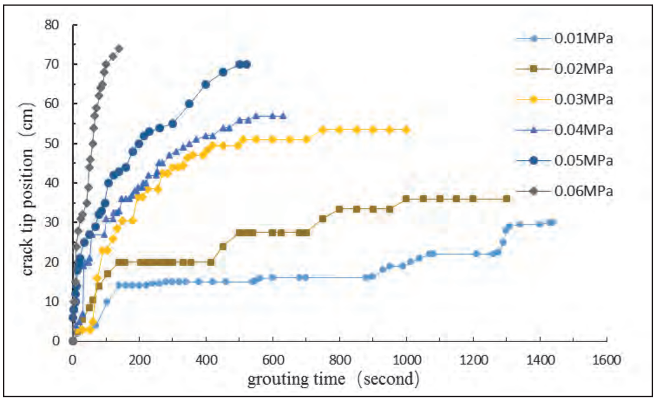


Fig. 4: Relationship between the position of crack tip and time under different grouting pressure

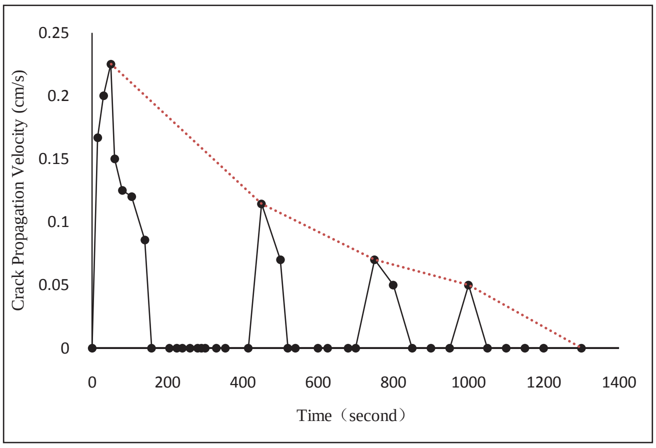
3.3. Influence of grouting pressure on crack propagation velocity

The crack propagation velocity is 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 Fig.5.

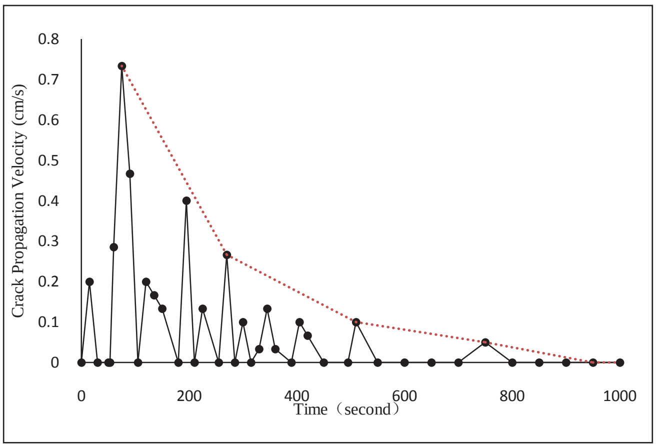
That describes the effect of grouting pressure on the magnitude of crack propagation velocity. The crack propagation velocity and time curve are not smooth, indicating that the speed does not decrease monotonically but fluctuates. There are several speed peaks and troughs in the fracture process, which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

The smaller is the grouting pressure, the longer is the crack tip stagnation time (0.02MPa). The larger the grouting pressure is, the shorter is the crack stagnation time, and more frequent are 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).

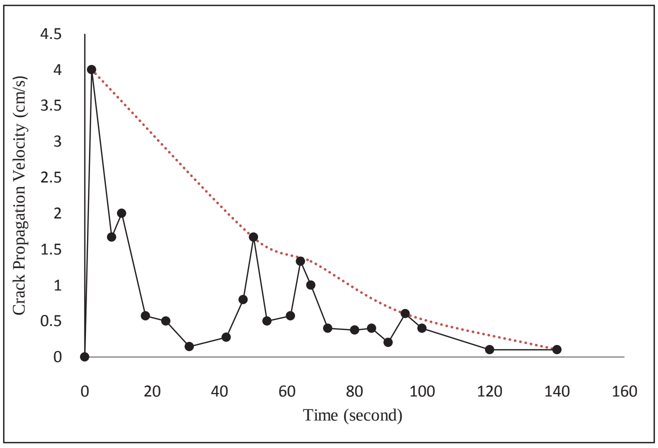
When connecting multiple peaks of the velocity and time curve, we can find that the crack propagation velocity gradually decreases overall. This is because of the pressure drop along the crack. At the beginning of grouting, the speed declines fastest, indicating that the pressure drop near the grouting hole is fastest.



(a) 0.02MPa



(b) 0.03MPa



(c) 0.06MPa

Fig. 5: Crack propagation velocity under different grouting pressure

We also get 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 (Fig. 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 properlycontrolled during the fracture grouting process.

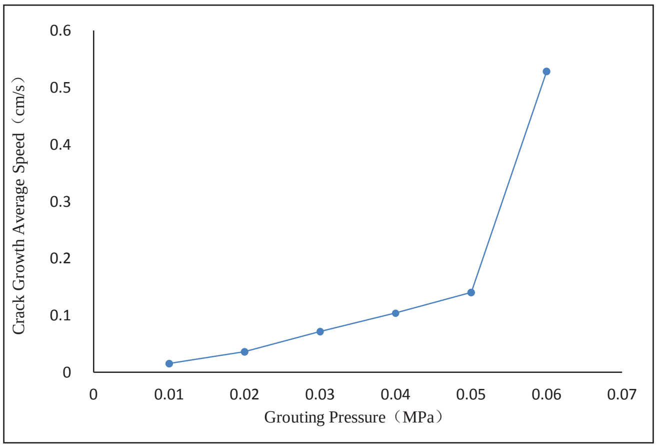


Fig. 6: Average propagation velocity under different grouting pressure

3.4. 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 (Fig. 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.

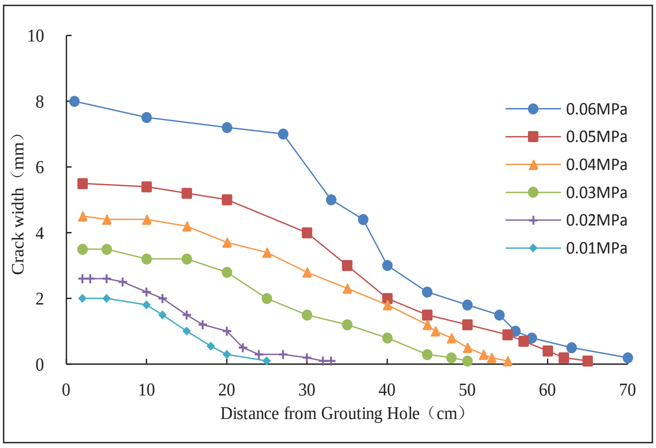


Fig. 7: Crack width distribution and grouting pressure

4. Conclusions

The objective of this research is to improve understanding of the fracture grouting process in clay. A model test is presented that links the grouting pressure to the propagation velocity and width of crack. It also shows the step mode of crack expansion.

The model text leads to the following conclusions:

(1) The crack is not one-time formed, but experienced multiple fracture and expansion stages. The step mode of crack propagation is a sequential mode of "initiation, expansion, stagnation, re-expansion, re-stagnation". The smaller is the grouting pressure, the longer is the stagnation time. While the larger is the grouting pressure, the shorter time is the crack tip stagnation and more frequent is the expansion and stagnation convert.

(2) The crack tip propagation and the increase of crack width exist and compete at the same time during fracture grouting. The crack width increases significantly when the crack tip stagnates or propagation velocity is small.

(3) The crack propagation velocity shows a fluctuating change rather than a monotonous decrease. There are several peaks and troughs on the velocity-time curve. When connected the peaks together, the crack propagation velocity continuously decreases over time. At the beginning of grouting, the speed decayed fastest, indicating that the pressure near the grouting hole decayed fastest.

(4) Crack width gradually decreases with distance from grouting hole. The larger is the grouting pressure, the greater is the final crack width.

These findings are essential in improving the theoretical understanding and numerical simulation of fracture grouting. The results are also important to better prediction of crack growth and containment in safe area where there are serious environmental concerns on the risk of groundwater involvment.

Acknowledgements

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