



A Conceptual Model for Estimation on the Strength of Soil Rock Mixture After Grouting Reinforcement

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Abstract. Soil rock mixture (SRM), which consists of rock blocks within soft matrix composed of sand, silt and clay, is often regarded as a kind of problematic geology during geotechnical engineering project. Grouting has been used as an effective method to improve mechanical behaviors of SRM. The main goal of this work is a comprehensive study of the physical mechanisms of grouting reinforcement on SRM. For this purpose, laboratory tests are carried out to simulate the process of grouting into SRM. Then, distribution of the grout in SRM is examined to investigate fracturing behavior of the grout suspension. The uniaxial compressive strength of the test samples are measured to investigate the influence of grouting process on the strength of SRM. Different controlling parameters are analyzed, such as volume of block proportion, block count and grouting volume. Based on the analysis, a concept model is proposed which considers three different mechanisms of grouting reinforcement. Finally, an empirical equation is proposed for estimation on the strength of grouted SRM. Results show that the proposed model can reasonably estimate the strength of the test samples.

Keywords: Soil rock mixture · Grouting suspension · Compressive strength
Empirical equation

1 Introduction

Soil rock mixture, which consists of rock blocks within soft matrix composed of sand, silt and clay, is a common geological condition during geotechnical engineering project. Medley (1994) proposed the concept of “bimrock”, which refers to mixtures of rocks composed of geotechnically significant blocks, within a bonded matrix of finer texture [1]. Soil rock mixture is also incorporated into this classification, and preferred for complex mixtures which include rock blocks surrounded by soil-like matrix material, such as colluvium and glacial tills [2]. In many cases, soil and rock mixture is regarded as a kind of problematic geology, which threatens the security of the construction of engineering project [3, 4].

Grouting has been used as an effective method for problematic geology treatment during construction of underground projects [5–8]. However, the grouting process is complex and the grouting results cannot be easily evaluated. This uncertainty mainly

attributes to two aspects. Firstly, it is difficult to measure geomechanical properties of the original geological masses [9, 10]. Moreover, the reinforcement mechanism of grouting in soil rock mixture is complex, since the penetration process and interaction between grout and the geological masses is invisible after grout material is injected into the stratum [11–13].

The main goal of this work is a comprehensive study of the physical mechanisms of grouting reinforcement on SRM. For this purpose, laboratory tests are carried out to simulate the process of grouting into SRM. Then, the uniaxial compressive strength (UCS) of the test samples are measured to investigate the influence of grouting process on the strength of SRM. Finally, a concept model and an empirical equation are proposed for estimation on the strength of grouted SRM. Results show that the proposed model can reasonably estimate the strength of the test samples (Fig. 1).

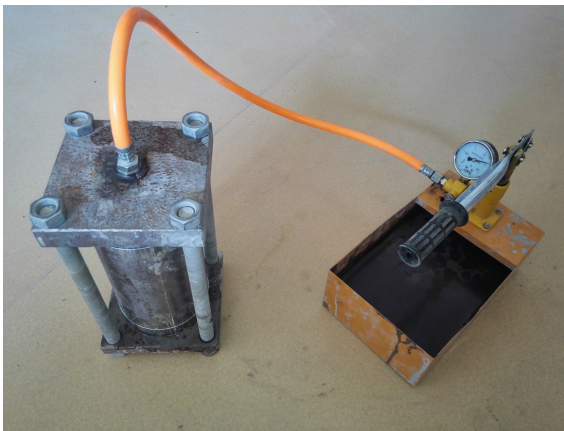


Fig. 1. Test equipment for grouting into SRM

2 Fundamental Mechanics of Soil Rock Mixture

The mechanical property of SRM is influenced by a series of factors, such as ratio between block and matrix strength, volumetric block proportion (VBP), etc.

One main characteristic of SRM is obvious contrast of strength between the block and the matrix. In this view, the mechanical behavior of SRM is similar to that of bimrock, despite the matrix is weaker for SRM. According to Lindquist [14, 15] and Medley [1], when test samples fail under normal load, the failure surface usually passes tortuously around blocks. Thus, the strength of blocks does not necessarily increase the overall strength of the bimrock. For SRM, the situation is the same. However, when the test samples are under high confining pressure, failure surfaces may directly penetrate blocks, instead of tortuously pass around them.

VBP can significantly influence the mechanical property of SRM [16–21]. When VBP is higher than about 60%, blocks begins to contact each other. A confining pressure may intensify the interlocking behavior between these blocks, which will change the strength and deformation property of SRM dramatically. In this case, the influence of surface roughness of blocks also increases, since a rough surface or irregular shape increases the interlocking behavior.

The mechanical property of SRM is also influenced by the number of blocks (block count). The interface between block and matrix is the weakest part in SRM. When block count increases, the total area of the interface also increase. VBP has no capability of defining the amount of the total area of the interface. While the VBP keeps unchanged, the overall strength of SRM will decrease as the block count increases, due to a larger area of interface. On the other hand, a bigger block count may lead to a more uniform distribution of block in SRM, which improves the overall strength of SRM. The total influence of block count should consider both the positive and negative aspect. Thus, block count should also be regarded as a crucial parameter for predicting the strength and deformation properties of SRM. The influences of block count on bimrock are systematically studied by H. Sonmez. However, for SRM, especially with consideration of grouting reinforcement, the influences of block count are not clear and need further investigation.

3 Sample Preparation and Experimental Tests

3.1 Device and Material Preparation

The experiments were performed using a rigid cylindrical steel container. The height of the interior of the container is 25 cm and the diameter is 10 cm. The thickness of the cylinder wall and lids is 1 cm. An injection hole is mounted on the top lid. The bottom lid is punched with five tiny holes with a diameter of 1 mm, which allows water to penetrate, but not soil. A tube is buried into the mixture and connected to the grouting entrance on the top lid before the container is screwed up. The tube is 20 cm long and coincides with the vertical, central axis of the container. There are several holes on the tube, so that the grout suspension can flow into the mixture from different point along the central axis, rather than only from the end of the tube. After the container is filled up with the mixture, it is connected to a pressure pump, and grouting suspension is injected from top of the container.

3.2 Material Preparation

SRM specimen was prepared using soil and gravel at different ratio. Particle size distribution analysis was performed on the mixture, as shown in Fig. 2. The soil is oven-dried at 120 °C for one day before being used for preparing the mixture. The gravel has irregular morphology with a density of 2830 kg/m³. The mixing and filling process were divided into several times. Each time a constant ratio of soil and gravel were mixed, and cylinder container is filled up layer by layer. The overall compaction degree is controlled by the total amount of mixture filled into the container. The first

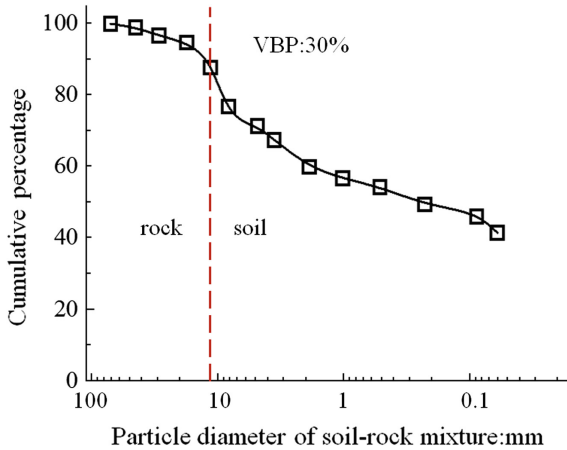


Fig. 2. Grain size accumulation curves for the soil–rock mixtures

layer and last layer are pure soil and compacted tightly. Each of them is 2.5 cm high after compaction. These two layers are expected not to be grouted and will be cut off before compression test. Therefore, the specimen used for compression test is 20 cm high in all, and the diameter is 10 cm.

3.3 Injection

The grout suspension is injected into the cylinder container from the pump. The water-cement ratio is 1:1 for preparation of the grout suspension. During injection, the grout suspension is being stirred persistently in case of sediment. The pump volume for one time is about 24 ml, and one pump takes 3 s. Thus, the injection rate is considered as 8 ml per second. During injection, water is bleed from the grout suspension and penetrates into the soil, and the grout suspension becomes thicker, so a higher pumping pressure is needed. The termination of the injection is controlled by two standards: the final injection pressure and the total suspension volume injected. If the injection pressure exceeds 2 MPa or the injected suspension volume reaches 1.5 kg, the injection is stopped.

3.4 Compression Test

After injection, the container was kept with the final pressure for 1 h before the specimens were unmolded. The specimens were cured for 28 days at the 100% relative humidity and temperature of 25 ± 5 °C, before used for compression test. The uniaxial compressive test was carried out in accordance with ISRM (1979) at a constant loading rate of 0.05 mm/s. In each test, the loading was continued until full failure of the specimen occurs.

4 Discussion of the Laboratory Test Results

4.1 Grouting Behavior

A comparison of grout distribution in specimen with different VBP was conducted. Results show that, the distribution of blocks significantly influences the grouting behavior, as shown in Fig. 3. For specimen composed of pure soil, there is only one grout vein, and the other area remains ungrouted. The thickness of the grout fracture is influenced by a series of factors, such as grouting pressure, compaction degree of the soil and the rheological behavior of the grout suspension. For specimen composed of

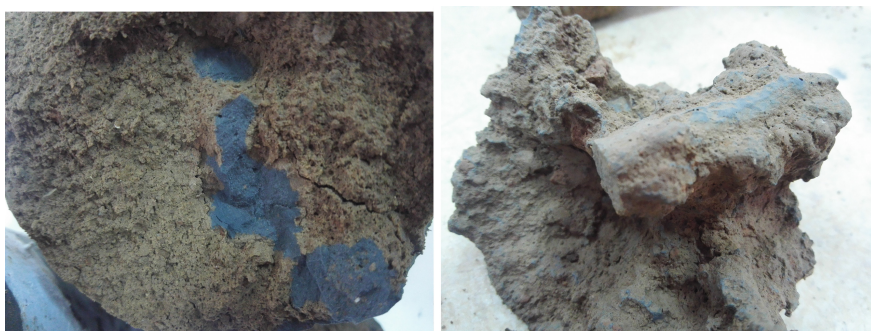


Fig. 3. Grout distribution in pure soil and SRM

SRM, the grout distribution is much different. The interface between block and soil is a weak place, compared with internal area in the soil. Thus, the grout suspension may penetrate along the boundary of the blocks with priority. The blocks change the original patterns of grout distribution, and cause grout suspension spread into a larger area compared with that in pure soil. Thus, a larger area is reinforced and the overall mechanical property is further improved.

4.2 Influence of Grouting on the Mechanical Property of Soil Rock Mixture

When VBP is high, the distance between blocks is comparatively small. Thus, different blocks become bonded together as a whole after grout have been hardened. In this case, the overall strength of the SRM is improved remarkably. On the other hand, when VBP is low, the distance between blocks is comparatively large. The pressure of the grout suspension should be high enough to overcome the internal stress in the soil, so that it can be fractured by grout suspension. If the pressure is not high enough, the grout suspension cannot always fracture the soil, and the grout suspension is more likely to be confined in a local area around some blocks, and the overall strength of SRM can be comparatively low.

4.3 Failure Pattern and Stress Strain Behavior

Failure patterns of test samples with different VBP are shown in Fig. 4. Before the

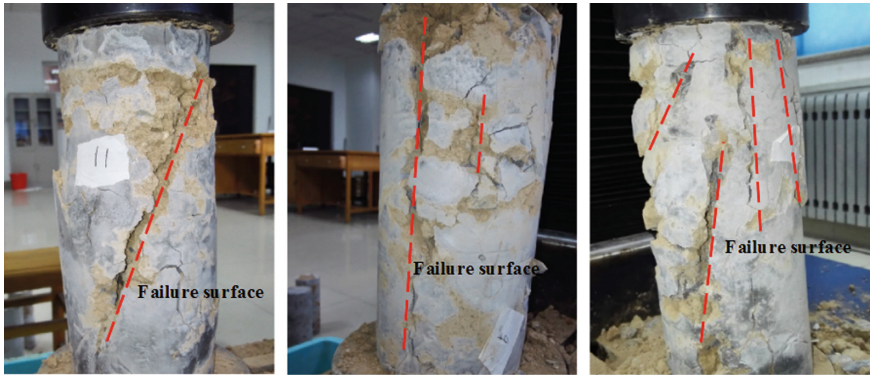


Fig. 4. Failure pattern of test samples with different VBP during uniaxial compressive test

normal stress reaches its peak value, it increase almost linearly with normal stain, and the test sample is considered to be at elastic stage. When VBP is low, the normal stress drops sharply after the peak, and the decreasing rate is very high. The failure surface is continuous and forms almost at once. On the other hand, When VBP is high, the normal stress decreases gradually until it reaches the residual stress. There are several sudden drops which are comparatively small and each of them may correspond to a failure in a local area. The test sample breaks into several parts, but they are not separated completely and can still bear the normal load (Fig. 5).

5 A Conceptual Model for Grouted SRM

Mechanical property of SRM can be reasonably described by Mohr-Coulomb criterion, which has been studied by a serious of researchers [16–21]. Thus, influence of grouting reinforcement can be reflected by improvement of the Mohr-Coulomb parameters, such as cohesive force and friction angle. Three aspects contribute to the improvement of mechanical property of SRM in grouting process: increasing the cohesive force on block boundary, connecting different blocks together, and adding components with higher strength than matrix. With these considerations, a conceptual model for grouting reinforcement on SRM is proposed, as shown in Fig. 6.

A specimen before grouting is represented by Fig. 6a. The blocks with different size distributed randomly in the soil. A potential failure surface is represented by the black dotted line. The specimen after grouting is represented by Fig. 6b. The grout suspension penetrates mainly around the blocks and connects them together. The original failure surface may be prevented, and replaced by a new one with different direction, as shown with the red and black dotted line. Figure 6c represents an ideal

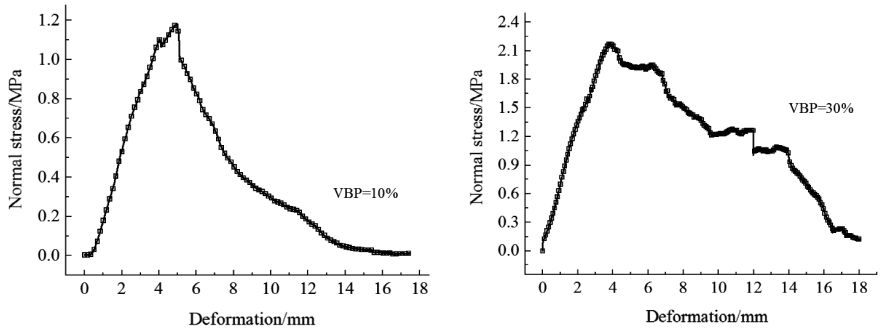


Fig. 5. Stress strain relationship of test samples with different VBP

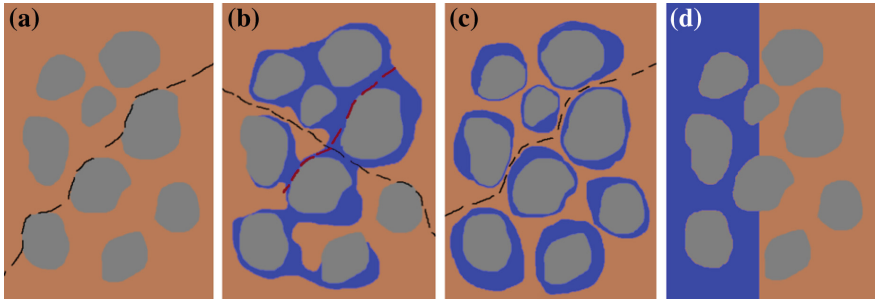


Fig. 6. Grout distribution in SRM: **a** before grouting; **b** a possible distribution after grouting; **c** an extreme case of grout distribution which represents only the first and the third mechanism; **d** an extreme case of grout distribution in which the sample is divided into two distinct parts

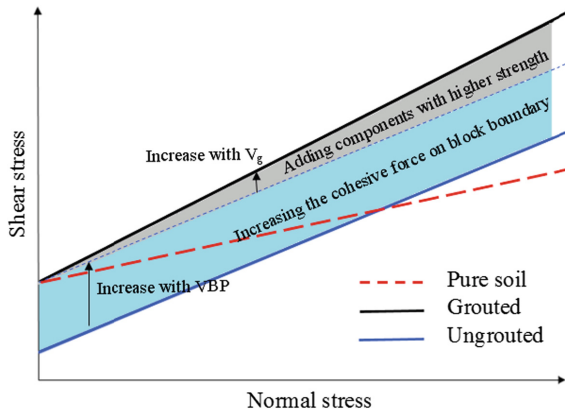


Fig. 7. Comparison of the mechanical behavior before and after grouting reinforcement

condition which only considers the first and the third mechanism. The failure surface may have morphology similar to Fig. 6a, but it propagates through the interior of the soil, rather than along the boundary of the block. Moreover, the boundary of the block is enlarged, and the failure surface becomes more tortuous than that of Fig. 6a, so the overall friction angle also increases. The total improvement is shown in Fig. 7 in terms of Mohr-Coulomb criterion.

The influence of VBP on cohesive has been studied by many researchers. According to their result, A roughly estimation on the cohesion force of SRM as a quarter of that of pure soil is made here. The improvement of internal friction angle is approximately proportional to VBP up to 75%, and the maximum improvement is about 30° but no more than that of the block. Since the injected grout suspension is regarded as an enlargement of blocks, it is reasonable to expect a linear relationship between grout volume and internal friction angle. Based on these rules, a quantitative relationship between the Mohr-Coulomb parameters after grouting is made, as shown in Eqs. (1) and (2).

$$c_{\text{grouted}} = k_1 c_{\text{SRM}} \quad (1)$$

$$\varphi_{\text{grouted}} = \varphi_{\text{SRM}}(1 + k_2 * v_g/A) \quad (2)$$

Here, k_1 and k_2 are both empirical parameters, and according to the analysis above, they are estimated as 4 and $2\pi/9$. “A” means the total volume of the specimen, and v_g means the volume taken by the cured grout.

Figure 6d represents an ideal condition, in which the second mechanism shows its maximal influence. The total area is divided into two distinct parts. One of them is sufficiently grouted, which means all the soils are replaced by grout, while the other one is totally ungrouted. A simplification is made here, which assumes that the grouted part is assumed to be composed of pure cement. The strength of the ungrouted part is neglected and the overall strength of the specimen is given in Eqs. (3)–(5).

$$c_{\text{grouted}} = a * c_{\text{cement}} \quad (3)$$

$$\varphi_{\text{grouted}} = a * \varphi_{\text{cement}} \quad (4)$$

$$\text{UCS}_{\text{grouted}} = a * \text{UCS}_{\text{cement}} \quad (5)$$

Here, a represents a reduction factor, which represents the ratio between the grouted area to the total area, as shown in Eq. (6).

$$a = V_g/A * (1 + \text{VBP}) / (1 - \text{VBP}) \quad (6)$$

The real distribution of grout suspension, which is represented by Fig. 6b, is between that of Fig. 6c, d. Thus, Eqs. (1)–(2) and Eqs. (3)–(5) should be regarded as a lower limit and upper limit for the strength of grouted SRM. The actual strength can be calculated based on Eq. (6) by considering another reduction factor b , which represents

the nonuniformity of grout distribution. This parameter is mainly influenced by block count, N .

When block count approaches infinity, b approaches 1, since the grout suspension is considered to be uniformly distributed in the specimen. Thus, the relationship between b and block count is supposed to obey an exponential function, as shown in Eq. (7).

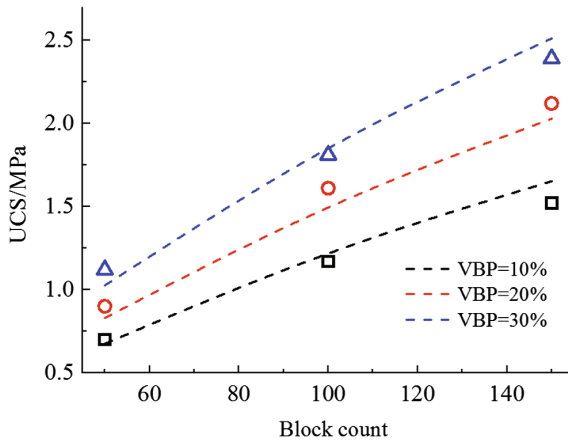


Fig. 8. Comparison of results from empirical equation and laboratory test

$$b = 1 - \exp(\alpha * N) \tag{7}$$

Here, N represents block count and α is a fitting parameter. The final equation for estimation of the UCS of grouted specimen is shown below:

$$UCS_{grouted} = V_g/A * (1 + VBP)/(1 - VBP) * [1 - \exp(\alpha * N)] * UCS_{cement} \tag{8}$$

The values of parameters are as follows: V_{inject} is 1000 ml, V_g is 625 ml, A is 1960 ml and UCS_{cement} is 8.8 MPa. α is -0.0044 , calculated by regression analysis according to test results. A comparison between calculated value and test value is shown in Fig. 8.

The dashed line represents the proposed empirical equation, and the scatters represent the test value. As can be seen, the UCS increases when block count and VBP increases, and the proposed equation can reasonably estimate the UCS of the test samples.

6 Conclusion

The main goal of this work is a comprehensive study of the physical mechanisms of grouting reinforcement on SRM. Laboratory tests are carried out to simulate the process of grouting into SRM. Then, grouting behavior and mechanical property of the grouted SRM are investigated. Finally, a concept model and empirical equation is proposed for estimation on the strength of grouted SRM. The main conclusions are as follows:

- (1) Blocks in soil significantly change the flow patterns of grout suspension. With a high VBP and block count, grout suspension can spread into a larger area compared with that in pure soil. On the other hand, when VBP and block count is low, grout suspension might be confined to some local area around some blocks instead of penetrate into further places, and the overall strength of SRM can be comparatively low.
- (2) The strength of the grouted SRM is influenced by VBP. When VBP is low, the normal stress drops sharply after the peak, and the decreasing rate is very high. When VBP is high, the normal stress decreases gradually until it reaches the residual stress. The compressive strength is several times higher than that of low VBP, and the test sample shows ductile property instead of brittle failure.
- (3) A conceptual model for grouting reinforcement on SRM is proposed. The model considers three aspects which contribute to the improvement of mechanical property of SRM in grouting process: increasing the cohesive force on block boundary, connecting different blocks together, and adding components with higher strength than matrix. A comparison is made between the test results and calculation from the proposed empirical equation, which shows that the empirical equation can reasonably estimate the UCS of the test samples.

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