Numerical modeling and verification of grouting with mold bag treatment on seepage failure in foundation excavation

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ABSTRACT
This article presents a numerical modeling and verification on a new grouting technique, called mold bag prestress reinforcing method, which was successfully used for grouting control on seepage failure during a foundation pit excavation project. A numerical model is established based on finite element method to simulate the prestress reinforcing and grouting process. The displacement and stress field during grouting process are calculated. Based on the calculation results, the rationale of the prestress method is clearly illustrated and the reinforcing mechanism is revealed. Results show that the horizontal displacements on the monitoring lines parallel to the mold bag are distributed in a parabola shape, and the prestress method effectively improves the mechanical properties of the soil. The influence of multimold bag interaction is also analyzed. The impermeability of the interior areas between two mold bags can be further improved due to a combining effect. The numerical results are compared with the actual excavation results of the foundation project. After grouting treatment, the water inflow amount reduced from 94 m$^3$/h to 4 m$^3$/h, which means more than 96% water inflow was successfully reduced. It is concluded that the numerical model can successfully simulate the process of prestress method and reveal the reinforcing mechanism.

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1. Introduction
In foundation engineering project, seepage failure is a common engineering disaster, such as piping and soil flow (Feld 2001; Houlbsy and Byrne 2005; Ding et al. 2013; Chatzivasileiou 2014; Harireche et al. 2014; Ding et al. 2015). As the excavation depth increases, the water head outside of the foundation become higher than inside. The seepage field is significantly changed, causing uplift force on the bottom of excavation surface. If the overburden pressure is not enough to resist the seepage force, failure...
would occur in the soil overburden and groundwater would flow into the foundation (Foster et al. 2000; Hagerty 2004; Fox and Wilson 2010; Fox et al. 2010; Fujisawa et al. 2010).

The influence of the seepage force on the stability of the foundation and the failure modes of the soil overburden have been extensively studied for many years, especially using numerical simulation of finite element method (Deng and Carter 2000; Zdravkovic 2001; Khafaji et al. 2003). Vasquez and Tassoulas (2000) proposed a finite element model with re-meshing technique to analyze the process of caisson penetrating into clay. Zeinoddini et al. (2011) carried out a similar simulation by implanting Drucker–Prager model into the calculation for characterizing the soil behavior. Some simulations also investigated the influence of uplift force on skirted foundations and suction caissons and the time-displacement response in the uplift process (Erbrich and Tjelta 1999; Houlsby and Byrne 2005; Gourvenec and Randolph 2009; Gourvenec and Randolph 2010). These studies have provided theoretical basis for seepage failure treatment and precaution on water inflow.

Dewatering method can be used to prevent seepage failure during foundation pit excavation. However, for a complex urban environment, dewatering method is not very applicable, since it often causes dramatic decrease of underground water level and significant land subsidence, which threatens the stability of surrounding buildings and underground utilities. (Zhou et al. 2004; Shi and Peng 2006; Wang et al. 2009) Alternatively, grouting has been used as an effective method to reinforce the formation in case of seepage failure during foundation pit excavation or other geotechnical engineering constructions (Wen-Jun 2005; Zhang et al. 2012; Li et al. 2013). During the grouting process, grout materials are injected into the stratum to fill the voids and provide cohesive force for the geological masses. Thus, the mechanical property and impermeability of the stratum is improved, which provide sufficient strength for resisting the seepage force during excavation. However, for some cases, the soil overburden is very soft and cannot effectively resist the grouting pressure, and the grout cannot reach the target area or even can fracture the soil and spread upward into the ground surface. Thus, special concern should be given to the stability of the soil overburden in the grouting process.
This article presents a case study and a numerical model of grouting control on seepage failure during foundation pit excavation. A new grouting method, called mold bag prestress reinforcing method (referred as prestress method in the following sections), was used to control groundwater inflow into the foundation. The main objective was to form a water resisting layer above the target grouting region of the foundation, as shown in Figure 1. Afterwards, the grout injected into the soil can be restricted in the area below the bottom of the mold bag. Fracturing of soil along the vertical direction is avoided and injected grout is prevented from spreading up to the ground surface.

In the following sections, the basic background of the construction site is first introduced. The main steps and the rationale of the prestress method are illustrated. Then a numerical model is established to simulate the reinforcement and grouting process. The influence of the reinforcement effect is analyzed and the mechanism of the prestress method is revealed, which provide experiences to other foundation projects with seepage failure.

2. Site description and background

The foundation project of Shangyuanmen station of No.3 subway line in Nanjing is located in the north of Nanjing province, China. The station is about 400 m away from Yangtze River. The hydrogeological condition is complicated. The overlying strata above bedrock are composed of multilayer structures, such as silt clay, silt and find sand. The groundwater has a strong hydraulic connection with Yangtze River. The burial depth of the foundation is 22 m and water level is about 1.5 m under the ground surface. Water inflow occurred at an excavation depth of 18 m, when the excavation level was approaching the interface between the soil overburden and the bedrock. Since the groundwater in the fractured rock could not be effectively drained out through dewater well, failure occurred in the remained soil overburden under the influence of groundwater pressure, as shown in Figure 2. The inflowing water contained 2%–3% amount of clay. Afterwards, the failure region expanded further and other water inflow points emerged and increased rapidly. In the most severely failed region, the maximum inflow amount of one point reached 50 m$^3$/h, and the total

![Figure 2. Construction site and seepage failure of the foundation.](image-url)
inflow amount of the foundation reached more than 100 m³/h, which severely threatened the safety of the excavation process.

3. Rationale of the prestress reinforcement mechanism using fabric mold bag

The process of prestress reinforcement using fabric mold bag includes the following steps: First, the fabric mold bag is banded on the grouting pipe. After preparation, the pipe is put into the grouting hole. During the grouting process, grout is first injected into the mold bag. The volume of the mold bag keeps growing until it reaches its maximum value. During this process, the compactness of the surrounding soil improves as the injected grouts occupy a large space. The original stress field is changed and the shearing strength of the soil is greatly improved. In this case, the stratum can bear a larger fluid pressure when the subsequent grout is injected. The resistance for surface uplift is also improved.

The mechanism of reinforcement on the mechanical behavior of soil using fabric mold bag can be divided into three aspects: (1) the grouts injected into the mold bag push out the surround soils. The volume of the mold bag is enlarged under the grouting pressure as the grouting volume increases. After the injected grouts solidified, the mold bag works as a cement pile, with similar functions of piles in composite foundation. (2) At the interface between soil and the mold bag, the normal pressure is very large, as the grouting pressure usually reaches 1 MPa to 2 MPa during mold bag injection. The soils are compacted tightly and the friction can transfer load from soil to the mold bag pile. (3) Excess pore water pressure is aroused as the soil is pushed out by the mold bag. Afterwards, the excess pore pressure dissipates, the soil becomes more compacted and the friction on the interface between soil and the mold bag also increases.

In sum, using the mold bag grouting, the horizontal stress in the soil increases and the shearing strength of the soil is greatly improved. Afterwards, the grout injected into the soil can be restricted under the bottom of the mold bag. Fracturing of soil along the vertical direction is avoided and injected grout is prevented from spreading up to the ground surface. Thus, the grouting effect is greatly improved. In the following sections, a numerical model is established to simulate the reinforcement process with mold bag injection. The mechanical characteristics of mold bag expansion and the interaction with the surrounding soil is analyzed, and the soil pushing-out effect is quantitatively evaluated. The influence rule of the mold bag length and enlarged volume on the compactness of the soil are acquired from calculation results. The influence of distribution distance during multimold bag grouting is also analyzed and the optimum value of the distance is acquired.

4. Establishment of the numerical model

4.1. Geometry and boundary conditions

The geometry domain of the mold bag grouting is simplified according to actual engineering dimension, which is 14 m wide and 9 m high. The distance between the grouting hole and the mold bag top is 3 m, and the maximum expansion volume of
the mold bag is 0.125 m³ for a 1 m of the grouting pipe. The influenced region around the mold bag is assumed to be within a distance of 7 m. The height of the stratum is 9 m. A trial calculation shows that the variation in further area can be neglected. Thus, the dimension of the calculation domain of the model is reasonable.

The boundary conditions are set as follows: the upper side of the domain is set as free moving boundary. The lateral sides of the domain are constrained of horizontal displacement but free to move along vertical direction. The lower side of the domain is totally restricted from moving. To improve calculation efficiency and insure the accuracy, a finer mesh is generated around the grouting hole and the mold bag during the mesh generation process, while a coarser mesh is generated in further places away from the grouting hole. Parameters of the simulation are shown in Table 1.

4.2. Controlling equation

During mold bag expansion, the pore water pressure increases as the soil is compressed by the mold bag. Afterwards, the excess pore water pressure dissipates. The flow of groundwater in this process can be described by Darcy’s law.

\[ \rho S \frac{\partial p}{\partial t} - \nabla \cdot (\rho u) = Q_m \]  

\[ u = -\frac{k}{\mu} (\nabla p + \rho gN) \]

Here, \( p \) represents the water pressure, \( S \) represents the coefficient of compressibility, \( Q_m \) represents source term, \( k \) represents the permeability of the soil, \( \rho \) represents water density, \( \mu \) represents water viscosity, \( u \) represents water velocity, \( g \) represents gravity and \( N \) represents unit vector in vertical direction.

The expansion of the mold bag changes the stress and deformation field of the soil. The stratum is regarded as elastic-plastic body which is permeable. The stress–strain relationship is expressed as:

\[ \sigma = D \varepsilon - \alpha_B p I \]

Here, \( \sigma \) represents Cauchy stress tensor, \( \varepsilon \) represents strain tensor, \( D \) represents elastic coefficient, \( \alpha_B \) represents Biot coefficient and \( I \) represents a unit tensor.

The Cauchy stress tensor is divided into two parts: spherical tensor and deviator tensor. The deviator tensor is independent of water pressure. The relationship between spherical tensor and water pressure is expressed as:

\[ \sigma_{ii} = K_s \varepsilon_{ii} - \alpha_B p \]

\[ \sigma_{ii} = \frac{1}{3} \text{trace}(\sigma) \]  

Here, \( K_s \) represents the bulk modulus of the stratum, \( \varepsilon_{ii} \) represents volumetric strain. As groundwater pressure leads to deformation of the stratum, the pore water is drained out of the voids of the soil. Thus, the source term is expressed as:

\[ Q_m = -\rho x_B \frac{\partial \varepsilon_{ii}}{\partial t} \]  

The equilibrium equation of the soil is expressed as:

\[ -\nabla \cdot \sigma = F \]  

Equations (1)–(7) provides the solution for the variation of fluid field and the deformation field of the stratum with consideration of the solid and fluid coupling behavior during mold bag expansion.

5. Results and analysis

5.1. Influence of mold bag expansion on displacement field of the soil

Figure 3 shows the horizontal displacement of the soil on each monitoring line (The lines are numbered and marked as in Figure 4). The length of the mold bags are 3.2 m, 2.8 m, 2.4 m and 2 m, respectively. As can be seen, these displacement curves are not smoothly distributed, since a heterogeneous property of soil is considered. Generally, the curves are distributed in a form of parabola shape. The peak value of the lateral displacement occurs at the middle of the mold bag (5 m in the \( y \)-coordinate), and decreases rapidly along both sides. At the top and bottom, the variation rate of the curves becomes very small and the displacement level off to zero. By comparing different displacement curves, it can be seen that: in the nearer areas of the mold bag, the displacement of the soil is influenced more intensely, while the influenced area is more concentrated. When the length of the mold bag is altered, the displacement field of the soil also changes. As the length of the mold bag become longer, a larger area of the soil is influenced, which means the compactness of the soil improves. However, the variation trends of the horizontal displacement are similar for each case.

Figure 5 shows the displacement field of the soil after reinforcement of mold bag. The length of the mold bags are 3.2 m, 2.8 m, 2.4 m and 2 m, respectively. As can be seen, the displacement is greatly changed after mold bag reinforcement. The soil is mainly compressed along lateral direction, and the displacement along the vertical direction is comparatively small, since the volume of the mold bag mainly expands along the radial direction. At the interface between soil and the mold bag, the maximum soil displacement is about 0.2 m, which is in accordance with the maximum expansion radius of the mold bag. The mainly influenced area is concentrated in the area around the mold bag. Soil in upper and lower areas is less influenced. As the
soil is compressed by the expansion of the mold bag, a plastic zone is formed in the soil around the mold bag. The plastic zone keeps growing in ellipse shape during the mold bag expansion process. Since the soil is compressed laterally, the plastic
zone expands mainly along the horizontal direction, while the expansion speed is relatively slow along vertical direction.

5.2. Influence of mold bag expansion on stress field of the soil

Figures 6 and 7 show the distribution of plastic region in the soil and the radial stress of the soil along different monitoring line. As can be seen, the stress distribution shows significant differences with different monitoring lines. The redial stress along line A and line E are very small, with an average value of about 0.1 MPa. The variation rate of the stress with horizontal distance is very small, which means the influence of the mold bag expansion on the stress field is not obvious in these areas.
Conversely, the stress variation of line B, C and D are much higher than those of line A and E, which means the mold bag expansion have a significant effect on the stress distribution. The radial stress improves remarkably when the horizontal distance is less than 1 m. As the horizontal distance increases, the radial stress decreases in a nonlinear trend. The decreasing rate is high around the mold bag, and it slows down as the distance increases. Finally, the radial stress level off until it reaches the original crustal field.

As shown in the variation of the radial stress in Figure 7, the influence is not obvious beyond 1 m. Thus, the reinforcement effect and the improvement of the stress field are limited when only one mold bag is used. As the injection pressure for the mold bag reaches 2 MPa, the expansion radius of the mold bag reaches its maximum value of 0.2 m. For a mold bag with length of 3 m, only the middle area with a range of 2 m height is assumed to be sufficiently reinforced. The lateral stress only improves significantly within 1 m around the mold bag, which is assumed as an effective reinforced area. In further areas, the reinforcement effect is neglected. In the practical engineering, a multimold bag reinforcement method was used. The grouting parameters and distribution of grouting hole should be determined based on the geological condition, rheological property of the grouting material and the grouting requirements. To determine a reasonable distribution distance, the reinforcement effect and the interaction between two mold bags with different distance are analyzed.

Figures 8 and 9 show the radius stress distribution on the central line of two mold bags and the fluid field when grouting into the soil after mold bag reinforcement. As can be seen, the variation trend of the radius stress for the condition of two mold bags is similar with that of one mold bag. The stress is significantly improved in the areas around the mold bag and decreases rapidly in further areas. In the area between the two mold bags, the increase of the stress is higher than that of one mold bag, due to a combination influence of the two mold bags. As the interval between the mold bags increases, this combination influence reduces. The minimum radius stress occurs at the midpoint between the two mold bags. The stress value is about 0.3 MPa when the interval is 3 m and it reduced to less than 0.1 MPa with an interval of 5 m, which means the soil is not well compacted. During the process of grouting into soil, an insufficient compactness of the soil may lead to fracturing of grout suspension along
Figure 8. Radial stress of the soil on the central line of two mold bags.

Figure 9. Fluid field when grouting into the soil after mold bag reinforcement.
vertical directions, and the grout suspension can spread upward to the ground surface.

The process of grouting into soil is simulated after the soil is reinforced by mold bag expansion, as shown in Figure 9. The deformation field of the soil is represented by gray level color, with the black color representing the highest deformation area. The blue lines represent the streamline of the fluid field as the grout is injected into the soil. As can be seen, the streamlines bypass the areas around the mold bag, which means impermeability and stress condition of the soil are highly improved after mold bag reinforcement. In the areas between the two mold bags, the soil undertakes a combining effect of compaction, so the grout suspension can hardly fracture the soil and spread up to the ground surface. In the outside areas, the compaction effect reduces as the distance increases. As the distance between the mold bag increases, the compaction effect in the interval area reduces. When the distance is 5 m, some of the grout suspension may split the soil and spread up to the ground surface, as shown in Figure 9(d).

Based on the analysis above, the distance between grouting holes can neither be too large or too small. For the first case, the compactness effect is insufficient and the grout would split the soil, and spread up to the ground surface. For the second case, the two mold bags would interfere with each other during expansion, and the compactness effect is limited. In the actual engineering process, the distance was set as 3 m. The actual reinforcement effect is shown in the next section.

6. Validation on the grouting effect after excavation

After grouting treatment, the water inflow amount reduced from 94 m$^3$/h to 4 m$^3$/h. That is, more than 96% water inflow amount was successfully reduced. During the grouting process, no grout suspension spread into ground surface, which means the
prestress method with mold bag effectively reinforced the soil overburden and highly improved its mechanical behavior. Examination holes were drilled to examine the grouting effect. The coring rate was 75%–80%, which means the stratum has a high strength after grouting reinforcement, as shown in Figure 10. The rock cores were composed of rock block, grout and clay. The interface between rock block and grout vein were tightly cemented, which means the grout suspension was sufficiently injected into the stratum with high injection pressure. The stratum revealed by excavation showed that the injected grout were totally restricted in the target area. In the areas with the same level of the mold bag, no grout was found, and in the areas below the mold bag, the injected grout sufficiently filled the voids of the stratum and formed an impermeability layer, as shown in Figure 10. The examination on the grouting effect showed that prestress method with mold bag effectively reinforced the soil overburden, and provided favorable condition for the successive grouting process.

7. Conclusions

This article proposed a numerical modeling and verification of the mold bag prestress reinforcing method, which was successfully used in the grouting treatment on seepage failure in the Shangyuanmen station foundation excavation project. The stress and displacement field during grouting are calculated. The rationale of the pretress method is clearly illustrated, and the reinforcing mechanism is revealed. The main conclusions are as follows:

- The horizontal displacements on the monitoring lines parallel to the mold bag are distributed in a form of parabola. The peak value of the displacement occurs at the middle of the mold bag, and drop down rapidly along upward and downward direction. In the top and bottom areas, the variation rate of the curves becomes very small and the displacement level off to zero. As the length of the mold bag become longer, a larger area of the soil is influenced, which means the compactness of the soil improves, while the displacement are similar for mold bags with different length.

- For a single mold bag, the reinforcement effect is limited. The effective reinforcing region is no more than 1 m long from the grouting hole. For a mold bag with a length of 3 m, only the middle area with a range of 2 m height is assumed to be sufficiently reinforced. In the multimold bag treatment, the impermeability of the interior areas between two mold bags can be further improved with a combining effect. The stress value is about 0.3 MPa when the interval is 3 m and it reduced to less than 0.1 MPa with an interval of 5 m, which means the soil is not well compacted.

- According to numerical simulation, the final distribution distance between the mold bags were set as 3 m, and the numerical results have been verified by excavation of the foundation project. In the regions above the mold bags, no grout was found, and in the regions below the mold bags, the injected grout sufficiently filled the voids of the stratum and formed an impermeability layer. After grouting treatment, the water inflow amount reduced from 94 m³/h to 4 m³/h, which means more than 96% water inflow was successfully reduced.
Disclosure statement

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