Study on the Mechanism of High-Pressure Jet Grouting Based on Computational Fluid Dynamics

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Abstract. High-pressure jet grouting (HPJG) is an effective method to reinforce soil mass and to prevent seepage in the practical engineering. It has been used in the different fields for many years, and achieved the significant social and economic benefits. In this study, the processes and mechanisms of HPJG are discussed based on the computational fluid dynamics (CFD). The related results show that it is a good way to reveal the processes and mechanisms of HPJG. Using the suitable injection pressure and flow rate, nozzle structure and velocity of nozzle movement are the effective ways to increase the working efficiency of HPJG. Moreover, the effects of impacting, cutting, mixing, lifting, replacing, filling, extrusion, permeation, concretion, displacement and packing are the main mechanisms of HPJG.

Introduction

High-pressure jet grouting (HPJG) was developed from the static pressure grouting and high-pressure water jet technologies. It uses high-pressure cement-slurry jet to impact and break the underground soil mass directly. Then, the cement-slurry interacts with soil particles by a series of comprehensive actions of admixing, lifting and replacement, coagulation. Finally, the concrement will be formed in the formation which we need to treat. HPJG has widely used to reinforce the soil mass and to prevent seepage in many different fields, including civil engineering, geohazard treatment, hydraulic and hydropower engineering, etc. During the whole process of HPJG implementation, the crucial step is to break soil mass by high-pressure cement-slurry jet. The better the effect of high-pressure cement-slurry jet, the better HPJG implementation [1-7]. Computational Fluid Dynamics (CFD) is an effective method to study the various problems about fluid has been applied in the many fields by all over the world [8]. In this study, the mechanisms of HPJG are discussed based on CFD, especially for high-pressure cement-slurry jet.

Modeling

The first step of CFD to study HPJG is modeling. Because the whole model is axisymmetric, so it just needs to create half model. Figure 1 shows the entire model for CFD. In which, the zone was circled by a green circle means nozzle, its internal structure affects the effect of high-pressure cement-slurry jet directly. Actually, the straight cone nozzle is the most commonly used in the practical engineering. Its internal structure is formed by the zone of ABCDEFGH, it is the flow channel for high-pressure cement-slurry. The zone of EFGHIJK means the nozzle’s external wall. Moreover, the zone ofQRSTU means soil mass. The other zones mean air. Thus, this model is to study the situation of high-pressure cement-slurry ejected from nozzle outlet into air, eventually impact the surface of the soil mass. The length of DU means jet distance, the best value is 50-100 times the outlet diameter (d). In this study, DU=400 mm. The effects of groundwater and the cement-slurry accumulated in the borehole on the high-pressure cement-slurry jet are ignored, it belongs to the non-submerged jet.
The concrete structure and the three-dimensional model of the straight cone nozzle as shown in Figure 2 and Figure 3. Its parameters mainly include inlet diameter ($D=32$ mm), outlet diameter ($d=4$ mm), contraction angle ($\theta=60^\circ$), and the length to diameter ratio of the outlet section ($l_2/d=2.5$). Moreover, its internal structure needs to meet the following equation [3,9,10]:

$$\frac{D-d}{L-l_2} = 2 \tan \frac{\theta}{2}$$

Figure 2. The diagram of the concrete structure of the straight cone nozzle.

(a) The entire model
(b) The cutaway view

Figure 3. The diagram of three-dimensional model of the straight cone nozzle for high-pressure jet grouting.

Meshing and Boundary Condition Setting

The second step of CFD to study HPJG is meshing and boundary condition setting. Generally, the quality of meshing determines the cost and result of CFD directly. Moreover, the more grids, the more accurate computational result, but the higher cost. It needs to spend more computational time and resource. Based on above reasons, the hybrid grid should be used for meshing in this study to fit the complex model. The entire nozzle zone is divided into three parts, they are the two rectangular areas ($ABGH$ and $CDEF$) and one trapezoidal area ($BCFG$). In the meantime, the zones of air are divided into four parts, they are three rectangular areas ($DEKTU$, $LMNS$ and $NOPQR$) and one irregular area ($KJILST$). The structured grids fit the rectangular areas meshing. The unstructured grids fit the trapezoidal and irregular areas meshing. The total grid cells are 35720. Figure 4 shows the situation of meshing for CFD.
The boundary conditions mainly include the Pressure Inlet (AH), the Pressure Outlet (IL, LM, MN, NO and OP), the Axis (AB, BC, CD, DU, UQ and QP) and the wall (other areas). The jet grouting pressure is 30 MPa, the surrounding environmental pressure is 10132 Pa. The materials include two phases: cement-slurry (primary phase) and air (secondary phase). In which, the water-cement ratio (W/C) of cement-slurry is 1:1, the cement is P.O 42.5.

**Post-Processing and Result Analysis**

The jet velocity is the key factor of HPJG, the higher jet velocity, the higher working efficiency. The cement-slurry jet power (it reflects the working efficiency of HPJG) can be roughly calculated as the following equation:

\[
N = P \cdot Q = P \cdot \mu \cdot F_0 \cdot v_0
\]  

Where \(N\) is the jet power, \(P\) is the jet pressure, \(Q\) is the flow rate, \(\mu\) is the flow coefficient, \(F_0\) is the area of nozzle outlet, \(v_0\) is jet velocity.

Figure 5 shows the velocity contour of cement-slurry jet based on CFD. The whole jet is a divergent shape. The highest velocity is in the middle area of jet, and the velocity decreases gradually to the sides. After the high-velocity cement-slurry jet ejects from nozzle outlet, the large velocity gradient exists in the area of the interface between jet and the surrounding static medium (such as soil particles, air, groundwater, etc.). Due to the rubbing action, the external medium near the jet boundary starts to move. Some static medium is carried away by entrainment, resulting in a low-pressure area is created around the jet boundary. The external medium moves to the jet boundary continually, other medium has a lower velocity than jet, resulting in the vertical moving. With the jet extending, the amount of the surrounding static medium increases, the width of jet becomes larger gradually. Because of the energy conversion and linear head loss, the dynamic pressure and velocity decreases gradually, resulting in the jet diverging gradually.
Discussion

In the process of HPJG, the high-pressure cement-slurry jet cutting effect on soil mass mainly include five effects, including the dynamic pressure effect of jet flow, the pulsed oscillation effect of jet flow, the water wedge breaking effect of jet flow, the cavitation effect of jet flow and the percussive effect of jet flow. Moreover, the main factors that affect the performance of jet cutting soil mass as follows: (1) Injection pressure and flow rate. Generally, the jet cutting efficiency with the injection pressure and flow rate increases. Furthermore, when the energy is constant, it is more obvious to increase the injection distance by increasing the flow rate than by increasing the injection pressure. (2) Nozzle outlet diameter. Generally, the jet cutting efficiency is proportional to the square of the nozzle outlet diameter. (3) Velocity of nozzle movement. Generally, the jet cutting efficiency decreases with the velocity of nozzle movement increases. Moreover, the velocity of nozzle movement slower, the diameter of jet grouting pile larger. (4) Hydrostatic pressure acting on the nozzle outlet. Generally, the jet cutting efficiency decreases with the hydrostatic pressure increases. (5) Physical and mechanical properties of soil mass. Generally, higher jet cutting efficiency in soft soil, and lower jet cutting efficiency in hard soil. In other words, the higher the compressive strength of the soil, the diameter of jet grouting pile smaller.

In addition, there are four different methods of HPJG in practical engineering, including single-tube method (CCP method), twin-tube method (JSG method), three-tube method (CJP method) and multi-tube method (SSS-MAN method). They have five same mechanisms in the process of HPJG as follows: (1) Impacting, cutting and mixing effect. Due to the high-efficiency cement-slurry jet impacting and cutting on the soil mass. In the meantime, the cement-slurry and soil particles are mixed by the entrainment diffusion. (2) Lifting and replacing effect. It improves and increases the density and strength of concrement effectively. In fact, this process only replaces fine soil particles, the coarse soil particles mix with cement-slurry coagulate into a concrement with higher strength. (3) Filling and extrusion effect. The end of high-pressure cement-slurry jet mainly extrudes the surrounding soil. In the meantime, the cement-slurry exerts constant extruding and infiltration on the soil mass, resulting in the concrement combines with the surrounding soil more tightly. (4) Permeation and concretion effect. In the process of HPJG, except for the formation of coagulates in the punching and cutting range, the infiltration effect of cement-slurry occurs in the coarse sands and gravel layer, resulting in the permeable condensation layer. (5) Displacement and packing effect. In the gravel-cobble and boulder formation, the filling materials between the big particles are cut and peeled by the high-pressure cement-slurry. In the meantime, some fine particles are lifted and replaced to the surface, other big particles are moved by the strong impacting and shocking forces, and they are packed by the cement-slurry.

Conclusions

High-pressure jet grouting (HPJG) is an effective foundation treatment method which has been widely used in the various practical engineering for many years. In this study, the computational fluid dynamics (CFD) is used for simulating the process of HPJG, the related results can better reveal the process of HPJG. In the practical engineering, the effective ways to increase the working efficiency of HPJG mainly include the suitable injection pressure and flow rate, nozzle structure and velocity of nozzle movement. In addition, the effects of impacting, cutting, mixing, lifting, replacing, filling, extrusion, permeation, concretion, displacement and packing are the main mechanisms of HPJG to reinforce the soil mass and to prevent seepage.

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