

Research Article

Experimental Study on Sonic Vibration Grouting in Fine Silty Sand Layer

Yu Wang ^{1,2}, Bairu Xia,^{1,2} Zhiqiao Wang ^{1,2} and Shouceng Deng^{1,2}

¹School of Engineering and Technology, China University of Geosciences, Beijing 100083, China

²Key Laboratory on Deep Geo-Drilling Technology, Ministry of Land and Resources, Beijing 100083, China

Correspondence should be addressed to Zhiqiao Wang; zqwang@cugb.edu.cn

Received 11 November 2017; Accepted 8 April 2018; Published 10 May 2018

Academic Editor: Arnaud Perrot

Copyright © 2018 Yu Wang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Fine silty sand layer is one of the common weak strata. It is easy to deform suddenly and induce accidents under the external load due to its loose structure and poor self-stability. To improve the stability of the strata in engineering construction, the grouting is usually used for antiseepage reinforcement in the fine silty sand layer. This paper presents the basic principle of the sonic vibration grouting, develops the experimental device and the simulated stratum condition, mixes the acidic water glass for engineering application, and carries out the experimental study on the sonic vibration grouting. The results show that the effect of the exciting force on the sonic vibration grouting is not obvious, and the vibration duration has a greater influence on it. With the increase of the vibration duration, the grouting diffusion distance is enlarging gradually and stabilizes eventually at a certain value. The vibration frequency has the greatest impact on the grouting. The grouting effect is the best when the vibration frequency is close to the natural frequency of the fine silty sand. The grouting diffusion distance is getting smaller, which means the grouting effect is becoming worse, when the vibration frequency is far away from the natural frequency of the stratum. The grouting effect in the fine silty sand layer can be improved effectively by vibration technology using the sonic vibration grouting which has excellent effect in engineering application. This paper lays a foundation for the further study on mechanism and engineering application of the sonic vibration grouting.

1. Introduction

Fine silty sand layer is one of the common weak strata [1]. It is easy to deform suddenly [2] and cause landslides [3] and quicksands under the external load due to the small diameter and loose structure of the fine silty sand. The poor self-stability after the excavation disturbance leads to the difficulty in forming a load-bearing arch [4], the surface subsidence and cracking [5], and the instability of the tunnel face. The fine silty sand layer gets loose while meeting water [6], and it is easy to cause accidents after excavation [7]. With the development of the urbanization in China, construction projects including utility tunnel [8], subway, tunnel, and so on are gaining momentum. The seepage control and reinforcement by grouting in the fine silty sand layer, especially in some constructions that are not suitable for dropping water, has always been a hot topic in the field of geological engineering.

Grouting can be divided into static pressure grouting, high pressure jet grouting, and vibration grouting. The basic principle of the vibration grouting technology is to use mechanical vibration to force the saturated fine silty sand and the silt foundation to be liquefied so as to lose strength [9], and then pour the grout into the foundation. As a new grouting technology, the vibration grouting is expanding its application range [10], and scholars at home and abroad have done some research in this field [11]. Pore water pressure [12] and dynamic constitutive model of the saturated sand have been studied abroad since the 1960s. The concept of the vibration grouting is proposed by Central South University in 1997 at home. Zhou et al. [13] who studied the vibration response of the sandy soil and the principle of the vibration grouting presented that the impact vibration from vibration machines can make the pore water pressure of the saturated sandy soil increase, make the effective stress and the shear strength decrease

[14], and finally form the softened zone in foundation. When the grout is pressed into the sandy soil, it can easily cause the extrusion deformation or splitting effect of the sandy soil, thereby increasing the grouting feasibility and the grouting diffusion distance, so as to reduce the penetration. Yuan et al. [15] who studied the mechanics of vibration exciter put forward the calculation method of vibration amplitude, exciting force, torque, and power of vibration exciter (2006). Based on the multivariate fitting correlation analysis of soil liquefaction factors, Sun et al. [16] solved the probabilistic model discriminant for soil dynamic liquefaction by probability processing. Based on the method of finite element, Lei et al. [17] obtained the relationship between the low frequency vibration parameters and the grouting effect by the numerical simulation and analysis for the saturated sandy soil vibration grouting using the double yield surface model under large displacement and strain. Jin et al. [18] carried out the study on the reinforcement of saturated sand by ultrasonic vibration grouting which proved that the strength of the saturated sand sample was improved significantly by the ultrasonic vibration grouting.

The traditional vibration grouting does not involve the influence of vibration characteristics, and the vibration frequency is generally less than 40 Hz due to the limitation of the mechanical structure. The frequency of sonic vibration is higher, which can be changed freely in the range of 50–200 Hz, and the high frequency vibration makes the soil liquefaction more adaptable. A drilling tool rotates slowly in the sonic vibration grouting, and it depends entirely on the exciting force to penetrate the stratum. This method with the characteristics of high drilling rate and efficiency can realize the grouting in a drilling process and has a good development prospect.

Based on the sonic vibration drilling technology [19], this paper proposes the basic principle of the sonic vibration grouting, develops the experimental device, and mixes the simulated fine silty sand layer. According to the demand of environmental protection, the physicochemical properties of the grout are studied, and the acidic water glass suitable for engineering application is mixed. Subsequently, the static pressure grouting experiment is carried out to determine the proper grouting pressure for the test sand. Finally, the simulation experiment of the sonic vibration grouting is carried out, which provides a reference for further theoretical research and engineering application.

2. Material and Methodology

2.1. Principle of Sonic Drilling Grouting. The principle of the sonic vibration grouting is shown in Figure 1. It uses a pair of reverse eccentric rotating shafts to produce the exciting force of 50–200 Hz that can be heard by human ears [20]. When the frequency of the drilling tool-grouting pipe coincides with the natural frequency of the stratum, it will produce a resonance [21] which drives the drilling tool and grouting pipe in the stratum and causes the liquefaction of the fine silty sand layer to form the softened zone. Meanwhile, the

grout is injected into the stratum through compaction, split, penetration, and other methods to reinforce the stratum.

2.2. Formation Engineering Features. The fine silty sand whose diameter is fine and even used in the experiment is sieved by a soil sieve. It is dried to ensure the same moisture content to minimize the differences at utmost during each experiment so as to eliminate the potential interference factors. A random sampling of the test sand is carried out, and then the particle refractive index is analyzed by a laser particle size analyzer to measure the particle diameter distribution range of the sample. As shown in Figure 2, the test sand whose diameter is in 0.075–0.25 mm accounts for 65.59%, more than 50%, which is the fine silty sand engineering definition, and satisfies the experiment requirement.

The basic physical and mechanical properties of the test sand are obtained by the indoor basic civil engineering test according to the civil engineering test specification. The specific values are shown in Table 1.

2.3. Grout Mixing. Grout characteristic is one of the decisive factors of the grouting effect, and the acid water glass is mixed in this experiment. In the molecular formula of sodium silicate ($\text{Na}_2\text{O} \cdot m\text{SiO}_2$), m , which is also called modulus, is the ratio of the number of molecules of SiO_2 to Na_2O and has an important influence on the properties of the water glass. It is positively related to the strength of the concretion, but negatively to the gel time. When the modulus of the acid water glass is too big or too small, it is not conducive to the grouting engineering. The calculation formula of the modulus is as follows:

$$m = \frac{\text{SiO}_2\%}{\text{Na}_2\text{O}\%} \times \frac{62}{60} \quad (1)$$

The concentration of the water glass is often represented by Baume degree. The water glass can react with an appropriate amount of acid and produce the silicic acid gel in the preset time to consolidate the stratum. At present, the acid of the acid water glass is concentrated sulfuric acid under normal conditions. Because the concentrated sulfuric acid is more corrosive and expensive, the oxalic acid is used to mix the acid water glass in this paper. The basic configuration is shown in Table 2.

The water glass solution is defined as solution A, and the oxalic acid solution made from the industrial solid oxalic acid is defined as solution B. While mixing the grout, solution A is poured into solution B at a uniform rate. The mixed grout is stirred fully until the grout is stable, and then the gel time is observed. The gel time of the grout should be controlled at about 10 min, so that the grout can fully diffuse, solidify, and stabilize the stratum when injected into the soil layer. Meanwhile, there is the sufficient time for grout preparation and grouting operation. The preparation experiments of different proportions are carried out, and finally, the proper proportion of the water glass is determined.

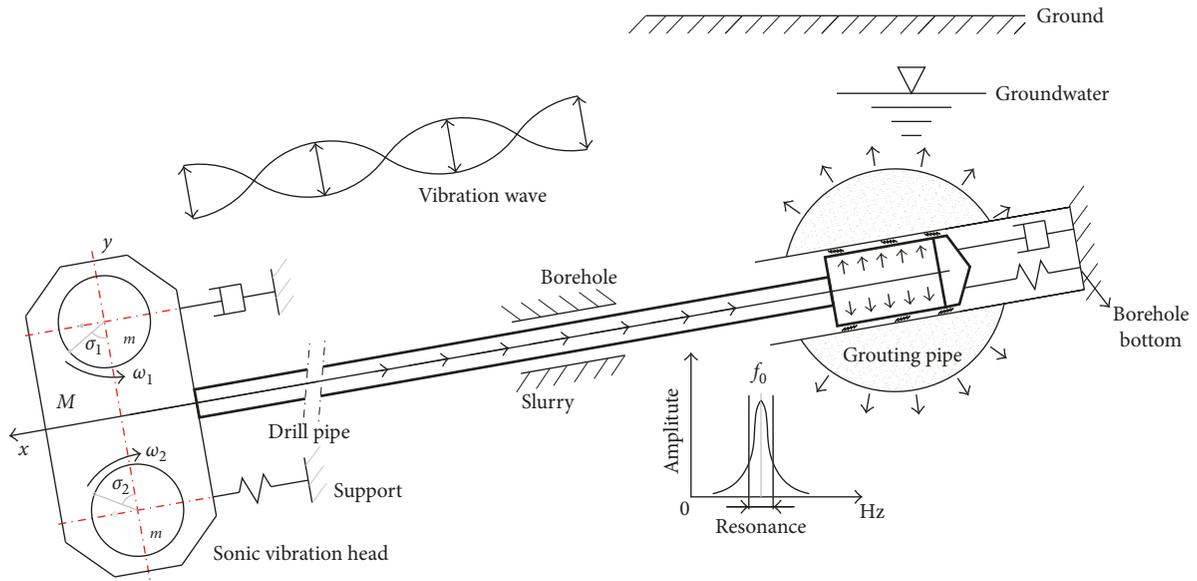


FIGURE 1: Principle of sonic vibration drilling grouting.

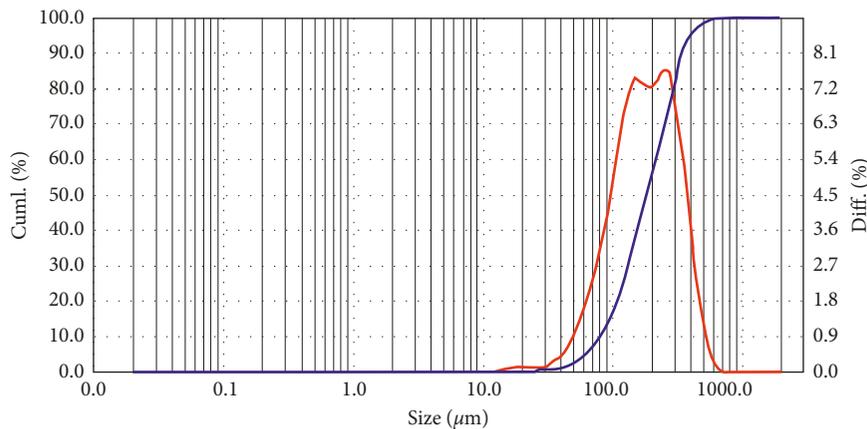


FIGURE 2: Distribution of particle diameter.

TABLE 1: Physical property indexes of the test sand.

Physical index	Permeability coefficient (cm/s)	Internal friction angle (°)	Porosity (%)	Moisture content (%)	Dry density (g/cm ³)	Specific gravity of soil particle
Value	5.46×10^{-3}	31.41	32.3	12.2	1.70	2.51

TABLE 2: Reagents used in the experiment.

Reagent	Parameter
Water glass	The modulus is 3.3, the Baume degree is 40° Bé Solid (industrial use)
Oxalic acid	

2.4. Experiment Methods. The grouting experimental device which is shown in Figure 3 mainly consists of sand storage box, grouting drilling tools, vibration source, support base, and grout circulation system. The outside diameter of the grouting drilling tool is 42 mm, and the inside diameter is 32 mm. The inside diameter of the grouting inlet located on the

top side of the grouting drilling tool is 15 mm. Eight grouting outlets in double rows whose diameters are 10 mm are arranged at the bottom of the grouting drilling tool. These grouting outlets are uniformly distributed in the circumferential direction, and the longitudinal spacing of them is 20 mm. During the experiment, the control valve is set to control the speed and

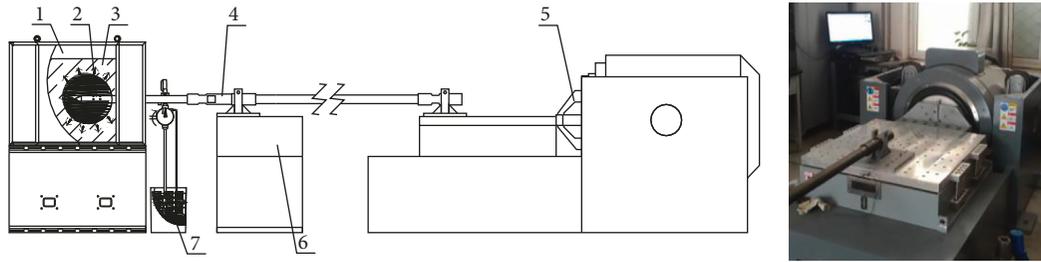


FIGURE 3: Grouting experimental device. (1) Sand storage box; (2) grouting concretions; (3) fine silty sand; (4) grouting drilling tools; (5) vibration source; (6) support base; (7) grout circulation system.

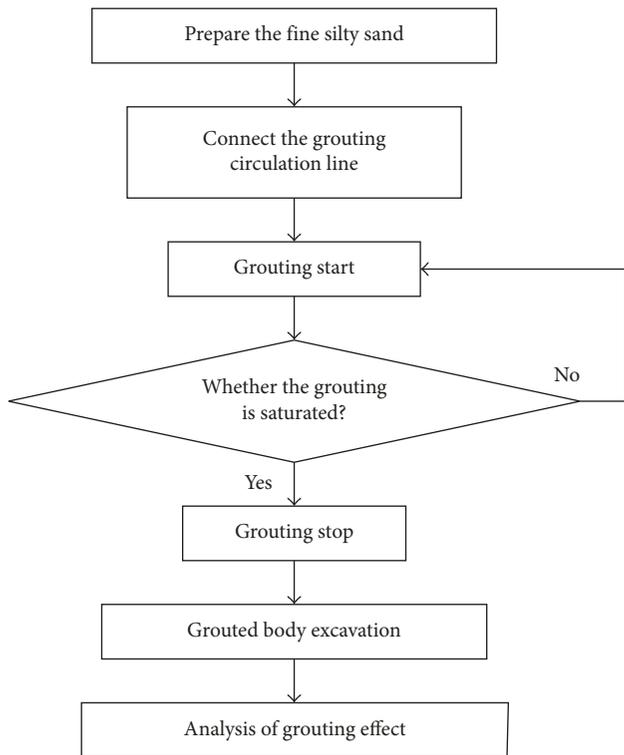


FIGURE 4: Flow chart of the grouting experiment.

quantity of the grout. The grouting effect can be tested by vibrating the grouting drilling tool to cause the diffusion of the grout in the sand storage box.

The flow of the grouting experiment is shown in Figure 4.

(1) The vibration drilling bit is placed in a pre-determined position in the sand storage box, the grouting outlets is wrapped with gauze, and then the fine silty sand is added and compacted layer by layer ensuring that the sand is high enough during each experiment; (2) the grouting storage bucket is connected with the grouting inlet, the grouting pressure is adjusted to 6 kPa, and the control valve of the grouting inlet is closed; (3) the vibration sensor is installed, the sensor and power amplifier are connected to the system controller, and the vibration parameters are set; (4) 2200 ml of the prepared acidic water glass is poured into the grouting storage bucket, and the gas in the connecting pipe is discharged; (5) the control

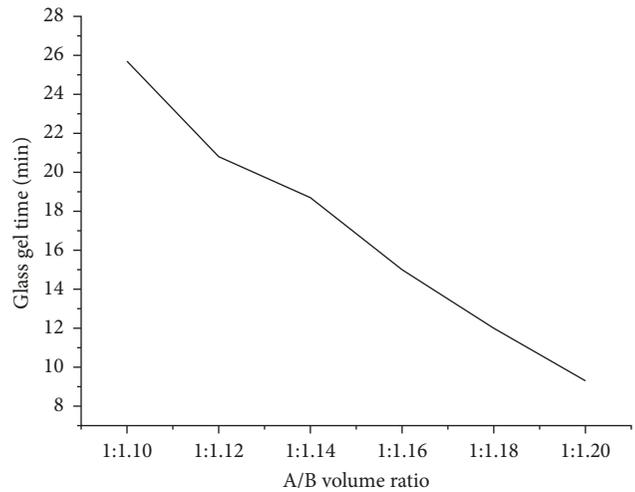


FIGURE 5: Gel time test curve.

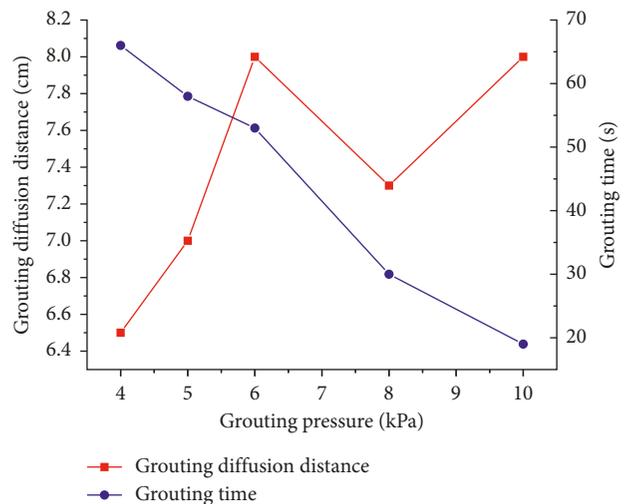


FIGURE 6: Effect of the static pressure grouting under different grouting pressures.

valve of the grouting inlet is opened, and the shaking table is run at the same time through the control system to inject the grout into the test sand layer; (6) the control valve is closed, the grouting is stopped, and the grouting duration is recorded when the liquid level of the grouting storage

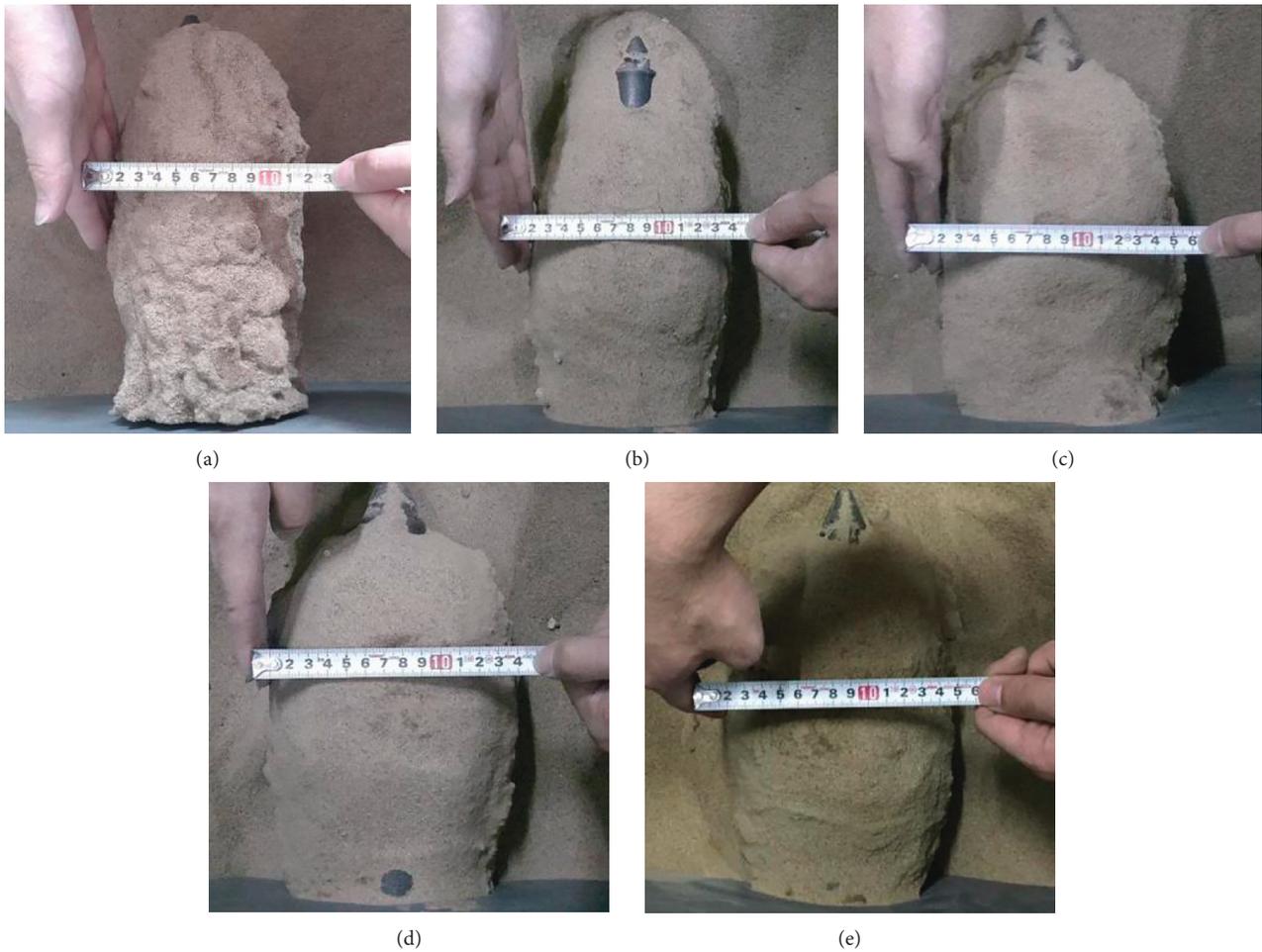


FIGURE 7: Concretions of the static pressure grouting under different grouting pressures. (a) 4 kPa; (b) 5 kPa; (c) 6 kPa; (d) 8 kPa; (e) 10 kPa.

bucket is no longer changing or the spillover appears in the experiment; (7) ten minutes after the grouting, the fine silty sand is dug carefully, the grout concretion is obtained, the shape of the concretion is observed, and the grouting diffusion radius is measured.

3. Results and Discussion

3.1. Grout Properties. The gel time can be adjusted effectively by adjusting the viscosity and pH of the acid water glass, which are the two key factors affecting the gel time. In the grout preparation process, the control variable method is used to mix the grout. The concentration of solution A is set as the influence factor 1, the concentration of solution B is set as the influence factor 2, and the solution volume ratio of A and B is set as the influence factor 3.

Figure 5 intuitively shows the variation trend of the acidic water glass gel time: the gel time decreases rapidly with the decrease of the volume ratio when the 30° Bé water glass and the 5% oxalic acid are selected to mix the grout. The solution with a volume ratio of 1:1.2 is used as the grout for subsequent experiments considering the difficulty of grout mixing, the container transfer after the grout preparation, and the full diffusion of the grout in the stratum after

grouting. The mixed grout whose initial viscosity measured by a six-speed rotary viscometer is 3.5 mPa·s has a good fluidity and grouting feasibility and can meet the requirement of the grouting experiment.

3.2. Results of Static Pressure Grouting. In general practical engineering, the grouting pressure in unconsolidated strata is between 0.3 and 0.5 MPa, and the grouting pressure is between 5 and 10 kPa in this paper considering the size effect of simulation experiment. The effect of the static pressure grouting and the shapes of the concretions are shown in Figures 6 and 7, respectively. When the grouting pressure increases from 4 kPa to 6 kPa, the longitudinal length of the concretion decreases slightly and the transverse width and the volume increase continuously and then basically remain unchanged. It shows that with the increase of pressure, the form of grouting diffusion changes from the initial pure penetration to the combined action of the penetration and compaction gradually.

However, the grouting volume under 8 kPa is slightly smaller than that under 6 kPa, which illustrates that overlarge grouting pressure not only increases the diffusion rate of the grout in the soil but also makes the grout break through the

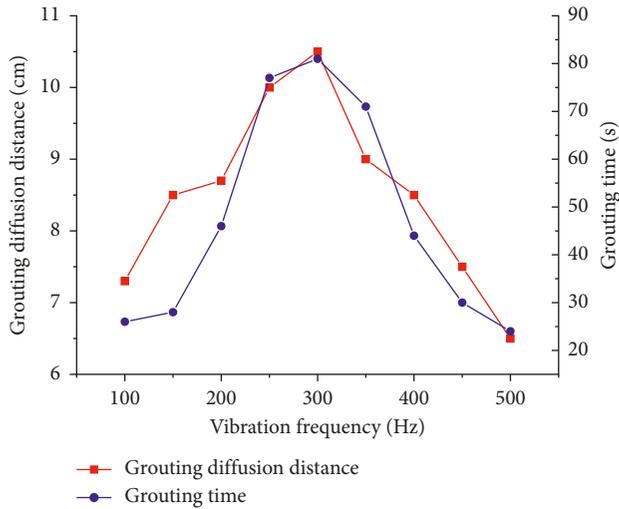


FIGURE 8: Variation of grout diffusion radius under different vibration frequencies.

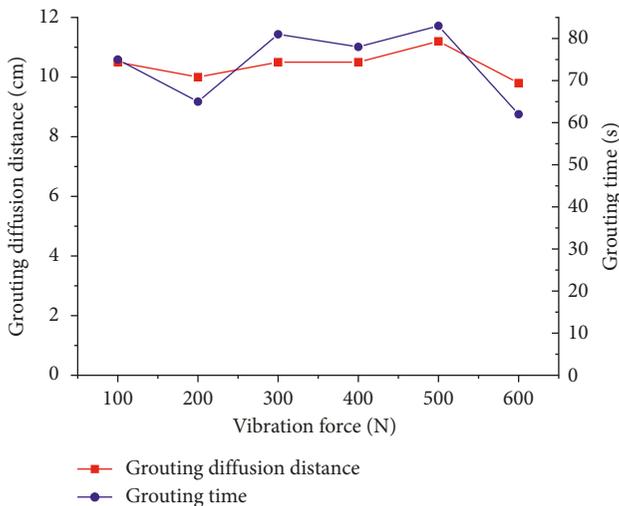


FIGURE 9: Variation of grout diffusion radius under different vibration forces.

closed environment formed by the overlying soil and produces spillover which will have side effects on the grouting.

3.3. Results of Sonic Drilling Grouting

3.3.1. Impact Analysis Experiment of Vibration Frequency. The variation of grouting diffusion radius under different vibration frequencies is shown in Figure 8. In the process of the vibration frequency increase from 100 Hz to 300 Hz, the transverse dimension and the volume of the concretion increase continuously, turning from an elongated columnar body into a spindle body, which indicates that the grouting volume also increases. When the vibration frequency increases from 300 Hz to 500 Hz, the transverse dimension of the concretion decreases gradually, changing from a spindle body to an approximate columnar body, which shows that the grouting volume decreases synchronously and the grouting effect becomes worse.

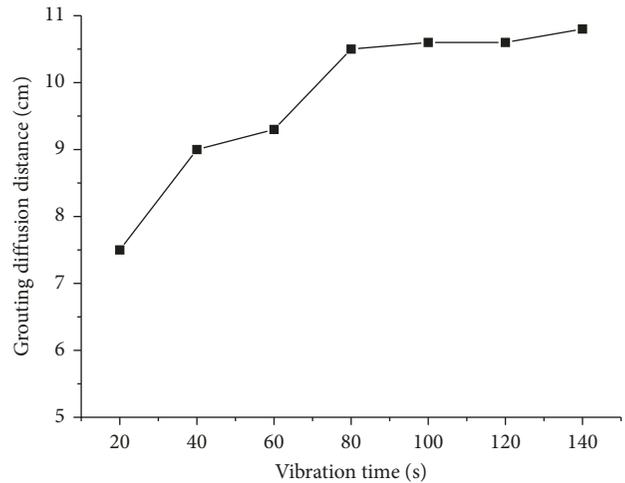


FIGURE 10: Variation of grout diffusion radius under different vibration durations.

3.3.2. Impact Analysis Experiment of Exciting Force. This experiment is based on various technological parameters obtained in the first group of experiments while getting the optimum grouting effect. The exciting force is changed to observe the change rule of the grouting effect when the grouting pressure is 6 kPa and vibration frequency is 300 Hz. As shown in Figure 9, when the exciting force increases from 100 N to 600 N, the concretion shape basically maintains unchanged showing a stubby spindle body which indicates that the grouting volume is little changed in this process, and the effect of the exciting force on the sonic vibration grouting is not obvious.

3.3.3. Impact Analysis Experiment of Vibration Duration. In this experiment, the change rule of grouting effect under different vibration durations is observed on the basis of various technological parameters (the grouting pressure is 6 kPa, the exciting force is 300 N, and the vibration frequency is 300 Hz) obtained in the previous experiments while getting the optimum grouting effect. As shown in Figure 10, when the vibration duration increases from 20 s to 140 s, the grouting diffusion rate and the concretion volume increase rapidly at the early stage. However, the grouting diffusion radius increases slowly, remaining constant basically with the increase of the vibration duration.

4. Conclusion

This paper innovatively presents the sonic vibration grouting technology, develops the grouting experimental device, and conducts the related experimental study on the grout mixing, the conventional static pressure grouting, and the sonic vibration grouting. Conclusions are as follows:

- (1) The sonic vibration grouting can effectively improve the grouting feasibility of the fine silty sand, raise the grouting volume, enlarge the grouting diffusion radius, and increase the concretion volume by vibration. Compared to the conventional static

pressure grouting, it has a better grouting effect and has a good development prospect.

- (2) The effect of the exciting force on the sonic vibration grouting is not obvious, the vibration duration has a greater influence, and the vibration frequency which is the key factor to improve the grouting effect in the fine silty sand layer has the greatest impact on the grouting.
- (3) The closer the vibration frequency is to the natural frequency of the fine silty sand, the larger the grouting volume and the grouting diffusion radius are and the better the grouting reinforcement effect becomes. When the vibration frequency is far away from the natural frequency of the stratum, the grouting diffusion distance is getting smaller, which means the grouting effect is becoming worse.
- (4) The grouting diffusion rate and the concretion volume increases rapidly at the early stage. However, the grouting diffusion radius increases slowly, remaining constant basically with the increase of the vibration duration, which indicates that the diffusion of the grout has reached its limit.

Conflicts of Interest

The author declares that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (no. 41672366), the Beijing Natural Science Foundation (no. 8182048), and the Fundamental Research Funds for the Central Universities (no. 2652017062). The authors sincerely acknowledge the previous researchers for their excellent work, which greatly assisted their academic study.

References

- [1] L. Li, "Numerical Analysis on grouted roof pipes of large span shallow buried tunnel in fine silt sand ground," *Tunnel Construction*, vol. 28, no. 6, pp. 656–659, 2008, in Chinese.
- [2] W.-J. Chang, S.-H. Ni, A.-B. Huang, Y.-H. Huang, and Y.-Z. Yang, "Geotechnical reconnaissance and liquefaction analyses of a liquefaction site with silty fine sand in Southern Taiwan," *Engineering Geology*, vol. 123, no. 3, pp. 235–245, 2011.
- [3] C.-S. Xu, M.-T. Luan, and Y. Guo, "Test of sand dynamic-strain behavior," *Journal of Beijing University of Technology*, vol. 34, no. 9, pp. 956–960, 2008, in Chinese.
- [4] Z. Zhu and X. Sun, "Pre-reinforcement and construction of tunnel in dry fine sand layers," *Chinese Journal of Rock Mechanics and Engineering*, vol. 32, no. 9, pp. 1909–1916, 2013, in Chinese.
- [5] X. Chen, Z. Xie, X. Zeng, W. Su, and J. Yang, "Risk analysis and control for large-diameter slurry shield passing under embankment in fine silty sand ground," *Chinese Journal of Underground Space and Engineering*, vol. 11, no. 4, pp. 1033–1038, 2015, in Chinese.
- [6] M. Belkhatir, H. Missoum, A. Arab, N. Della, and T. Schanz, "The undrained shear strength characteristics of silty sand: an experimental study of the effect of fines," *Geologia Vroatica*, vol. 64, no. 1, pp. 31–39, 2011.
- [7] X. C. Zhong, J. Zuo, Q. Liu, and Y. Han, "Reuse of excavated fine sand for back grouting of shield tunnelling," *Rock and Soil Mechanics*, vol. 29, no. S1, pp. 293–296, 2008, in Chinese.
- [8] J. Canto-Perello, J. Curiel-Esparza, and V. Calvo, "Strategic decision support system for utility tunnel's planning applying A'WOT method," *Tunnelling and Underground Space Technology*, vol. 55, pp. 146–152, 2016.
- [9] G. Chen, X. Liu, and H. Zhuang, "Experimental study of liquefaction resistant characteristics of silty clay with fine sand interbed and fine sand in Nanjing," *Journal of Seismology*, vol. 23, no. 2, pp. 28–34, 2003, in Chinese.
- [10] X. Zhang, Z. Wang, Z. Xu, and C. Lü, "Shaking table tests on flow effects of liquefied sands," *Rock and Soil Mechanics*, vol. 37, no. 8, pp. 2347–2352, 2016, in Chinese.
- [11] E. Akyol and T. Korkmaz, "Effects of cement grouting on seismic performance of building foundations," *Cement Wapno Beton*, vol. 20, no. 5, p. 313, 2015.
- [12] S. Y. Wang, D. H. Chan, K. C. Lam, and S. K. A. Au, "A new laboratory apparatus for studying dynamic compaction grouting into granular soils," *Soils and Foundations*, vol. 53, no. 3, pp. 462–468, 2013.
- [13] H. Zhou, B. Liu, and X. Wang, "A study on the saturated sand dynamic response in vibrating grouting method," *China Railway Science*, vol. 24, no. 2, pp. 129–131, 2003, in Chinese.
- [14] X. Wang, H. Zhou, and X. Yang, *Principle of Vibration Grouting and its Theoretical Basis*, China Railway Press, Beijing, China, 2007, in Chinese.
- [15] X. Yuan, N. Lu, and X. Ling, "Mechanics analysis for vibrator of vibration grouting," *Construction Machinery*, vol. 4, pp. 61–65, 2006, in Chinese.
- [16] B. Sun, C. Ling, X. Ling, M. Jin, and G. Zhu, "The research of soil liquefaction estimation method for the design of vibration grout machine," *Journal of Disaster Prevention and Mitigation Engineering*, vol. 26, no. 2, pp. 158–163, 2006.
- [17] J. Lei, J. Yang, and X. Yang, "Finite element simulation on dynamic grouting in saturated sand," *Journal of Vibration and Shock*, vol. 29, no. 9, pp. 235–238, 2010, in Chinese.
- [18] W. Jin, L. Zhang, Z. Cheng, and C. Deng, "Study of the micp superaudible vibration in saturated sandy soils," *Bulletin of Science and Technology*, vol. 32, no. 5, pp. 177–179, 2016, in Chinese.
- [19] Y. Wang, B. Liu, Q. Zhou, Y. Hu, and G. Li, "Design of a sonic drill based on virtual prototype technology," *Transactions of the Canadian Society for Mechanical Engineering*, vol. 37, no. 2, pp. 185–196, 2013.
- [20] M. J. Burlingame, D. Egin, and W. B. Armstrong, "Unit weight determination of landfill waste using sonic drilling methods," *Journal of Geotechnical and Geoenvironmental Engineering*, vol. 133, no. 5, pp. 609–612, 2007.
- [21] Y. Wang, Q. Zhou, B. Liu, Z. Li, and M. Huang, "Design and model analysis of the sonic vibration head," *Journal of Vibroengineering*, vol. 17, no. 5, pp. 2121–2131, 2015.



Hindawi

Submit your manuscripts at
www.hindawi.com

