ANALYSIS ON THE STABILITY OF THE TEMPORARY SUPPORT FRAME OF THE TUNNEL EXCAVATED IN REINFORCED SAND MEDIUM

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Abstract

This paper presents the effect of sand reinforcement by pumping water into the sand around the support frame to evaluate the stability of the support frame system. The sand was collected in the Central region in Vietnam and experimented in the laboratory with different water content and void ratio. The most suitable water content for the reinforcement to achieve high efficiency is W = 15% from the experimental results. Conduct numerical tests to evaluate the working of the temporary support system before and after the sand is reinforced as well as to evaluate the effectiveness of the reinforced sand layer thickness. The research results have practical implications for the construction of tunnels in the sand.

Keywords: *Sand; water content; void ratio; temporary support frame; sand reinforcement.*

1. Introduction

In Vietnam, the construction of underground works in the sand is becoming more and more popular and urgent and constantly developing, including the system of underground works located on the sea and islands; system of road tunnels across rivers; water pipeline system, and so on. Under current conditions, the construction of underground works in the sand mainly uses manual methods or combines manual methods with mechanization. Therefore, there are many unpredictable risks causing unsafety and affecting the quality and the life of the construction. To ensure safety and speed up tunnel construction in the sand, water is pumped into the sand to compact the sand, before installing the temporary support frame system in the sand. In fact, there has been little research on the stability of the temporary supporting frame system after the sand is reinforced. Therefore, the study and evaluation of the effectiveness of sand reinforcement to the stability of the support frame and the stress state of the sand around the support frame are really necessary. This decisive issue will contribute to improving the progress and safety of tunnel construction in the sand. Research results serve as the

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https://doi.org/10.56651/lqdtu.jst.v4.n01.333.sce

basis for design and construction problems in the sand. The results of this study can contribute to improving the progress and safety of tunnel construction in the sand.

Because the problem posed above is a large-scale problem, and so only a small part of the problem is presented within this article. The experimental study to determine the shear strength parameters of the sand depending on the void ratio and compression of sand. It provides data for the modeling and evaluation of the stability of the frame system when tunneling in the sand.

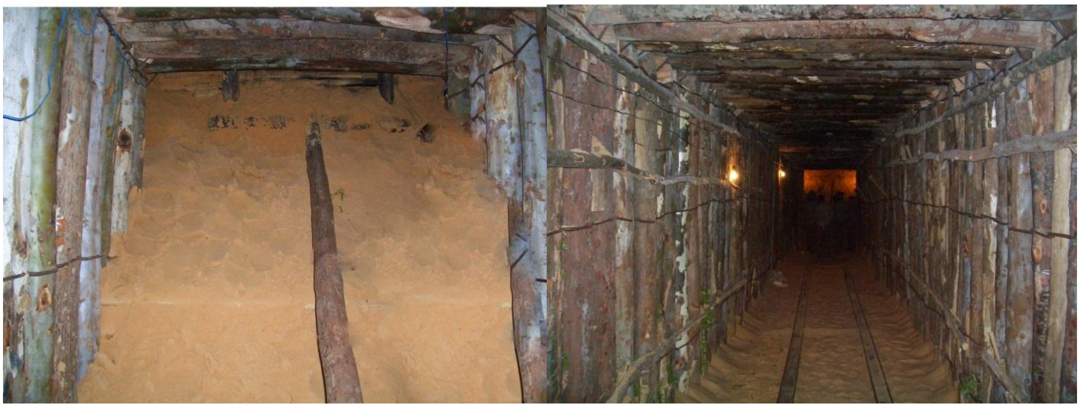


Figure 1. Construction of frame system for temporary tunneling in the sand

2. Determine the shear strength parameters according to different compression of sand and water content of white sand

In the south-central region, with the long dry season and high temperature, the sand layers near the surface of the tunnel opening are often dry and porous. This causes difficulties in the construction of the tunnel. To overcome the above difficulties, before the temporary frame system is installed, the water is often pumped to reinforce the sand. Experiments show that the average water content of sand in its natural state is W = 2%, and the void ratio is e = 0.8÷0.9. After pumping water in a certain time, the void ratio is increased to e = 0.65÷0.7, and the water content is about 15÷20%. In this study, white sand samples were taken in the south-central region of Vietnam near the constructed tunnel area. The experiments are conducted to determine the shear strength parameters of the sand (internal friction angle, cohesion) according to different water content and void ratio. From there, we can determine the behavior of the sand and provide data for the process of modeling the stability of the frame system.

With the natural water content of sand determined (W = 2%), the authors prepared sand samples with different water content (W = 10%; 15% and 20%) to serve the flat cutting experiment.

Figure 2. The sand samples are processed according to different water content

The white sand sample flat cutting test was conducted on the Controls firm's Model SHEARMATIC automatic flat cutting machine at the Geotechnical Laboratory - Institute of Techniques for Special Engineering - LQDTU (Figure 3). With natural water content, experiment with void ratio e = 0.9 (natural state), and with other water content, experiment with void ratio e = 0.7 (state after reinforcement).

Figure 3. Conducting sample cutting experiment

Figure 4 and Figure 5 show that the different compression of sand will lead to the difference in the behavior of white sand. Moreover, when sand is in a porous state, the relationship curve between shear force - horizontal displacement does not clearly appear to the peak value. The shear force value increases gradually until it reaches its maximum value and then tends to go horizontal. Therefore, with the aforementioned white sand in the porous state, it can be approximated that the white sand behaves according to the Mohr-Coulomb model. When the sand is in a more compressive state, the curvature of the shear force - horizontal displacement appears to have a distinct peak value, and the sand has softened behavior after the peak (post-peak softening).

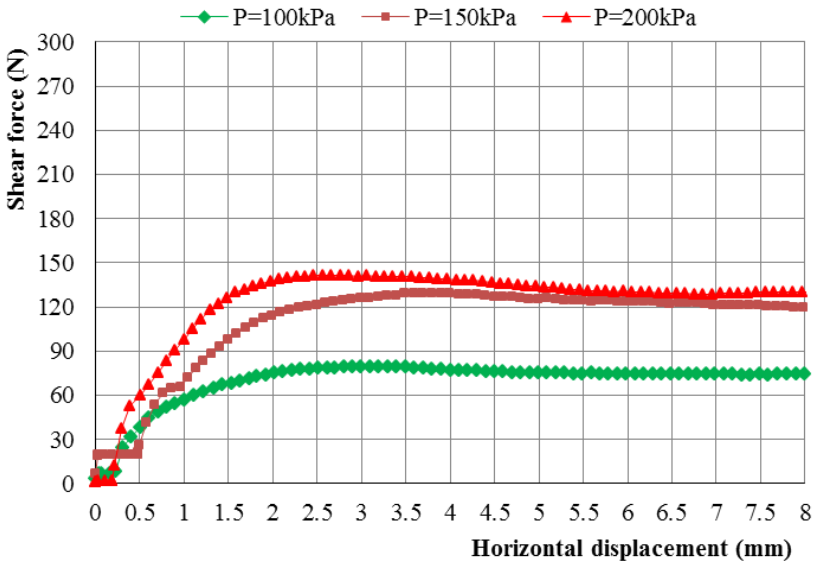


Figure 4. Relationship of shear force-horizontal displacement of sample with water content W = 2%, void ratio e = 0.9

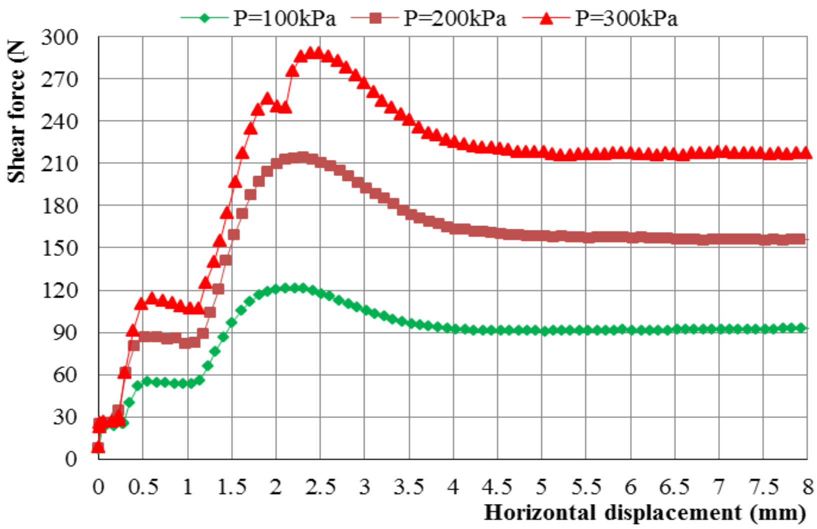


Figure 5. Relationship of shear force-horizontal displacement of sample with water content W = 15%, void ratio e = 0.7

Based on experimental results, it can determine the maximum value of shear force for each load level. Using the least-squares method, the shear strength parameters of white sand are determined as shown in Table 1.

Table 1. Summary of experimental results to determine shear strength parameters of white sand according to water content and compression of sand

Serial	Water content, W (%)	Void ratio, e	Characteristic of shear strength		Note the type of test sample
			Internal friction angle, φ (degree)	Cohesion, C (kN/m^2)	
1	2	0.90	31.62	24.32	Natural sand sample
2	10	0.70	37.53	38.75	Reproduced sample
3	15	0.70	39.88	40.94	Reproduced sample
4	20	0.70	44.74	14.10	Reproduced sample

Based on the experimental results summarized in Table 1, it can be given some comments and evaluations as follows:

- The above white sand has both internal friction angle and apparent cohesion strength. When the water content increases from 2% to 15%, the value of the shear strength parameters of soils increases, but the water content increases up to 20%, the shear strength parameters tend to decrease. As Maslov [5] explains, the apparent cohesion strength of loose soil is determined by the force of the hook interaction between the particles. The effect of fastening increases with the increase of the loose compression of soil. On the other hand, due to water in the sand sample, surface tension increases the cohesion between the grains of sand. But this happens at a certain limit of water content until the surface tension of the moist film between the pores ruptures. When water continues to be pumped, the moist sand begins to lose its cohesion again and reduces the shear strength.

- When the compression of sand increases (void ratio decreases), the shear strength parameters of sand also increases.

- To promote the shear strength of the sand in the reinforced area, the following should be noted: after pumping the reinforcement water, it is necessary to choose a reasonable time to start constructing the temporary frame system. If the construction is done right after the water pump is completed, the sand usually has high water content, then the shear strength parameters of sand have not reached the maximum value. We need to wait for the water content of the sand to reach about 15%, then start construction.

3. Research on the stability of the temporary support frame of the tunnel in the sand by reinforcing the sand around the support frame

Based on the experimental results on the sand, it is used to evaluate the stability of the temporary frame system before and after pumping water to tighten the sand around the supporting frame for five cases as follows (Table 2):

- The effect of sand reinforcement around the tunnel (before and after pumping water);

- The effect of the temporary horizontal strut on the bottom after the sand is reinforced;

- Effect of sand reinforcement area around the temporary support frame.

The paper uses the Plaxis 2D ver 2020 software [4] to simulate study cases (Figure 6).

Table 2. Study cases

Serial	Study cases	Mechanical and physical properties of sand						The horizontal strut under the temporary support frame	The range of reinforcement around the temporary support frame (m)
		Water content, W (%)	Void ratio, e	Cohesion, C (kN/m^2)	Internal friction angle, φ (degree)	Dilatancy angle, Ψ (degree)	Young's modulus, E (kN/m^2)		
1	Case 1	2	0.9	24.32	31.62	1.62	17 000	-	-
2	Case 2	15	0.7	40.94	39.88	9.88	30 000	-	1
3	Case 3	15	0.7	40.94	39.88	9.88	30 000	x	1
4	Case 4	15	0.7	40.94	39.88	9.88	30 000	x	1.5
5	Case 5	15	0.7	40.94	39.88	9.88	30 000	x	2

The temporary support frame is made from round, straight wood and usually belongs to group VI. According to the reference documents, the wood parameters are shown in Table 3 as follows [3]:

Table 3. Mechanical properties of the VI temporary wooden struts

Characteristic	Basement roof strut and vertical wall struts (D = 27 cm)	Vertical wall struts (D = 20 cm)
Specific gravity (kN/m^3)	7.1	7.1
Young's modulus, E (kN/m^2)	10^7	10^7
Axial stiffness, EA (kN)	$2.7x10^6$	2×10^6
Flexural rigidity (bending stiffness), EI ($kN.m^2$)	1.64×10^4	6.67×10^3

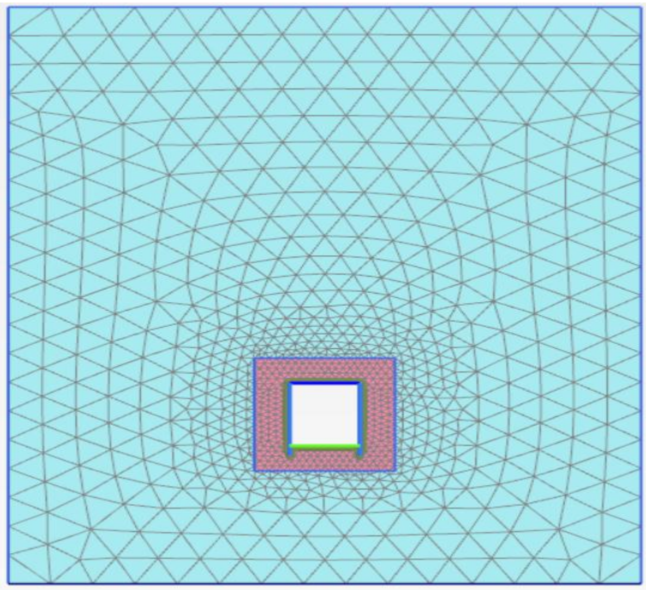


Figure 6. Geometry mesh of the cases studied

Investigate study cases with the following frame sizes:

- Width of temporary support frame B = 2 m;

- Height of temporary support frame H = 2.5 m;

The thickness of the soil layer above the temporary support frame is H_n = 15m.

To model the slip and separation between the struts and the surrounding sand under external load, the paper used the contact element along the length of the struts. The intensity reduction coefficient of the contact element is Rinter = 0.85.

To model sand, the paper used the Mohr-Coulomb model with sand parameters in Table 1.

Figure 6 shows the model used in these studies. The size of the sand model around the support frame is selected large enough to control the displacement both horizontally and vertically; The width of the reinforced sand around the support frame is 1m. Mesh of sand elements is divided automatically by software, consisting of 15-node triangular elements. Around the support frame, the mesh is finer separated.

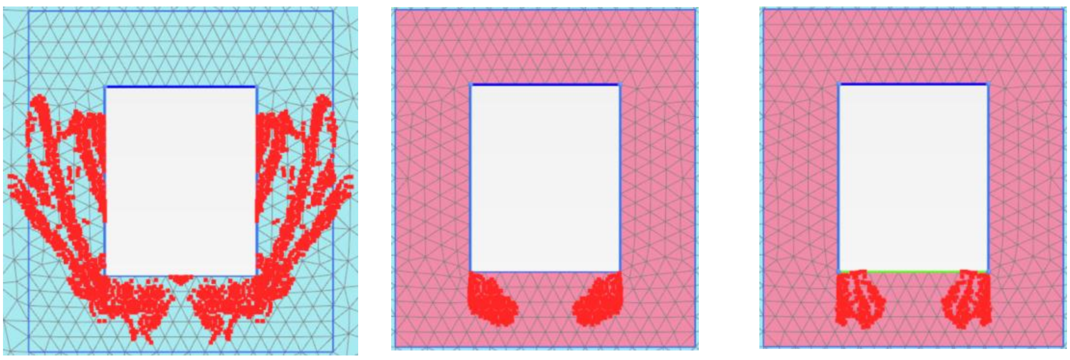
The sequence of numerical testing steps is as follows:

Step 1: Set up the sand, model of all dry sand and reinforced sand areas. In the paper, the study cases do not consider the groundwater level.

Step 2: Model the temporary supports frame in the foundation. Activate the beam element to model the struts in the strut. Then dig sand in the temporary supports frame.

Step 3: Assign the contact elements along the length of the struts. For each specific case, the influence parameters of sand and horizontal struts will be changed. After the program completes the calculation process, the results of the plastic deformation zone around the temporary support frame, maximum moment and maximum displacement in the struts are given. These figures will be used to analyze the influence of the surveyed parameters on the stability of the temporary support frame system of the tunnel construction in the sand.

In turn, analyze five cases (see in Table 2). The results are a development of the plastic deformation zone around the temporary support frame system, a moment in the strut, the horizontal displacement of the vertical strut, the vertical displacement of the horizontal strut on the roof are as follows (Figure 7-12, Table 4, 5):



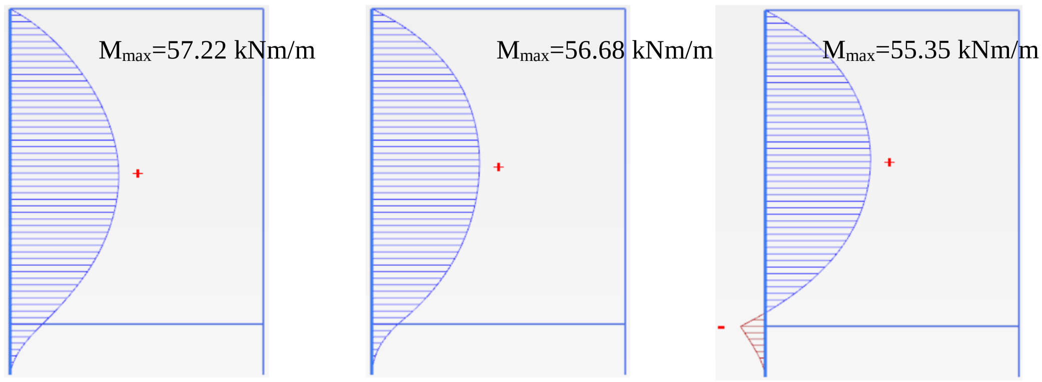
a) *b)* *c)*

Figure 7. Development of plastic deformation zone:

a) Natural sand with horizontal strut at bottom;

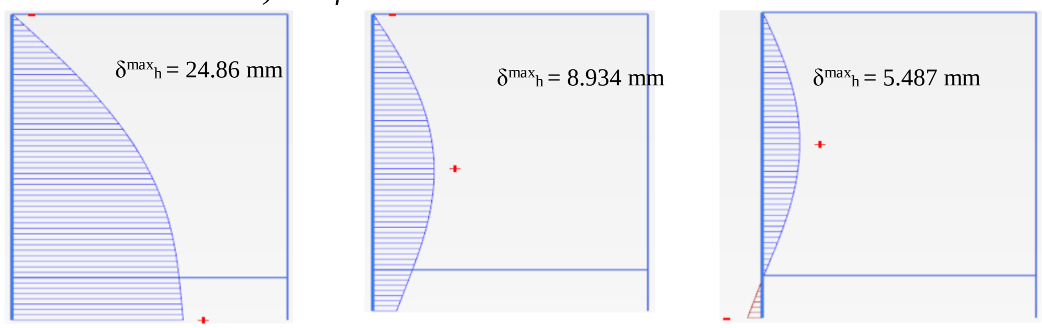
b) Reinforced sand without horizontal strut at bottom;

c) Reinforced sand with horizontal strut at bottom



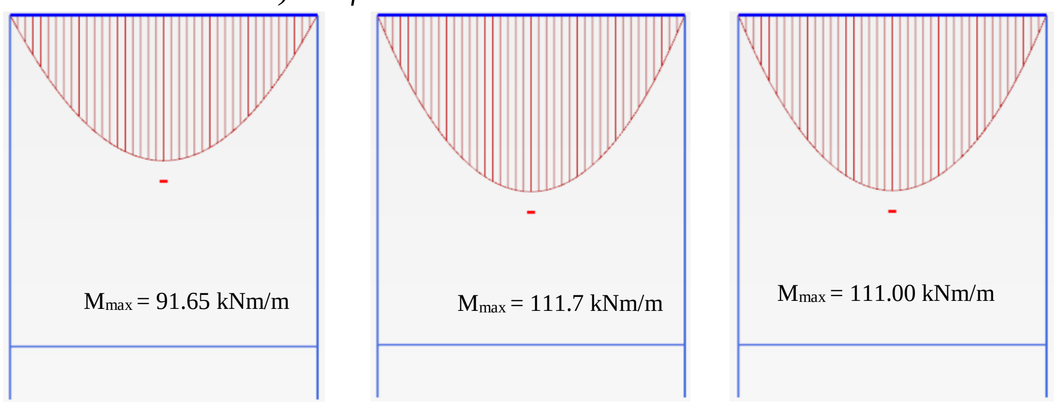
a) *b)* *c)*

Figure 8. Bending moment diagram of vertical struts:
a) Natural sand with horizontal strut at bottom;
b) Reinforced sand without horizontal strut at bottom;
c) Reinforced sand with horizontal strut at bottom



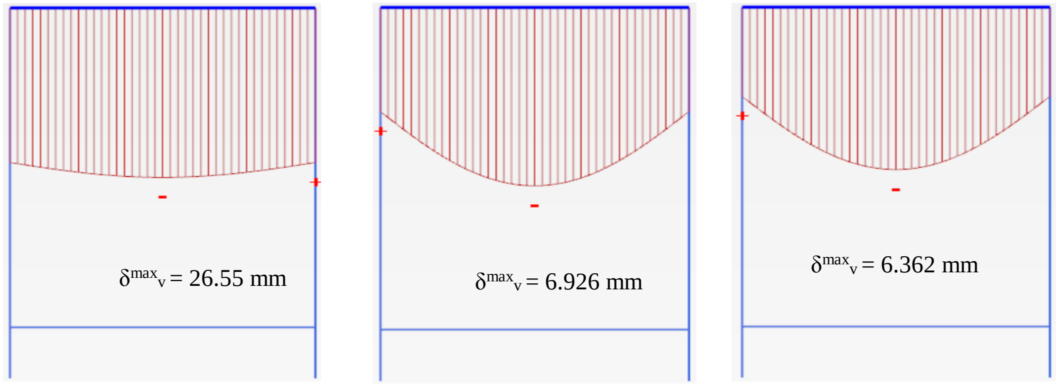
a) *b)* *c)*

Figure 9. Horizontal displacement chart of vertical struts:
a) Natural sand with horizontal strut at bottom;
b) Reinforced sand without horizontal strut at bottom;
c) Reinforced sand with horizontal strut at bottom



a) *b)* *c)*

Figure 10. Diagram of bending moment of the roof struts:
a) Natural sand with horizontal strut at bottom;
b) Reinforced sand without horizontal strut at bottom;
c) Reinforced sand with horizontal strut at bottom



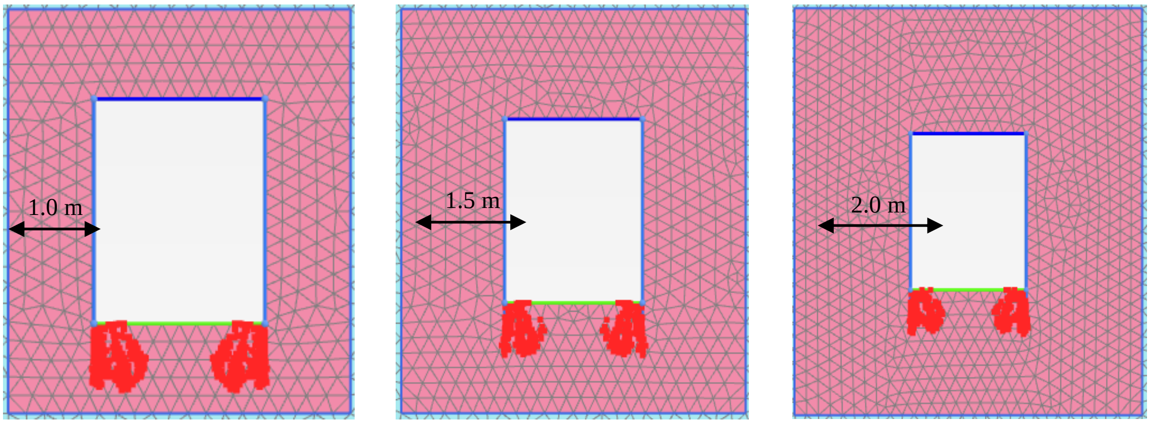
a) *b)* *c)*

Figure 11. Diagram of vertical displacement of roof struts:

a) Natural sand with horizontal strut at bottom;

b) Reinforced sand without horizontal strut at bottom;

c) Reinforced sand with horizontal strut at bottom



a) *b)* *c)*

Figure 12. Development of plastic deformation zone around the temporary support frame when changing the width of reinforced area: a) case Br = 1.0 m; b) case Br = 1.5 m; c) case Br = 2.0 m

Based on the experimental results in Table 4 and Table 5 and Figure 7-12, some comments and evaluations are shown as follows:

- In the absence of reinforcement and no horizontal strut at the bottom of the foot, the plastic deformation development area is very wide, including almost the entire bottom of the support frame and the two sides of the vertical strut. In case there is sand reinforcement around the support frame, the plastic deformation development area is significantly reduced.

Table 4. Maximum displacement and maximum moment in the support frame

Serial	Study cases	Vertical struts		Horizontal struts	
		Maximum horizontal displacement (mm)	**Maximum moment (kN.m)**	**Maximum vetical displacement (mm)**	**Maximum moment (kN.m)**
1	Case without reinforcement and without the horizontal strut below	24.860	57.22	26.55	91.65
2	Case reinforcement and without the horizontal strut below	8.934	56.68	6.926	111.70
3	Case reinforcement and with the horizontal strut below	5.487	55.35	6.362	111.00

Table 5. Investigating the effects of the reinforcement area width on moment and displacement of the struts

Serial	Structures	M_{max} (kN.m)			Maximum displacement (mm)		
		B_r=1.0m	B_r=1.5m	B_r=2.0m	B_r=1.0m	B_r=1.5m	B_r=2.0m
1	Horizontal struts on the roof	111.0	109.6	108.7	6.362	6.281	6.213
2	Vertical struts	55.35	52.90	51.73	5.487	5.257	5.142

- Comparison of the case with reinforcement and with struts under the foot with the case without reinforcement and struts shows that: The moment in the struts decreased not significantly (3.26%) but the displacement decreased significantly, respectively: 77.93% and 76.04%.

- When the thickness of the sand reinforcement around the support frame is increased from 1m to 1.5m and 2m, the development of plastic deformation around the support frame system is significantly reduced. However, the internal force in the struts and the displacement in the struts decreased not considerably. Specifically, the maximum moment decreased by 6.54%, and the maximum displacement decreased by 6.29%.

4. Conclusion

With the analysis of laboratory experiment results and numerical experimental results, the following conclusions can be shown:

- The reinforcement of sand around the temporary support frame by pumping water increases the compression of sand and its shear parameters. When the water content increases from 2% to 15%, the value of the shear strength parameters increases, but the water content increases up to 20%, the shear strength parameters tend to decrease. Therefore, during the construction of the temporary support frame, it is necessary to choose a reasonable time corresponding to the time when the sand reaches the optimum water content (for the scope of the research paper, W = 15%);

- The reinforcement of the sand around the support frame with water pumping is effective. For the installation of the horizontal strut under the temporary strut, the plastic deformation area is not significantly reduced but the horizontal displacement of the vertical struts is significantly reduced. So during the construction process, the horizontal struts should be installed to limit the horizontal displacement of the vertical struts and increase the stiffness of the strut system.

- The development area of plastic deformation around the temporary support frame is reduced when the width of the reinforced sand is increased from 1.0m to 2.0m. Still, the internal force and displacement of the struts are not significantly reduced. Therefore, to speed up the construction progress, it can be recommended in practice to reinforce sand around the tunnel with a thickness of 1m is acceptable.

5. Recommendation

- In this paper, the authors use the Mohr-Coulomb model to model the sand in its natural state and reinforced it. Still, the experimental results show that this model is only suitable for natural sand. And for reinforced sand, to determine the correct model, it is necessary to conduct a three-axis compression test.

- It is necessary to investigate studies with 3D models to determine the shear stability in front of the tunnel mirror.

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PHÂN TÍCH SỰ ỔN ĐỊNH CỦA HỆ KHUNG CHỐNG TẠM CỦA HẦM TRONG CÁT BẰNG GIẢI PHÁP GIA CỐ CÁT XUNG QUANH KHUNG CHỐNG

Tóm tắt: *Bài báo trình bày tác dụng của việc gia cố cát bằng cách bơm nước vào cát xung quanh khung đỡ để đánh giá độ ổn định của hệ khung chống. Cát được lấy ở miền Trung Việt Nam và thí nghiệm trong phòng thí nghiệm với các độ ẩm và hệ số rỗng khác nhau. Kết quả thí nghiệm cho thấy độ ẩm thích hợp nhất để gia cố cát đạt hiệu quả cao là W = 15%. Tiến hành thử nghiệm số để đánh giá sự làm việc của hệ khung chống tạm trước và sau khi gia cố cát cũng như đánh giá hiệu quả của chiều dày lớp cát gia cố. Kết quả nghiên cứu có ý nghĩa trong việc thi công hầm trong cát.*

Từ khóa: Cát; độ ẩm; hệ số rỗng; khung chống tạm; gia cố cát.

Received: 16/4/2021; *Revised:* 07/6/2021; *Accepted for publication:* 13/07/2021

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