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Use two- and three-dimensional models to assess the stability of trench walls for underground construction in sand and sandy silty clay, supported by bentonite suspension

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ABSTRACT

A trench excavation is the first step in the underground wall construction process. Today, the technique of excavating trenches supported by bentonite suspension to prevent collapse and ensure trench stability has become common in many countries worldwide. Following this trend, this article applies the technique to a typical stratum in Hue City, Vietnam. Simultaneously, the study utilizes the Finite Element Method (FEM) with the RS software program and the Finite Difference Method (FDM) with the FLAC software program. Additionally, the Shear Strength Reduction (SSR) technique and the Mohr-Coulomb material model are employed to develop 2D and 3D models and analyze the stability of the bentonite suspension trench. The analysis is conducted under a scenario where no surcharge load is applied on the ground surface, and the surface is not reinforced with a concrete layer. The trench dimensions are 1 m in width, 6 m in length, and 10 m in depth, the densities of the bentonite suspensions are 10.5 kN/m^3 and 12 kN/m^3, with the level of bentonite suspension in the trench maintained equal to the ground surface level. The obtained results are as follows: (1) An evaluation of the safety factor of the bentonite suspension trench under the specified scenario; (2) A prediction of the influenced zone caused by the excavation of the bentonite suspension trench. Determining the influenced zone caused by trench excavation is closely related to the safety of neighboring structures near the excavation trench. Structures located outside the influenced zone are considered safe.

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1. Introduction

Today, the trench excavation using the support of bentonite suspension is a relatively new technique and has been commonly employed in many countries around the world. Excavating a vertical trench is the first stage in the construction of diaphragm walls or underground barriers. The excavation technique supported by bentonite suspension, commonly referred to as "slurry wall" or "slurry trenching," is particularly convenient for vertical trench excavation. Consequently, assessing the stability of vertical excavation trenches is a critical task.

This topic has drawn significant interest from researchers, who have developed various stability calculation solutions for specific cases. Piaskowski (1965) conducted an early study in 1965 on the 3D stability of suspension-supported trench in sand, based on the balance between soil mass at the trench wall and suspension pressure. In 1996, Tsai and Chang's article (1996) presented research based on limit equilibrium and arching theory, a three-dimensional stability analysis was proposed for slurry-supported trenches in cohesionless soil. An interesting study by Washbourne (1984) in 1984 introduced a 3D solution for trench stability assessment, building on Bell's earlier 2D solution. Additionally, Li et al. (Li & Zhang, 2019) presented a notable study on the stability analysis of a slurry trench in cohesive-frictional soils, one of the methods utilized for the analysis was numerical simulation using FLAC3D.

In this article, numerical simulations were performed to evaluate the stability of a trench supported by bentonite suspension under the actual D1 stratum located in Hue City, Vietnam. This stratum is situated in an area that is not near any major roads or tall buildings (Figure 1).

The Shear Strength Reduction (SSR) technique, combined with the Mohr-Coulomb material model, was used to analyze the overall stability in both two-dimensional and three-dimensional models, utilizing RS (Finite Element Method - FEM) and FLAC (Finite Difference Method - FDM) software programs. The analyzed scenario assumes the absence of a surcharge load on the ground surface, which is left unreinforced by concrete and remains in its natural state. The objective of this scenario was not only to evaluate the safety factor of trench excavation supported by bentonite suspension with densities of 10.5 kN/m^3 and 12 kN/m^3 but also to define the influence zone of the bentonite suspension trench. The results of this analysis are also presented.

2. Research Methodology

Utilizing geotechnical data from a representative stratum in the Hue City area (Table 1), a numerical model was developed to simulate trench excavation with temporary bentonite suspension support during the construction of diaphragm or underground walls. Since trench excavation serves as the first stage in building these structures, the model evaluates the stability of the bentonite-supported trench and its impact zone throughout the construction phase.

Figure 1. Location of stratum: D1.

Table 1. Soil mechanical characteristics.

Layer of soil	Thickness (m)	Young modulus (MPa)	Density (kN/m^3)	Cohesion (kPa)	Friction (deg)	Depth of GWL (m)
(0) Sand	0.8	10.000	17.93	0	28.3	3.5
(3d) Sandy silty clay	6.2	12.267	20.27	9.93	16.3	
(6) Sandy	13.0	57.720	20.20	18.20	22.7	

To prevent trench wall collapse during excavation, bentonite suspension with densities of 10.5 and 12.0 kN/m^3 are used as temporary support. This process involves filling the trench with bentonite suspension while excavating with a mechanical bucket. A steel frame is then placed inside the trench, followed by the underwater pouring of concrete grout through a pipe. As a result, the bentonite suspension is displaced and rises to the surface.

This study specifically focuses on analyzing trench stability and its influence zone during excavation with bentonite suspension support (Figures 3 and 4). The Shear Strength Reduction (SSR) technique, along with the Mohr-Coulomb material model, was employed to assess the trench's overall stability.

The shear strength reduction (SSR) technique was developed and has become a widely used method for evaluating the factor of safety, particularly in numerical methods such as the finite element method (FEM) with the RS software program (Rocscience, 2012, 2023; Rocscience Inc., 2001) and the finite difference method (FDM) with the FLAC software program (Itasca Consulting Group, 2011, 2023). In 1975, Zienkiewicz (1975) applied this technique to evaluate the safety factor of slopes. Later, it was further applied, discussed, and demonstrated for use with computers by Matsui & San (1992), Dawson et al. (1999), and others (Oblozinsky et al., 2001; Cala et al., 2023, 2006, 2014; Li & Zhang, 2019).

A slope fails when the material's shear strength along the sliding surface is insufficient to resist the actual shear stresses (Matsui & San, 1992). The factor of safety (FS) is used to assess slope stability. An FS value greater than 1 indicates that the slope is stable, whereas an FS value less than 1 indicates instability. The factor of safety against slope failure due to shear failure is calculated as follows (Itasca Consulting Group, 2011, 2023; Luo et al., 2020; Rocscience, 2012, 2023; Rocscience Inc., 2001):

$$FS = \frac{\tau}{\tau_f} \quad (1)$$

Where τ is the shear strength of the slope material, which is calculated through the Mohr-Coulomb criterion as:

$$\tau = c + \sigma_n tan\phi \quad (2)$$

And τ_f is the shear stress on the sliding surface. It can be calculated as:

$$\tau_f = c_f + \sigma_n tan\phi_f \quad (3)$$

The SSR technique is based on reducing the soil strength parameters until the soil fails (Figure 2). That means that Mohr-Coulomb material shear strength reduced by a strength reduction factor (SRF) can be determined from the equation:

$$c_f = \frac{c}{SRF} \quad (4)$$

$$\phi_f = tan^{-1}(\frac{tan\phi}{SRF}) \quad (5)$$

To achieve the correct FS, it is essential to trace the value of SRF that will cause the slope to fail. These values can be input into a FEM or FDM model and analysed based on a basic algorithm.

In the paper A New Era in Slope Stability Analysis: Shear Strength Reduction Finite Element Technique (Rocscience, 2004), the paper mentioned as follows: For Mohr-Coulomb materials, the steps for systematically searching for the critical factor of safety value FS or SRF, which brings a previously stable slope to the verge of failure, are as follows:

Step 1: Develop a FEM or FDM model of a slope using the deformation and strength properties established for the slope materials. Compute the model and record the maximum total deformation in the slope.

Step 2: Increase the value of SRF and calculate factored Mohr-Coulomb material parameters as described above. Enter the new strength properties into the slope model and recompute.

Record the maximum total deformation.

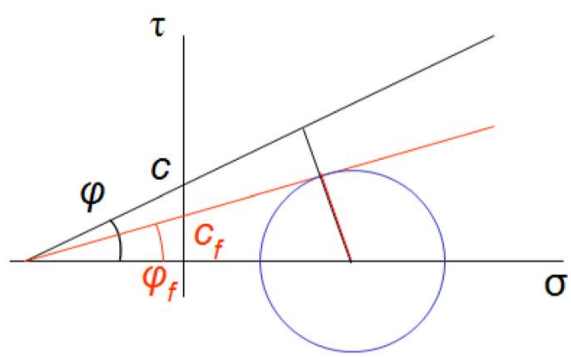

Figure 2. Mohr-Coulomb failure envelope after strength reduction.

Step 3: Repeat Step 2, using systematic increments of SRF, until the FEM or FDM model does not converge to a solution, i.e., continue to reduce material strength until the slope fails. The slope safety factor will be the critical FS value beyond which failure occurs.

In case of a slope that is initially unstable, the factor of safety values in steps 2 and 3 must be reduced until the FEM or FDM model converges to a solution.

The schematic of the overall model dimensions:

In two dimension-2D (RS2 v. 11.0 (Rocscience, 2012) and FLAC2D v.7.0 (Itasca Consulting Group, 2011)), the numerical model is built based on the geometry of half of the model (Figure 3) with the size for each bentonite suspension trench panel as follows: X-direction x Z-direction = ½ Width x Depth = 0.5 m x 10 m (In actual soil ground: Width x Depth = 1.0 m x 10 m)

In three dimension-3D (RS3 v. 4.0 (Rocscience, 2023) and FLAC3D v. 7.0 (Itasca Consulting Group, 2023)), the numerical model is built based on the geometry of a quarter of the model (Figure 4) with the size for each bentonite suspension trench panel as follows: X-direction x Y-direction x Z-direction = ½ Width x ½ Length x Depth = 0.5 m x 3 m x 10 m (In actual soil ground: Width x Length x Depth = 1.0 m x 6 m x 10 m).

3. Results

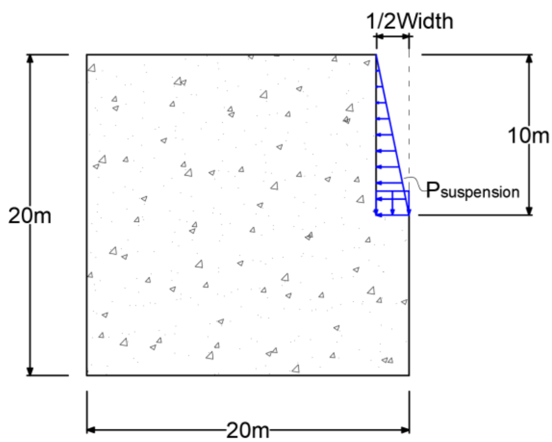

Figure 3. The model dimensions of the bentonite suspension trench in 2D.

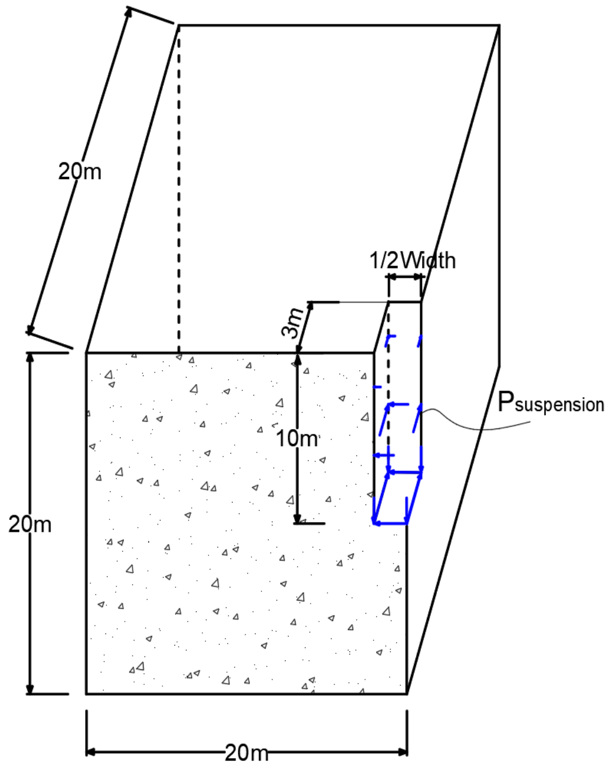

Figure 4. The model dimensions of the bentonite suspension trench in 3D.

Use the 2D model analysis method to forecast the overall stability coefficient, which tends to be lower than that predicted by the 3D model (Table 2).

Stability analysis results from different methods demonstrate the effectiveness of using bentonite suspension in controlling both vertical and horizontal displacements of the excavation trench in sand, sandy. In particular, when using a high-density bentonite suspension, soil displacement around the trench wall decreases (Figures 6, 7, 8, 9 and Tables 4, 5). This trend is opposite to that of the stability coefficient (FS), as a higher suspension density corresponds to a higher FS (Table 2). This is similar to the findings reported by Cała et al. (2024).

Table 2. FS of the bentonite suspension trench.

Case of bentonite suspension: 10.5 kN/m³			
RS3	FLAC3D	RS2	FLAC2D
1.970	1.965	1.281	1.250
Case of bentonite suspension: 12.0 kN/m³			
2.477	2.470	1.607	1.550

The numerical models of FEM (RS3 and RS2) and FDM (FLAC3D and FLAC2D) are utilized to predict the safety factor (FS), and the results are presented in Table 2. The FS ranges from 1.25 to 1.607 in 2D (RS2 and FLAC2D) and from 1.965 to 2.477 in 3D (RS3 and FLAC3D) for the cases under consideration. These factors indicate that the excavation trench with temporary support of bentonite suspension satisfies safety requirements if a FS ≥ 1.2 is chosen (Bamford et al., 2014; Ke, 2010; Oblozinsky et al., 2001).

Besides estimating the FS, the displacement of soil around the bentonite suspension trench is also predicted using numerical models. Because the deep excavation always impacts the nearby area, the level of influence is often assessed based on the range of the influence zone. Specifically, the influence is categorized into three zones, as shown in Figure 5 and the range limits of the influence zones are also provided in Table 3 (Clough et al., 1990; Godlewski et al., 2023; Instrukcja ITB 367/2002, 2020; JasińSki et al., 2024; Karolina Gorska, 2009).

Based on Table 3, in this research, the bentonite suspension trench is excavated in the cohesive soil, therefore the range of influence zone is:

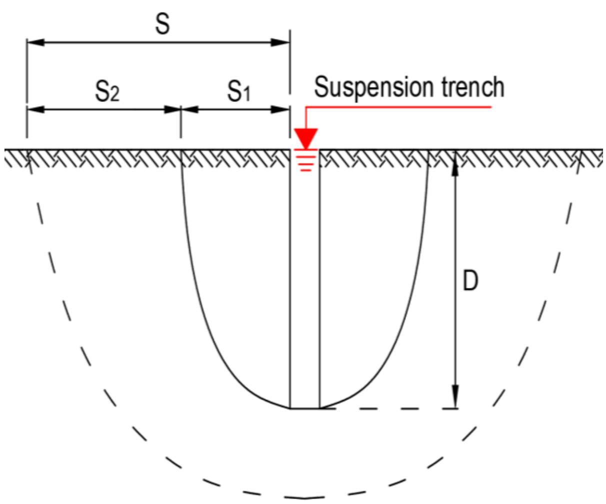

Figure 5. The range of influence zone, S_1 - direct influence zone (m), S_2 - indirect influence zone (m) and S - total influence zone (m), D – Depth of excavated trench (m) (Clough et al., 1990; Godlewski et al., 2023; Instrukcja ITB 367/2002, 2020; JasińSki et al., 2024; Karolina Gorska, 2009).

Table 3. The range of influence zone is proposed (Clough et al., 1990; Godlewski et al., 2023; Instrukcja ITB 367/2002, 2020; JasińSki et al., 2024; Karolina Gorska, 2009).

Type of soil	S_1	S
Non-cohesive or highly stiff soil	0.5 D	2.0 D
Cohesive soil	0.75 D	2.5 D
Loam or high plastic soil	1.0 D	3 ÷ 4 D

Direct influence zone: S1 = 0.75 D = 0.75 x 10 = 7.5 m.

Total influence zone: S = 2.0 D = 2.0 x 10 = 20 m.

And based on the analysis of the numerical models using RS3, FLAC3D, RS2, and FLAC2D (Figures 6a & b, 7, 8a &b, 9 and Tables 4, 5), at S1 = 0.75D = 7.5 m:

For the case of 10.5 kN/m^3 suspension, the settlements are: 0.25 mm (RS3), 0.23 mm (FLAC3D), 0.896 mm (RS2), and 0.7 mm (FLAC2D), all much less than 0.1%D.

For the case of 12 kN/m^3 suspension, the settlements are: 0.13 mm (RS3), 0.093 mm (FLAC3D), 0.268 mm (RS2), and 0.7 mm (FLAC2D), also much less than 0.1%D.

At S = 2.0D = 20 m, the settlement is negligible for the cases under consideration.

On the other hand, based on the numerical models, it is shown that (Figures 5a & b, 6, 7a & b, and 8):

Maximum Settlement (at ground surface)

The maximum settlement occurs at a horizontal distance of 2 m to 3 m from the edge of the bentonite suspension trench, specifically:

For the 10.5 kN/m^3 suspension case: 0.66 mm (RS3) = 0.0066%D, 0.67 mm (FLAC3D) = 0.0067%D, 1.81 mm (RS2) = 0.0181%D, 1.1 mm (FLAC2D) = 0.011%D.

For the 12 kN/m^3 suspension case: 0.27 mm (RS3) = 0.0027%D, 0.24 mm (FLAC3D) = 0.0024%D, 0.34 mm (RS2) = 0.0034%D, 1.12 mm(FLAC2D) = 0.0112%D.

Maximum Horizontal Displacement

The maximum horizontal displacement occurs at a depth of 6 m, specifically:

For the 10.5 kN/m^3 suspension case: 5.6 mm (RS3) = 0.056%D, 4.98 mm (FLAC3D) =

0.0498%D,
7.31 mm (RS2) = 0.0731%D,
5.9 mm (FLAC2D) = 0.059%D.

For the 12 kN/m³ suspension case: 3.3 mm (RS3) = 0.033%D,
2.65 mm (FLAC3D) = 0.0265%D, 3.42 mm (RS2) = 0.0342%D,
3.7 mm (FLAC2D) = 0.037%D.

All these values indicate that the settlement and horizontal displacement are very small, much less than 0.1%D. This indicates that the excavation trench, with 1 m in width, 6 m in length, and 10 m in depth, supported by bentonite suspension with densities of 10.5 and 12.0 kN/m³ under the considered stratum, has minimal impact on the nearby area and remains in a stable state.

4. Conclusion

This study examines the trench excavation method using temporary bentonite suspension support with densities of 10.5 and 12.0 kN/m³. The trench dimensions are 1 m in width, 6 m in length, and 10 m in depth. To simulate and predict the safety factor of the bentonite-supported trench, as well as to evaluate its impact on the surrounding area, the article utilized numerical models developed with RS (FEM) and FLAC (FDM) software programs, employing the SSR technique and Mohr-Coulomb material model to perform these tasks. The analysis results obtained demonstrated that:

The safety factor (FS) is greater than 1.2 in 2D (RS2 and FLAC2D) and greater than 1.9 in 3D (RS3 and FLAC3D) (Table 2). This indicates that in 2D, the FS is predicted to be lower than in 3D. The analysis in 2D is more conservative than in 3D because 2D considers only two dimensions (width and depth), whereas 3D considers three dimensions (width, length, and depth). This raises the question of whether to use 2D or 3D models in design to predict the stability of trench walls. According to the author, it is necessary to choose the appropriate prediction method for each stage of design. For example, during the preliminary design stage with simple geological conditions, 2D models may be sufficient. However, in the detailed design stage, where complex conditions exist and more detailed analysis is required, 3D models should be used. This is because, as mentioned earlier, 3D models take all three dimensions into account, allowing for a more comprehensive and detailed analysis than 2D models.

The settlement in the direct influence zone due to the bentonite suspension trench is predicted to be very small, much less than 0.1%D = 10 mm. The maximum settlement and maximum horizontal displacement are also very small, much less than 0.1%D = 10 mm (Figures 5a & b, 6, 7a &b and 8). This indicates that, under the considered conditions, the trench excavation has very little impact on the surrounding area.

In summary, when excavating a trench with 1 m in width, 6 m in length, and 10 m in depth under the considered geotechnical conditions or similar conditions, it is predicted to remain in a stable state with minimal impact on the surrounding area.

Contributions of authors

Tuong Cat Thi Le - conceptualization, methodology, writing, software, review & editing; Marek Cała and Agnieszka Stopkowicz - software, review & supervision; An Phuong Thi Tran - review & editing.

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