horizontal wall

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Horizontal Wall Movement and Ground Surface Settlement Analysis of Braced Excavation Based on Support Spacing

W. Hidayat[1*]

[1*]*Department of Civil Engineering, Pertamina University*

Email : [1*] *wirman.hidayat@universitaspertamina.ac.id*

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A B S T R A C T

Lateral supports, including walls and bracing systems on deep excavation, are generally required to prevent excessive horizontal wall movement and ground surface settlement which can cause damage to the excavation construction itself and adjacent structures. These criteria are influenced by the stiffness of the excavation system, including the spacing of vertical and horizontal supports (struts). This paper presents the parametric study using the variation of struts spacing in the vertical and horizontal direction to analyze the influence on horizontal wall movement and ground surface settlement. The analysis was carried out using finite element software, PLAXIS performed in 2D plain strain and 3D. This study shows that struts spacing in the horizontal and vertical direction is equally important and equally significant on the deformation that occurs with a maximum difference of about 0.06%. The maximum horizontal wall movement ratio computed by 3D analysis to the 2D analysis is defined as plain strain ratio (PSR). The PSR value decreases when the system stiffness is decreased. Meanwhile, when the system stiffness was higher, the PSR value will be higher and closer to 1, showing that the difference in the 3D and 2D models is relatively small.

1. Introduction

On deep excavation with straight vertical faces, the lateral supports, including walls and bracing systems with braced excavation methods, are generally required to prevent excessive horizontal wall movement and ground surface settlement. The increasing needs of infrastructures and limited land conditions are reasons for excavation construction to optimize land use. Regarding this condition, the dimensions and depth of excavation are also increasing, which may cause deformations, including the horizontal wall movement and ground surface settlement that occurs in the area around the excavation to increase significantly. Deformation

Analysis in excavation construction is very important, especially for excavations with a limited working area, to prevent damage on the adjacent building due to horizontal wall movement and ground surface settlement induced by the excavation.

The stiffness of the excavation system is the structural parameter that significantly influences the deformation of the excavation. This parameter is determined by the spacing of the vertical and horizontal supports (strut), support stiffness, excavation geometry, and retaining wall stiffness. The stiffness of the excavation system is a complex model and requires good numerical accuracy. The deformation analysis using finite element analysis (FEM) has a good level of accuracy compared to empirical methods verified using field measurements[1]–[5].

Then it is also found that the analysis deformation using two-dimensional (2D) and three-dimensional (3D) models has differences due to the arching effect that occurs at the corner of excavation on the 3D models [1], [2], [4]–[9]. Previous studies on deformation in excavation and specific case analysis have been discussed, including analyzing the reduction of deformations [10]–[15][16].

This study presents the influence of support spacing on horizontal wall movement and ground surface settlement of braced excavation. The analysis was carried out using the FEM method in PLAXIS 2D and 3D, which is useful for analyzing the arching effect on the parametric study results.

2. Literature Review

2.1 Horizontal Wall Movement and Ground Surface Settlement

Braced excavation is a soil retaining system that has structural components, which consist of walls and bracing. This system was designed to retain the movement and provide the stability of the excavation. The braced excavation deformations include the horizontal wall movement and ground surface settlement, as seen in **Figure 1 (a)**. Horizontal wall movement occurs on the wall in a lateral direction on the inner side of the excavation, while ground surface settlement can occur on the surface behind the wall. Previously, a method for determining the ground surface settlement profile and determining the maximum value of settlement based on the ratio to horizontal wall movement was conducted [17]. The accuracy of this method is highly dependent on the value of the deformation ratio used. The horizontal wall movement and ground surface settlement in the longitudinal direction of the wall have a small deformation value at the excavation corner and the maximum value at the center of the excavation span, as

shown by **Figure 1 (b)** [18]. Semi-empirical methods using the finite element and measurement data are also provided. From the results of the semi-empirical study, it was found that the model. Created to predict the maximum horizontal wall movement and ground surface settlement for soft clay and medium clay [19].
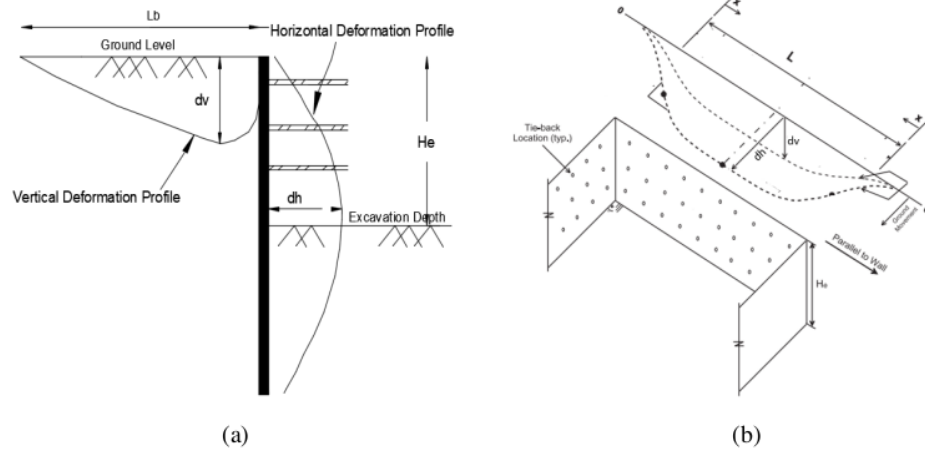
(a)	(b)
Source: (Hsieh & Ou, 1998)	*Source: (Roboski & Finno, 2006)*

Figure 1. Deformation Profile (a) Horizontal Wall Movement (dh) and Ground Surface Settlement (dv) Behind the Wall (b) dh and dv Profile Parallel along the wall.

2.2 System Stiffness

System stiffness of braced excavation may be affected by many factors. Based on a previous iterative study [20] on the effect of system stiffness parameters, it was found that the practical method by calculating the system stiffness to determine the lateral deformation of the excavation retaining wall using the chart as shown in **Figure 2.** These parameters consist of wall stiffness, strut spacing, depth, and excavation dimensions which formulated in an equation called a system stiffness factor with the following equation:
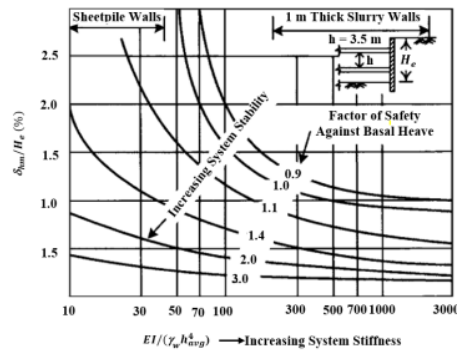
$$K = \frac{EI}{\gamma_w h^4}$$

Where:

EI = wall bending stiffness per unit length (kN/m2/m)

I = Moment inertia per length of the wall (m4/m)

γ_w = Unit weight of water (kN/m3)

h = spacing between supports (m)

Source: (Clough and O'Rourke, 1990)

Figure 2. Design Curve Lateral Wall Deformation for Excavation

3. Research Method

The excavation deformations carried out in this study include horizontal wall movement and ground surface settlement behind the wall. This research determines soil parameters and the excavation geometry model created in 2D and 3D geometry models. In the next step, the system stiffness parameters are determined using the variations in the vertical and horizontal spacing of struts. The results of this modeling are used to analyze the effect of system stiffness which includes spacing of vertical and horizontal supports against the deformations that occur. The research flow chart is shown in **Figure 3**.

This research was conducted using PLAXIS 2D and PLAXIS 3D software with a calculation basis using the Finite Element Method (FEM). This method is widely used to analyze the stability, deformation, and flow of groundwater. The results of the analysis of finite element-based software are strongly dependent on the input given, including the constitutive soil model [21], [22], [23]. To provide reasonable analysis results, a constitutive soil model should be capable of modeling soil elastoplastic properties. Therefore a hardening soil constitutive model is used. This constitutive model can comply with the elastoplastic properties of the soil by calculating the decrease in the value of stiffness to strain and simultaneously calculating the irreversible plastic strain (a plastic strain that does not recover) [24]–[26].
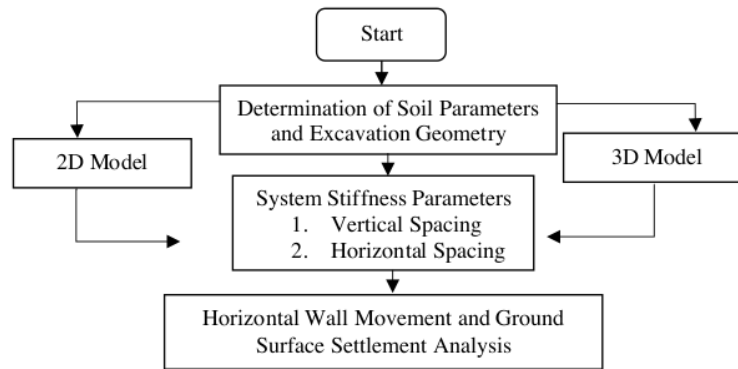
Source: Research Result

Figure 3. Research Flow Chart

3.1 Technical Specifications

3.1.1 Soil Parameters

Soil parameters must be provided in advance for numerical analysis. In this research, the soil parameter obtained from the consolidated undrained (CU) triaxial test on clay is shown in **Table** 1. To model soil parameters of hardening soil [27], there are γ which represent the unit weight of soil. The deformation parameters consist of three types of stiffness parameters, including young modulus at 50% failure stress which represents a small strain modulus (E_{50}^{ref}), unloading reloading modulus (E_{ur}^{ref}), and oedometer modulus to calculate plastic volumetric strain (E_{oed}^{ref}). Strength parameters used are cohesion (c'_{ref}) and friction angle (ϕ') to define the failure criteria. It also provided the permeability parameters, k_x And k_y as hydraulic conductivity of water flows through the soil, the soil profile along the depth remains uniform to simplify the model and limit the deformation factors.

Table 1. Soil Parameters Used for Modeling

Constitutive Model Parameters	Units	Hardening Soil Value
γ_{unsat}	[kN/m3]	8.67
γ_{sat}	[kN/m3]	15.1
kx	[m/day]	4x10-6
ky	[m/day]	2x10-6
E_{50}^{ref}	[kN/m2]	26000
E_{oed}^{ref}	[kN/m2]	26000
E_{ur}^{ref}	[kN/m2]	78000
C'_{ref}	[kN/m2]	10
ϕ	[°]	33
vur	[-]	0.3

Source: Research Result

3.1.2 Excavation Geometry

The excavation geometry used for parametric study has a simple rectangular with dimensions of length, *P*, 40 meters and width, *L*, 30 meters, and excavation depth, *He*, 17 meters. The excavation geometry developed using PLAXIS 2D and 3D software, as shown in **Figure 4**.
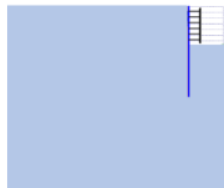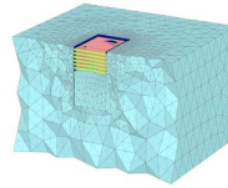

(a)	(b)
Source: Research Result	*Source: Research Result*

Figure 4. (a) 2D Geometry Model (b) 3D Geometry Model

3.1.3 Structural Elements

The structural elements modeled in this analysis include retaining walls using diaphragm walls with a thickness of *h*, 80 cm to a depth, *H*, 40 meters with reinforced concrete material. The supporting systems consist of struts using section properties steel pipe pile (SPP) with a type of rolled steel with a diameter of 609 mm and a thickness of 12 mm. For connecting the struts to the diaphragm wall, a waller is used with section properties was H-Welded profile type HE 1000x584. The structural parameters used in the analysis are shown in **Table 2** and **Table 3.**

Table 2. Diaphragm Walls Parameters Used for Modeling

Parameters	Units	Value
h	m	0.80
A	m2/meter	0.80
I_1	m4/meter	0.04
fc'	MPa	35.00
E	kN/m2	27805575
γ	kN/m3	24.00

Source: Research Result

Table 3. Wallers and Struts Properties Used for Modeling

Structural Elements		Wallers	Struts
Section Properties		HE 1000x584	SPP.609.12
Parameter	Units		
A	m2	743.70	225.30
γ	kN/m3	78.50	78.50

Structural Elements		Wallers	Struts
Section Properties		HE 1000x584	SPP.609.12
E	kN/m2	210000000	210000000
$I_2 = I_x$	m4/meter	1246100	101000
$I_3 = I_y$	m4/meter	33430	101000

Source: Research Result

3.2 Parametric Study

The parametric study carried out included two different variations in vertical struts spacing, Sv, and horizontal struts spacing, Sh, as shown in **Table 4** and **Table 5**, the distance of each strut was varied arithmetic in one direction, and another direction was held constant to evaluate the influence of each variation. The variation of the vertical spacing of the struts causes the different excavation stages in each analysis. This was related to the depth of excavation for each construction step and the position of the vertical struts installation, while the stages of construction of horizontal struts spacing variation were using constant vertical struts spacing 2.5 meters. The excavation stages in each parametric study are shown in **Table 6**.

Table 4. Variation in Vertical Struts Spacing (Sv) Used in Parametric Study

No	Sv (m)	Sh (m)
1	2.5	2.5
2	5.0	2.5
3	7.5	2.5

Source: Research Result

Table 5. Variation in Horizontal Struts Spacing (Sh) Used in Parametric Study

No	Sv (m)	Sh (m)
1	2.5	2.5
2	2.5	5.0
3	2.5	7.5

Source: Research Result

Table 6. Stages of Construction

No	Events	Elevation (m)	Sv (m) *2.5	5.0	7.5
1	Construction of diaphragm wall	Top: +0.00 m Toe: -40.00 m	√	√	√
2	Excavation Stage 1	-2.50 m	√	√	√
3	Installation of Struts 1	-2.00 m	√		
4	Excavation Stage 2	-5.00 m	√	√	√
5	Installation of Struts 2	-4.50 m	√	√	
6	Excavation Stage 3	-7.50 m	√	√	√
7	Installation of Struts 3	-7.00 m	√	√	√
8	Excavation Stage 4	-10.00 m	√	√	√
9	Installation of Struts 4	-9.50 m	√	√	
10	Excavation Stage 5	-12.50 m	√	√	√
11	Installation of Struts 5	-12.00 m	√		

No	Events	Elevation (m)	Sv (m)		
			*2.5	5.0	7.5
12	Excavation Stage 6	-15.00 m	√	√	√
13	Installation of Struts 6	-14.5 m	√	√	√
14	Excavation Stage 7	-17.00 m	√	√	√
15	Construction of Base Slab	-17.00 m	√	√	√

* *Stages of construction for variation of horizontal struts spacing used vertical struts spacing 2.5 meters.*
Source: Research Result

4. Results and Discussions

4.1   Influence of System Stiffness

To evaluate the effect of stiffness systems on deformations, the ratio of system stiffness parameters in vertical, Kv, to horizontal, Kh, were used based on [20], which compared against normalized deformation with the depth of excavation, dh/He, and dv/He. An increase in the strut spacing causes the system stiffness to decrease.

Table 7. Relationship between the Maximum Deformation and Variation of Struts Spacing

Model	Maximum Deformation	$Sh = 2.5$ m			$Sv = 2.5$ m		
		Sv			Sh		
		2.5 m	5.0 m	7.5 m	2.5 m	5.0 m	7.5 m
2D	Horizontal (dh)	46.84	57.68	72.59	46.84	55.31	62.20
	Vertical (dv)	-25.90	-32.16	-42.52	-25.90	-31.10	-41.49
3D	Horizontal (dh)	42.88	51.50	62.20	42.88	50.50	54.80
	Vertical (dv)	-23.59	-28.71	-36.38	-23.59	-27.04	-34.80

Source: Research Result

The effects of variation in struts spacing on the maximum deformation are shown in **Table 7**. It can be seen that the highest maximum dh value was 72.59 mm, which was obtained from the 2D model at the value of $Sv = 7.5$ m and $Sh = 2.5$ m. There was an increase in horizontal wall movement of 54.97% compared to the conditions with values of $Sv = 2.5$ m and $Sh = 2.5$ m. In contrast, the maximum dh value when $Sh = 7.5$ m was 62.2 mm, this value was 17% lower compared to the highest maximum horizontal deformation value for vertical spacing variation at the same distance. For the ground surface settlement value, dv, a negative sign (-) is given to indicate that the deformations that occur were in the form of settlement. The highest maximum dv was obtained with -42.52 mm in 2D models at $Sv = 7.5$ m, while the lowest maximum dv values occur when $Sh = 2.5$ m was -25.90 mm, which was 64.17% difference. This indicates that the effect changes in vertical spacing give larger deformation changes than In horizontal spacing, this is also reflected in the results of deformations in other variations in 2D and 3D models, where all the deformation values of the increment of vertical struts spacing

have a higher value than horizontal spacing. However, it is necessary to analyze each further parameter's significance to obtain the optimum combination of strut spacing.

Table 8. Influence of System Stiffness on Deformation

Ratio (%)	Model	Horizontal System Stiffness $Kh = 12112$			Vertical System Stiffness $Kv = 12112$		
		Vertical System Stiffness (Kv)			Horizontal System Stiffness (Kh)		
		12112	757	150	12112	757	150
		Kv/Kh			Kv/Kh		
		1	0.063	0.012	1	16	81
dh/He	2D	0.28	0.34	0.43	0.28	0.33	0.37
dv/He		0.15	0.19	0.25	0.15	0.18	0.24
dh/He	3D	0.25	0.30	0.37	0.25	0.30	0.32
dv/He		0.14	0.17	0.21	0.14	0.16	0.20

Source: *Research Result*

Table 8 presents the maximum dh/He values are 0.43% and 0.37% which were found when the Kv/Kh = 0.012 for 2D and 3D models, respectively, while the minimum dh/He values were 0.28% and 0.25% at the Kv/Kh value = 1 for 2D and 3D models. The result regarding normalized ground surface settlement, dv/He, obtained the similar trend, while the highest values of dv/He were 0.25% and 0.21% at Kv/Kh = 0.012 for 2D and 3D models, while the lowest dv/He values were 0.15% and 0.14% at Kv/Kh = 1 for 2D and 3D models.

It can be seen that the difference in normalized deformation that occurs was relatively small for variation of vertical and horizontal spacing with the corresponding increment with a maximum difference of about 0.06% between Kv= 150 and Kh =150. It is necessary to consider the parameters of the horizontal spacing parameters as important as vertical spacing. In several analyses carried out in retaining walls, the vertical spacing design emphasizes more than horizontal spacing. This study found that the design for vertical and horizontal spacing is equally important, and performing these calculations can be done with 2D plain strain models for simplification. However, 3D models can examine the geometric effects of the excavation.

Figure 5 shows the relationship between the ratio of system stiffness and normalized deformation. It observed that the relationship between the ratio of vertical and horizontal system stiffness to deformation indicates a good approximation to the polynomial equation, which was illustrated by the consistent regression equation was $ax^2 + bx + c$. The results for each variable obtained from parametric data generated from numerical analysis.
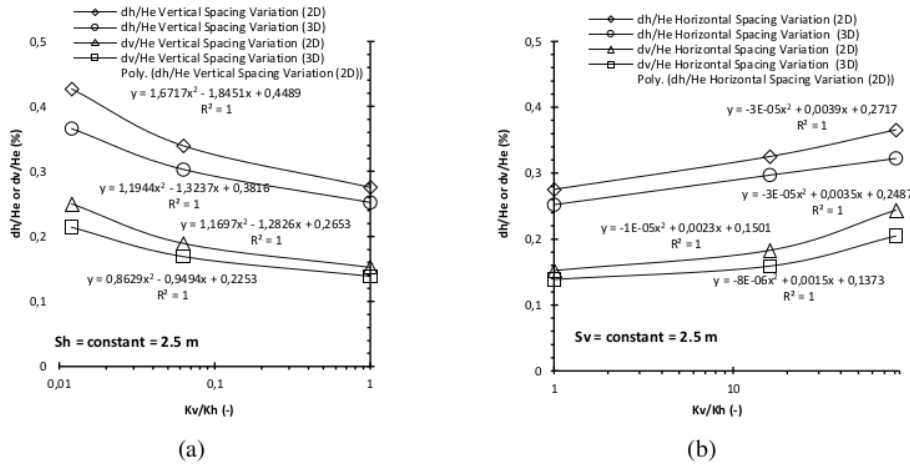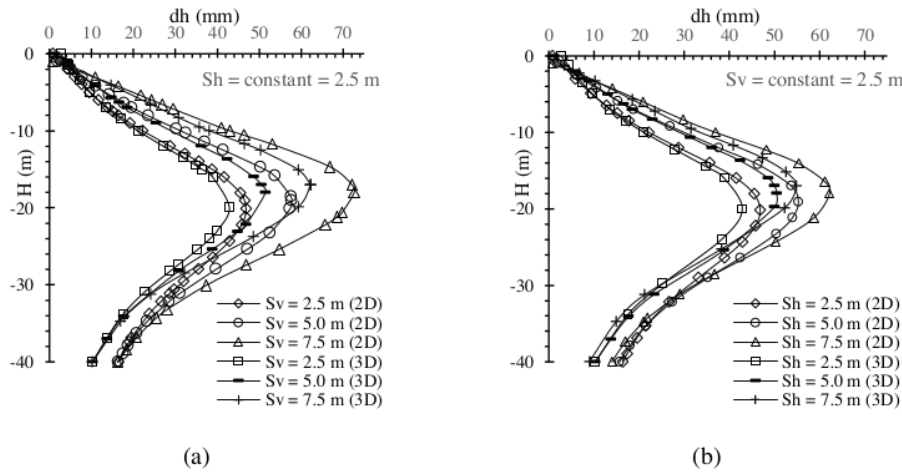
Source: Research Result

Figure 5. Relationship between System Stiffness Ratio on Normalized Deformation (a) Variation of Vertical Spacing (b) Variation of Horizontal Spacing

4.2 Effects of 2D and 3D Modeling

The 2D and 3D modeling effect evaluation refers to the ratio of the maximum value of horizontal wall movement and ground surface settlement. It was found that the horizontal wall movement and ground surface settlement strongly related to 2D and 3D models.
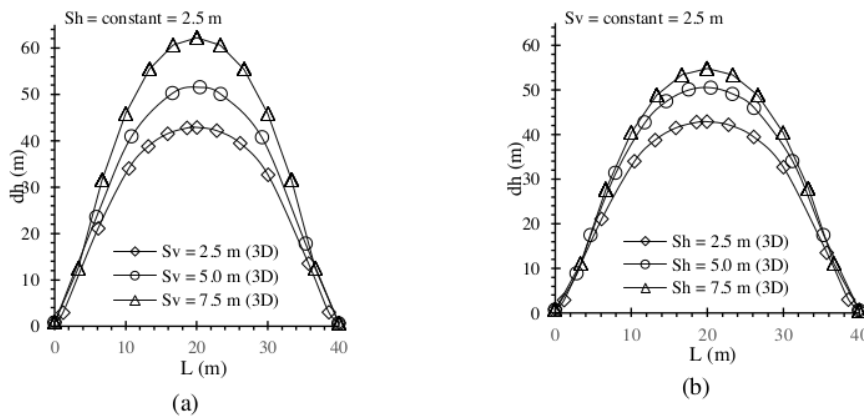

Source: Research Result

Figure 6. Horizontal Wall Movement (a) Variation of Vertical Spacing (b) Variation of Horizontal Spacing

(a)   (b)
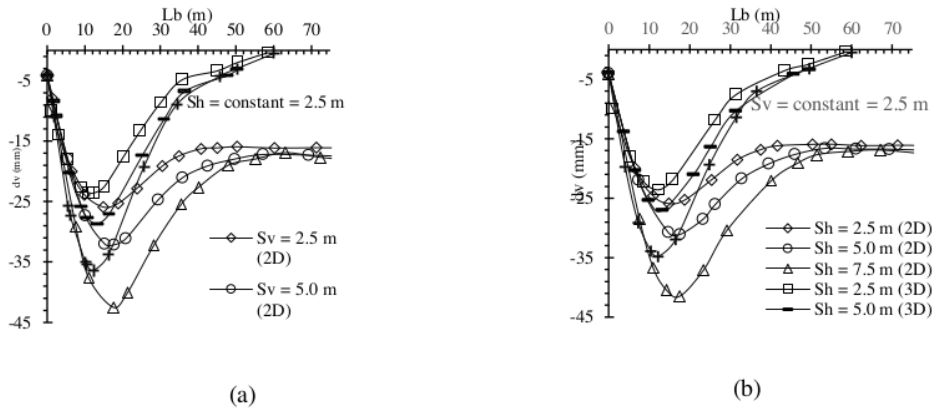
Source: Research Result

Figure 7. Ground Surface Settlement (a) Variation of Vertical Spacing (b) Variation of
Horizontal Spacing

Figure 6. shows the horizontal wall movement profile with the depth of excavation.
The computed deformation patterns that occur likely have the same consistency, the depth of
maximum deflection point was around 17 m to 20 m, and the system stiffness influenced this
depth, the more increment of system stiffness, the deflection point becomes deeper. Moreover,
for ground surface settlement can be seen in **Figure 7,** for 2D models, it was found that the
deformation pattern that occurs at a distance from the wall, for $Lb > 60$ m, dv was constant
around -18 mm, this was different from the 3D model where at the same distance, there was no
longer any ground surface settlement.

(a)   (b)

Source: Research Result

Figure 8. Horizontal Wall Movement Profile along with Longitudinal Section of the Wall in
3D Model (a) Variation of Vertical Spacing (b) Variation of Horizontal Spacing

The effects of the 3D model can be observed on the longitudinal horizontal wall movement profile along the wall in **Figure 8**. It can be seen that the horizontal deformation value at the excavation corner has a small value and gradually increases and reaches maximum deformation in the center of the excavation wall. The ratio of the maximum horizontal wall movement in the center of the wall computed by 3D analysis to the maximum deformation in the plain strain condition is defined as plain strain ratio, *PSR* [1], [5], [6].

Table 9. Plain Strain Ratio for Various Struts Spacing

| Plain Strain Ratio (PSR) | $Sh = 2.5$ m | | | $Sv = 2.5$ m | | |
| | Sv (*m*) | | | Sh (*m*) | | |
	2.5	5.0	7.5	2.5	5.0	7.5
dh_{3D}/dh_{2D}	0.92	0.89	0.86	0.92	0.91	0.88

Source: Research Result

Table 9 and **Figure 9** present the *PSR* value for various struts spacing, it was found that the highest *PSR* value was 0.92 at the value of $Sv = 2.5$ m and $Sh = 2.5$ m, while the lowest *PSR* value was 0.86 at the value of $Sh = 2.5$ m and $Sv = 7.5$ m. It is found that the *PSR* value decreases when the system stiffness value is decreased, meanwhile, when the system stiffness was higher, the PSR value will be higher and closer to 1, which shows that the difference in the 3D and 2D models is relatively small, whereas, the smaller the *PSR* value indicates that the plain strain calculation results have the significant differences with the 3D modeling results, where the excavation model is more representative in 3D in nature.
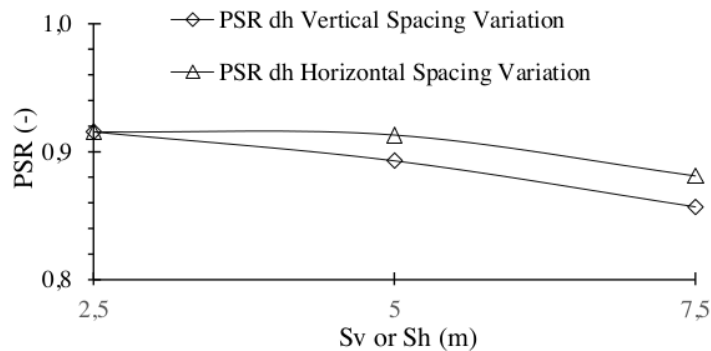
Source: Research Result

Figure 9. Relationship Between Variation of Struts Spacing and Plain Strain Ratio.

5. Conclusion and Suggestion

5.1 Conclusion

Based on the results of the analysis carried out, the following conclusions can be obtained:

1. An increase in vertical spacing generally results in a higher increase of the horizontal wall movement and ground surface settlement than an increase in horizontal spacing. However, it should be considered that the difference of normalized deformation to the depth of excavation shows a small value. Hence the design for vertical and horizontal spacing is equally important.

2. The relationship between the ratio of system stiffness in the vertical and horizontal direction to normalized deformation shows a good approximation to the polynomial equation, which was illustrated by the consistent regression with the equation that was $ax^2 + bx + c$.

3. The horizontal wall movement and ground surface settlement obtained in the 2D plain strain model show a higher value than the 3D model. It is also found that the area of influence on the 2D plain strain model has more distance behind the wall. This is because the 3D model is affected by the corner effect so that the system stiffness in the direction of deformation is higher.

4. To evaluate the difference in horizontal wall movement that occurs in 2D plain strain and 3D models, the plain strain ratio, PSR, is used, it is found that the stiffer the excavation system is, the PSR value is closer to 1, which mean that the difference in the 3D and 2D models is relatively smaller.

5.1 Suggestion

To provide a comprehensive result on the factor affecting deformation, additional parametric modeling can be added. The results of numerical modeling need to be verified with measurement data in the field so that the reliability of the modeling results can be measured.

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horizontal wall