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Analysis of the Effects of Soil Parameters and Depth on the Lateral Movement of Soil Improved by Combined PVD-Vacuum Consolidation

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Abstract

One method for improving highly compressible, low-permeability soft soils is the combination of Prefabricated Vertical Drains (PVDs) and vacuum consolidation. Chai et al. (2005) proposed an analytical method for estimating lateral soil movement based on field measurements using inclinometers. However, the model parameter (α) in their method lacks an explicit explanation of its relationship with soil properties and depth. This study aims to investigate the influence of soil parameters and depth on lateral ground displacement by comparing inclinometer measurements from a case study with an enhanced analytical model derived from Chai et al. (2005). The results identify the compression index (Cc) as the most influential soil parameter, while the depth effect (z) is represented by the function $f(z) = 0.001z^3 - 0.0317z^2 + 0.2328z + 0.3345$. The proposed model was evaluated against field data using quantitative error metrics, yielding a coefficient of determination (R^2) of 0.9710, a mean absolute error (MAE) of 0.0435, and a root mean square error (RMSE) of 0.0482. These results indicate strong agreement with field measurements and relatively low prediction errors. Nevertheless, further validation under different soil conditions is required to establish the model's broader applicability.

Keywords: *Consolidation, Displacement, Lateral, PVD, Vacuum*

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INTRODUCTION

Soft soils characterized by high compressibility and low permeability require ground improvement to enhance their engineering performance. One ground improvement method that can be applied is the use of Prefabricated Vertical Drains (PVDs) combined with vacuum preloading [1], [2]. The application of PVDs in combination with vacuum consolidation aims to accelerate the rate and degree of consolidation settlement, reduce post-construction settlement during the operational period, increase the bearing capacity of the soil, and improve embankment stability. In addition, this method can reduce or eliminate the need for surcharge fill material required in conventional preloading by utilizing the atmospheric pressure induced by the vacuum consolidation process. It can also eliminate the need for additional soil fill along the edges of the improved area to enhance slope stability [3], [4].

Field applications of ground improvement using Prefabricated Vertical Drains (PVDs)

combined with vacuum preloading include the construction of roads, embankments, reclamation areas, ports, airports, building or tank foundations, and other infrastructure. To assess and validate the performance of PVD–vacuum consolidation ground improvement in the field, appropriate monitoring instrumentation should be installed. One of the essential field monitoring instruments is the inclinometer [3], [5]. The primary purpose of inclinometer installation is to monitor lateral soil displacement resulting from the preloading process.

The greatest lateral soil displacement induced by embankment loading generally occurs at the toe of the embankment; therefore, inclinometers are typically installed along the embankment perimeter [6], [7]. In PVD–vacuum consolidation ground improvement, the direction of lateral soil movement is generally toward the improved area [8], [9]. Monitoring the magnitude of lateral soil displacement is essential to ensure that ground stability within the improved area is maintained throughout the improvement period and to minimize potential adverse effects on the surrounding environment [10].

One of the existing methods for estimating lateral soil displacement is the method proposed by Chai et al. (2005), which was developed based on field experiments using inclinometers as field monitoring instruments [11]. In this method, an empirical assumption is introduced through the variation of the model parameter (α), although the factors governing this variation are not explicitly explained. Chai et al. (2005) developed this approach for estimating lateral soil displacement based on field observations.

The assumption involved in estimating lateral soil displacement in PVD–vacuum consolidation ground improvement using the Chai et al. (2005) method should therefore be minimized. Such assumptions introduce uncertainty and may limit the applicability of the method when it is applied to case studies with different soil and site conditions. Compared with the method of Chai et al. (2005), the proposed modification explicitly relates variations in the model parameter (α) to soil parameters and soil depth, which are not explicitly considered in the original method. This modification is based on the theoretical relationship between the increase in vertical stress induced by loading and soil depth, as well as the soil deformation response to loading, which is generally governed by the geotechnical properties of the soil.

METHOD

Based on the Universal Transverse Mercator (UTM) coordinates, the study area is located within the coordinate boundaries presented in **Table 1**. The location of the study area is shown in **Figure 1**.

Figure 1. Study Site

The data required for this study consisted of secondary data obtained from relevant and authorized institutions or agencies. The collection of secondary data is presented in **Table 2**.

Table 1. Study site boundaries

Left Boundary	Right Boundary
Upper: 683326.635 m E and 9333945.675 m S	Upper: 683401.839 m E and 9333740.501 m S
Lower: 683309.290 m E and 9333940.572 m S	Lower: 683385.629 m E and 9333732.609 m S

Table 2. Data acquisition

No.	Data	Source (Collection Period)	Purpose
1	Study location map	Google Earth (2024)	To identify the coordinates of the study site.
2	Geological map	Geologi ESDM (2024)	To analyze the types of rock formations present at the study site.
3	Standard Penetration Test & (SPT) & borlog	Geosistem (2024)	To analyze the soil stratification and soil types at the study site.
4	Laboratory soil test results	Geosistem (2024)	To determine the soil parameters for each soil layer at the study site.
5	Soft soil distribution map of Indonesia	Geologi ESDM (2024)	To verify and confirm that the soil at the research site is classified as soft soil based on the Indonesian soft soil distribution map.
6	Technical data and drawings of the PVD Combined with Vacuum Consolidation Ground Improvement Works	Geosistem (2024)	To identify the technical data and drawings related to ground improvement using PVD combined with Vacuum Consolidation, which support the analysis of lateral ground movement.
7	Summary of lateral ground displacement	Geosistem (2024)	To verify the actual lateral ground displacement occurring at the study site.

The research flowchart is presented in **Figure 2**.

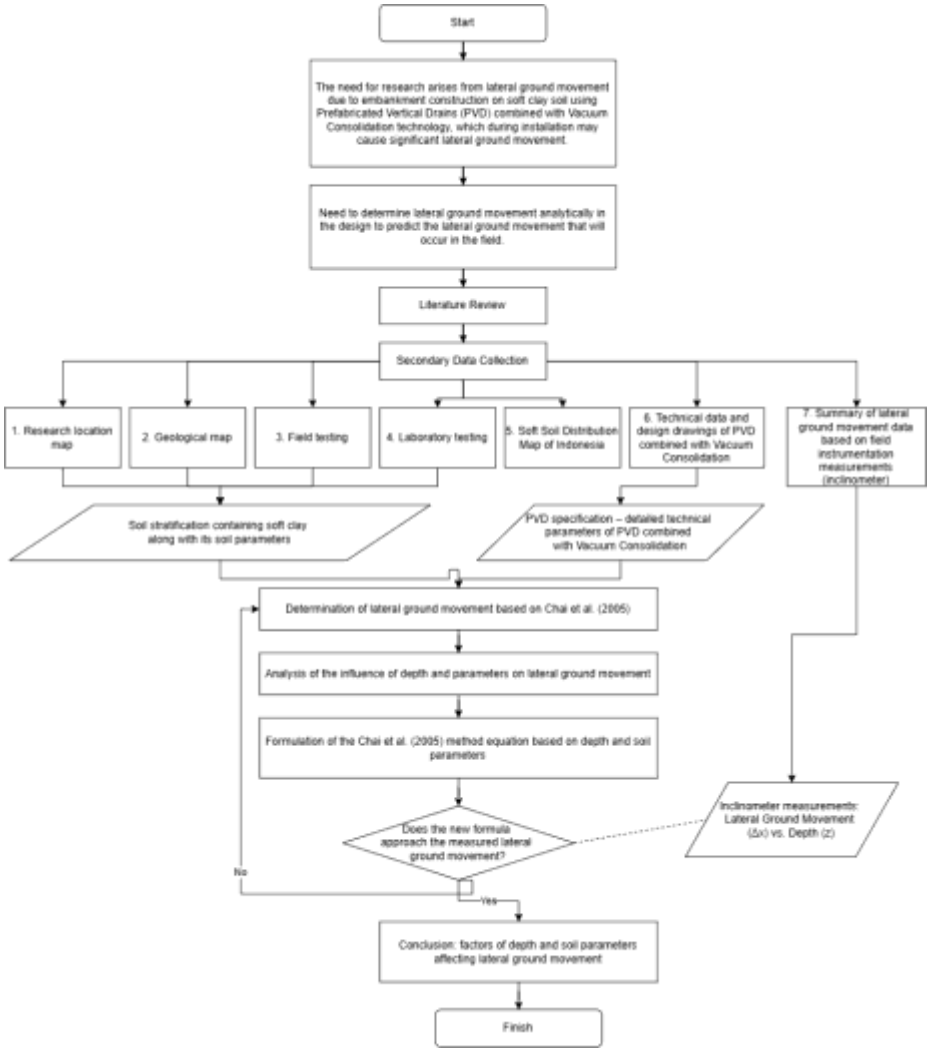

Figure 2. Research flowchart

RESULTS AND DISCUSSION

Chai et al. (2025) developed one of the methods for estimating lateral ground displacement based on field experiments using field instrumentation, specifically inclinometers (Hu & Liu, 2021; Song et al., 2022). The method incorporates an assumption regarding the variation of the model parameter. The lateral ground displacement (δ_h) at the boundary of the improved soil area is determined using Equation (1).

$$\delta_h = \varepsilon_h B \quad (1)$$

where:

$\boldsymbol{\varepsilon_h}$	:	Horizontal strain
$\boldsymbol{B}$	:	Half the width of the improved soil area

The horizontal strain is determined using Equation (2).

$$\varepsilon_h = \frac{1}{2}(1-\alpha)\frac{\lambda}{1+e}\ln\left(1+\frac{\Delta\sigma_{vac}}{\sigma'_{v0}}\right) \quad (2)$$

where:

$\boldsymbol{\alpha}$	:	Assumed variation in the model parameter
$\boldsymbol{\lambda}$	:	Virgin Compression Index (Cc) from the $e - \ln p'$ Curve
$\boldsymbol{e}$	:	Void ratio
$\boldsymbol{\Delta\sigma_{vac}}$	:	Additional vacuum pressure in the improved ground area
$\boldsymbol{\sigma'_{v0}}$	:	Vertical effective stress of the soil in the improved ground area

The visualization of ground improvement using PVD combined with Vacuum

Consolidation [12], [13] is presented in **Figure 3**.

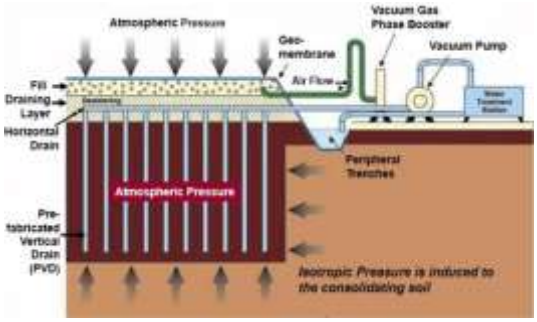

Figure 3. Soil Improved with PVD Combined with Vacuum Consolidation

An illustration of lateral ground displacement in soil improved with PVD combined with Vacuum Consolidation [14], [15] is shown in **Figure 4**.

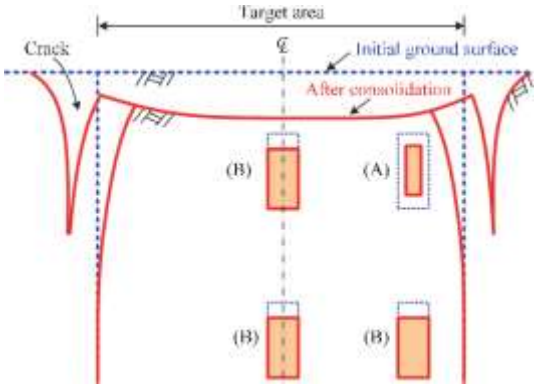

Figure 4. Lateral Ground displacement in Soil Improved with PVD Combined with Vacuum Consolidation

The soil stratification at the study site, based on the processed data, is shown in **Figure 5**.

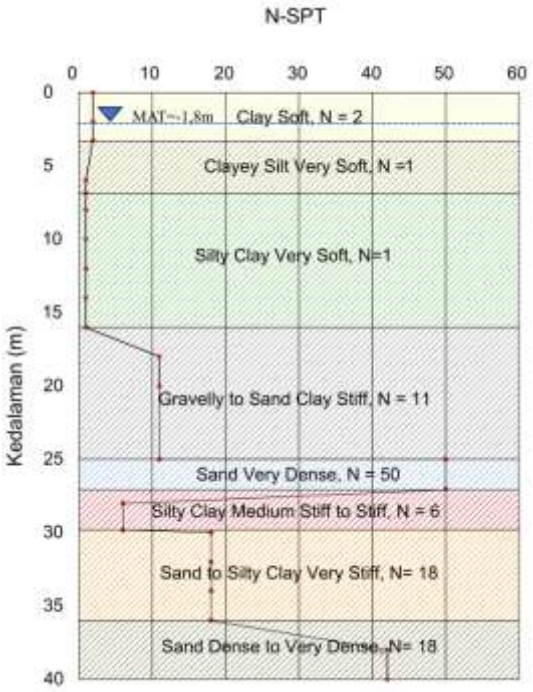

Figure 5. Soil Stratification at the study site

The lateral ground displacement data for soil improved with PVD combined with Vacuum Consolidation at the study site are shown in **Table 3**.

Table 3. Summary of measured lateral ground displacement at the study site

Depth (m)	Initial Reading (mm)	12/7 (mm)	12/8 (mm)	12/9 (mm)	12/10 (mm)	12/11 (mm)	12/12 (mm)	12/13 (mm)
0.50	0.00	304.57	305.26	305.93	306.58	307.35	308.11	308.86
1.00	0.00	256.78	257.35	257.91	258.45	259.09	259.72	260.35
1.50	0.00	229.06	229.56	230.10	230.60	231.19	231.76	232.34
2.00	0.00	221.09	221.58	222.07	222.54	223.10	223.65	224.19
2.50	0.00	211.83	212.30	212.76	213.21	213.74	214.26	214.78
3.00	0.00	205.29	205.71	206.11	206.51	206.98	207.44	207.90
3.50	0.00	195.62	195.97	196.32	196.67	197.07	197.46	197.86
4.00	0.00	186.25	186.58	186.89	187.20	187.57	187.92	188.28
4.50	0.00	176.22	176.50	176.78	177.05	177.37	177.69	178.00
5.00	0.00	174.16	174.41	174.65	174.88	175.16	175.43	175.70
5.50	0.00	160.77	160.97	161.16	161.35	161.58	161.80	162.02
6.00	0.00	148.37	148.54	148.71	148.87	149.06	149.25	149.44

6.50	0.00	141.18	141.31	141.44	141.56	141.71	141.86	142.01
7.00	0.00	135.16	135.24	135.32	135.40	135.50	135.59	135.68
7.50	0.00	131.83	131.86	131.89	131.91	131.95	131.98	132.01
8.00	0.00	123.75	123.73	123.71	123.69	123.67	123.65	123.62
8.50	0.00	114.16	114.09	114.02	113.95	113.87	113.79	113.71
9.00	0.00	102.06	102.06	102.06	102.06	102.05	102.05	102.05
9.50	0.00	90.36	90.32	90.27	90.23	90.18	90.13	90.08
10.00	0.00	77.58	77.44	77.31	77.18	77.03	76.88	76.73
10.50	0.00	66.37	66.18	66.00	65.81	65.60	65.39	65.18
11.00	0.00	57.41	57.22	57.04	56.86	56.64	56.43	56.22
11.50	0.00	47.61	47.45	47.29	47.14	46.96	46.78	46.61
12.00	0.00	37.51	37.42	37.33	37.24	37.14	37.04	36.94
12.50	0.00	30.86	30.76	30.66	30.56	30.44	30.33	30.22
13.00	0.00	23.06	23.05	23.05	23.04	23.03	23.02	23.01
13.50	0.00	14.33	14.47	14.61	14.75	14.90	15.06	15.21
14.00	0.00	7.71	7.94	8.16	8.37	8.62	8.87	9.11
14.50	0.00	4.96	5.21	5.46	5.70	5.99	6.26	6.54
15.00	0.00	2.07	2.30	2.53	2.75	3.01	3.26	3.52
15.50	0.00	0.67	0.79	0.90	1.02	1.15	1.28	1.41
16.00	0.00	0.81	0.87	0.99	1.11	1.17	1.29	1.17
16.50	0.00	-0.70	-0.66	-0.62	-0.58	-0.53	-0.49	-0.44
17.00	0.00	0.94	0.97	0.99	1.02	1.05	1.08	1.11
17.50	0.00	1.18	1.19	1.21	1.23	1.25	1.27	1.29
18.00	0.00	0.81	0.83	0.84	0.86	0.87	0.89	0.91
18.50	0.00	-0.27	-0.26	-0.24	-0.23	-0.21	-0.20	-0.18
19.00	0.00	-1.81	-1.80	-1.80	-1.79	-1.78	-1.77	-1.76
19.50	0.00	-1.93	-1.93	-1.94	-1.95	-1.96	-1.97	-1.97
20.00	0.00	-2.21	-2.23	-2.24	-2.26	-2.28	-2.30	-2.32
20.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The soft clay layer requiring ground improvement using Prefabricated Vertical Drains (PVD) combined with Vacuum Consolidation at the research site has a thickness of 15 m. The analytical calculation of the lateral ground displacement was performed using the formulation proposed by Chai et al., as modified by Fitriana Sarifah, as presented in **Table 4**.

Table 4. Comparison of Lateral Ground displacement Based on Field Inclinometer Measurements and the Chai Method Modified by Fitriana Sarifah

B =	**10**	**m**		**H =**	**15**	**m**						
GWL	**z**	**γ**	**σ'$_{vo}$**	**Δσ'$_{vo}$**	**Cc**	$\overline{C_c}$	**e**	**f(z)$_{field}$**	**ε$_{vol}$.B (Chia et al)**	**f(z)$_{model}$ (Fitriana Sarifah)**	**δ$_h$ (Chai et al modified by Fitriana Sarifah)**	**δ$_h$ field**
m	m	kN/m^3	kN/m^2	kN/m^2				cm			cm	cm
	0.5	16	8	81.02	0.5	1.45	1.50	0.44	697.17	0.44	30.89	30.89
	1	16	16	81.02	0.5	1.45	1.50	0.50	521.51	0.54	27.98	26.04
	1.5	16	24	81.02	0.5	1.45	1.50	0.54	427.11	0.62	26.30	23.23

	2	16	32	81.02	0.5	1.45	1.50	0.61	365.11	0.68	24.87	22.42
	2.5	16.76	40.38	81.02	1.61	1.45	1.50	0.67	318.50	0.73	23.38	21.48
	3	16.76	48.76	81.02	1.61	1.45	1.50	0.73	283.25	0.77	21.94	20.79
	3.5	16.76	57.14	81.02	1.61	1.45	1.50	0.77	255.47	0.80	20.54	19.79
	4	16.76	63.558	81.02	1.61	1.45	1.50	0.79	237.81	0.82	19.56	18.83
3.8	4.5	16.76	67.033	81.02	1.61	1.45	1.50	0.78	229.28	0.83	19.06	17.80
	5	16.76	70.508	81.02	1.61	1.45	1.50	0.79	221.37	0.83	18.40	17.57
	5.5	16.76	73.983	81.02	1.61	1.45	1.50	0.76	214.01	0.82	17.60	16.20
	6	16.76	77.458	81.02	1.61	1.45	1.50	0.72	207.14	0.81	16.70	14.94
	6.5	16.76	80.933	81.02	1.61	1.45	1.50	0.71	200.72	0.78	15.72	14.20
	7	16.76	84.408	81.02	1.61	1.45	1.50	0.70	194.70	0.75	14.68	13.57
	7.5	16.76	87.883	81.02	1.61	1.45	1.50	0.70	189.04	0.72	13.60	13.20
	8	16.76	91.358	81.02	1.61	1.45	1.50	0.67	183.71	0.68	12.49	12.36
	8.5	16.76	94.833	81.02	1.61	1.45	1.50	0.64	178.68	0.64	11.38	11.37
	9	13.87	96.863	81.02	1.61	1.45	1.50	0.58	175.87	0.59	10.39	10.21
	9.5	13.87	98.893	81.02	1.61	1.45	1.50	0.52	173.16	0.54	9.39	9.01
	10	13.87	100.923	81.02	1.61	1.45	1.50	0.45	170.52	0.49	8.40	7.67
	10.5	13.87	102.953	81.02	1.61	1.45	1.50	0.39	167.97	0.44	7.42	6.52
	11	13.87	104.983	81.02	1.61	1.45	1.50	0.34	165.50	0.39	6.46	5.62
	11.5	13.87	107.013	81.02	1.61	1.45	1.50	0.29	163.10	0.34	5.55	4.66
	12	13.87	109.043	81.02	1.61	1.45	1.50	0.23	160.77	0.29	4.68	3.69
	12.5	13.87	111.073	81.02	1.61	1.45	1.50	0.19	158.50	0.24	3.88	3.02
	13	13.87	113.103	81.02	1.61	1.45	1.50	0.15	156.30	0.20	3.14	2.30
	13.5	13.87	115.133	81.02	1.61	1.45	1.50	0.10	154.17	0.16	2.47	1.52
	14	13.87	117.163	81.02	1.61	1.45	1.50	0.06	152.09	0.12	1.89	0.91
	14.5	13.87	119.193	81.02	1.61	1.45	1.50	0.04	150.07	0.09	1.41	0.65
	15	13.87	121.223	81.02	1.61	1.45	1.50	0.02	148.10	0.07	1.02	0.35
	15.5	13.87	123.253	81.02	1.61	1.45	1.50	0.01	146.18	0.05	0.74	0.14
	16	13.87	125.283	81.02	1.61	1.45	1.50	0.01	144.32	0.04	0.58	0.12
	16.5	13.87	127.313	81.02	1.61	1.45	1.50	0.00	142.50	0.04	0.53	-0.04
	17	13.87	129.343	81.02	1.61	1.45	1.50	0.01	140.73	0.04	0.62	0.11

A comparison of the field-measured lateral ground displacement with the results obtained using the Chai et al. method, as modified by Fitriana Sarifah, is presented in **Figure 6**. The maximum lateral ground movement at the research site was 30.89 cm, occurring at a depth of 0.5 m below the ground surface. Since the soil compression index (Cc) varies along the 15 m thick, soft soil layer, an average compression index (Cc) was adopted to represent the soil layer in the analysis. This approach was inspired by using average soil parameter values for site classification in SNI 8460:2017. The influence function describing the relationship between soil depth and lateral ground movement is expressed as $f(z) = 0.001z^3 - 0.0317z^2 + 0.2328z + 0.3345$, as presented in **Figure 7.**

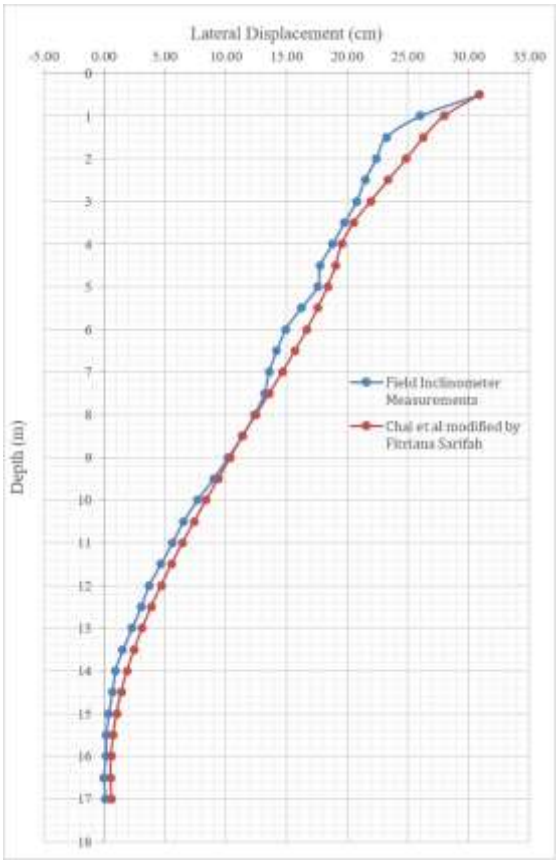

Figure 6. The comparison between the field-measured lateral ground movement and the Chai et al. method modified by Fitriana Sarifah

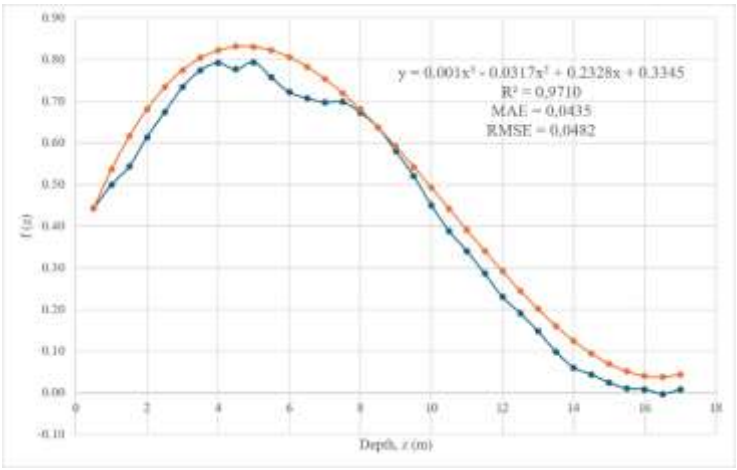

Figure 7. Influence function of soil depth on lateral ground movement in soil improved with PVD combined with vacuum consolidation

The accuracy of the proposed model was evaluated by comparing its predictions with field data using the coefficient of determination (R^2) according to the equation (3), mean absolute error (MAE) according to the equation (4), and root mean square error (RMSE) according to the equation (5) as quantitative error metrics.

$$R^2 = 1 - \frac{\sum_{i=1}^{n}\left(f(z)_{field} - f(z)_{model}\right)^2}{\sum_{i=1}^{n}\left(f(z)_{field} - \overline{f(z)_{field}}\right)^2} \quad (3)$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|f(z)_{field} - f(z)_{model}\right| \quad (4)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(f(z)_{field} - f(z)_{model}\right)^2} \quad (5)$$

The obtained (R^2) value of 0.9710 indicates a strong agreement between the model predictions and field measurements, with 97.10% of the variance in the field data explained by the model. Furthermore, the MAE and RMSE values of 0.0435 and 0.0482, respectively, indicate relatively small prediction errors in the units of the evaluated parameter. The slightly higher RMSE than MAE suggests that some prediction errors are larger than the average absolute error, although the difference between the two metrics is relatively small. Overall, these results indicate that the proposed model can adequately reproduce the general trend of the field data with relatively low prediction errors, supporting its accuracy in representing the observed depth-dependent profile.

CONCLUSION

This study identifies the compression index (Cc) as the predominant soil parameter influencing lateral ground displacement during PVD and vacuum consolidation. Considering the variation of Cc along the 15 m thick, soft soil layer, an average Cc approach is proposed, with the depth effect represented by $f(z) = 0.001z^3 - 0.0317z^2 + 0.2328z + 0.3345$. The proposed model was evaluated against field data using quantitative error metrics, yielding a coefficient of determination (R^2) of 0.9710, a mean absolute error (MAE) of 0.0435, and a root mean square error (RMSE) of 0.0482. These results indicate strong agreement with the field measurements and relatively low prediction errors. However, further validation under different soil conditions is necessary to assess the model's general applicability.

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