Settle3D

Ground Improvement Feature

Verification of Settlement Calculations for Vibro-Compaction

Problem Description

The hypothetical embankment problem from '*Simplified homogenization method in stone column designs'* by **K.S. Ng, and S.A. Tan** (October 21, 2014) was used to verify the Stone Column calculations for Settle3D's newest Ground Improvement feature. However, some changes were made from the original problem including removal of the 1 m top crust layer and replacement with soft soil. The stone columns, 10 m in length, were used to support a 4 m high embankment fill constructed above a 20 m soft soil layer. Also to simplify the calculations we assumed a constant loading stress across the entire depth (80kPa). The embankment had a 1:2 (V:H) slope gradient with a top width of 40 m. Figure 1 shows the geometry used for the model. The stone columns were 1 m in diameter with center-to-center spacing of 2m in a square grid pattern. The material properties are summarized in Table 1.

Table 1: Material Properties

Name	**Depth**	**Unit Weight [kN/m^3]**	**Elastic Modulus [kPa]**
Soft Soil	1-20 m	18	5,000
Embankment fill	4 m high	20	15,000
Stone Column	10 m deep	19	50,000

Table 3: Vibro-Compaction Parameters

D_{50}	1.2	**mm**
Target D_r	75	**%**
Alpha	1.5	**-**

D_{50}: mean grain size (mm)
Target D_r: Target Relative Density
Alpha: Coefficient to account for the type of sand = {5 for sands with fines, 10 for clean sands (Normally Consolidated), 15 for clean sands (Over Consolidated)}

Using the above values, the following steps were taken to estimate the new equivalent modulus of elasticity of the sand after vibro-compaction:

a) Compute the SPT N value corrected for 60% of the theoretical free-fall hammer energy based on the correlation proposed by Cubrinovski and Ishihara (1999) and the equation was rearranged to isolate for N_{60}:

$$N_{60} = 9Dr^2 \left(\frac{100}{\sigma'_{z0}}\right)^{-0.5} (0.23 + \frac{0.06}{D_{50}})^{-1.7}$$

Where σ'_{z0} = effective overburden stress (kPa)
D_{50} = mean grain size (mm)
Dr = relative density
N_{60} = SPT N value (corrected for 60% of free-fall hammer energy)

b) Compute the modulus of elasticity of after vibro-compaction using the correlation by Kulhawy and Mayne (1990)

$$E = \alpha p_a N_{60}$$

Where N_{60} = SPT N value corrected for 60% of the theoretical free-fall hammer energy

p_a = atmospheric pressure of 101.325 (kPa)

$$\alpha = \begin{Bmatrix} 5 \text{ for sands with fines} \\ 10 \text{ for clean normally consolidated sands} \\ 15 \text{ for clean overconsolidated sands} \end{Bmatrix}$$

c) Compute the vertical strain in each sublayer is calculated using:

$$\varepsilon_i = \frac{\Delta\sigma_i}{E}$$

where ε_i = strain in sublayer *i*

E = constrained modulus of clay

$\Delta\sigma_i$ = change in effective stress in sublayer *i*

where $\Delta\sigma_i$ is the change in vertical total stress in the *i*th sublayer. Initial settlement is then calculated from these strains.

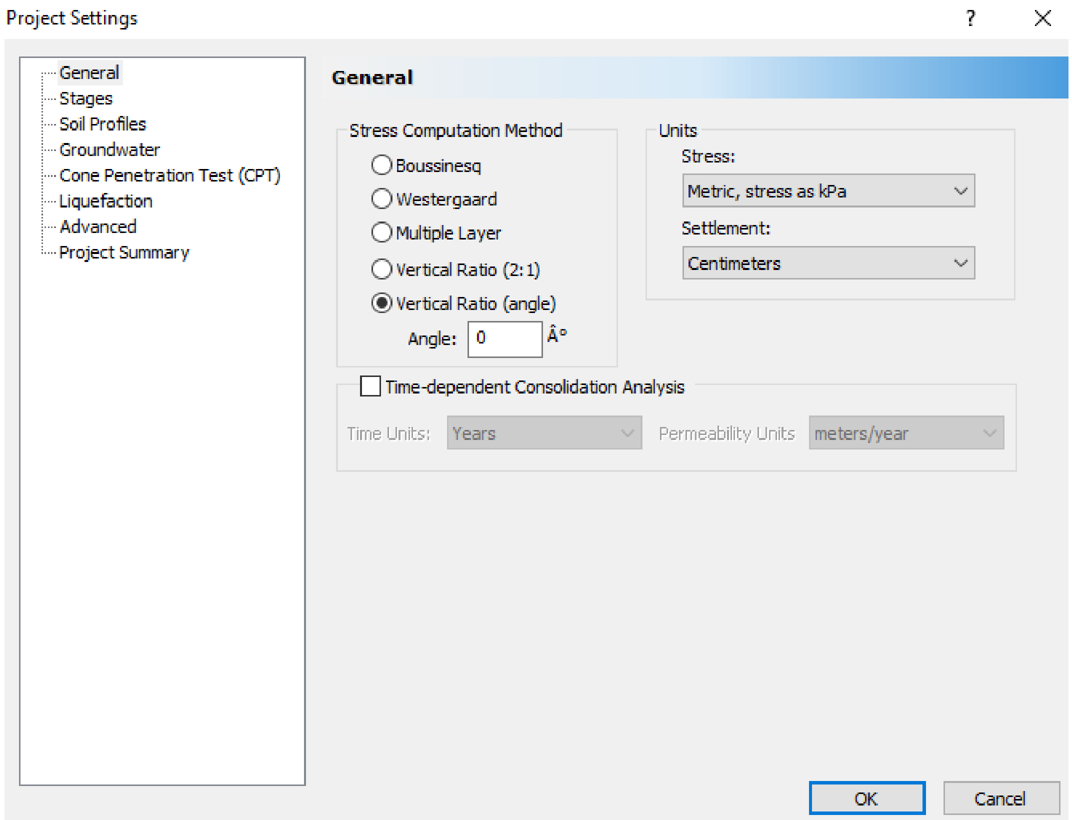
A spreadsheet was created to compare theoretical results to the Settle3D output values for the following three cases:

1. Immediate Settlement (using Constant Stress Method)
2. Immediate Settlement (using Boussinesq's Stress Method)
3. Immediate Settlement (using Westergaard's Stress Method)

Since Vibro-Compaction is a ground improvement technique only used for sands only immediate settlement is considered.

Case 1: Constant Stress Method

For the constant stress method, the stress computation method in project settings dialog was set as 0º angle in the Vertical Ratio (angle) option as shown below:



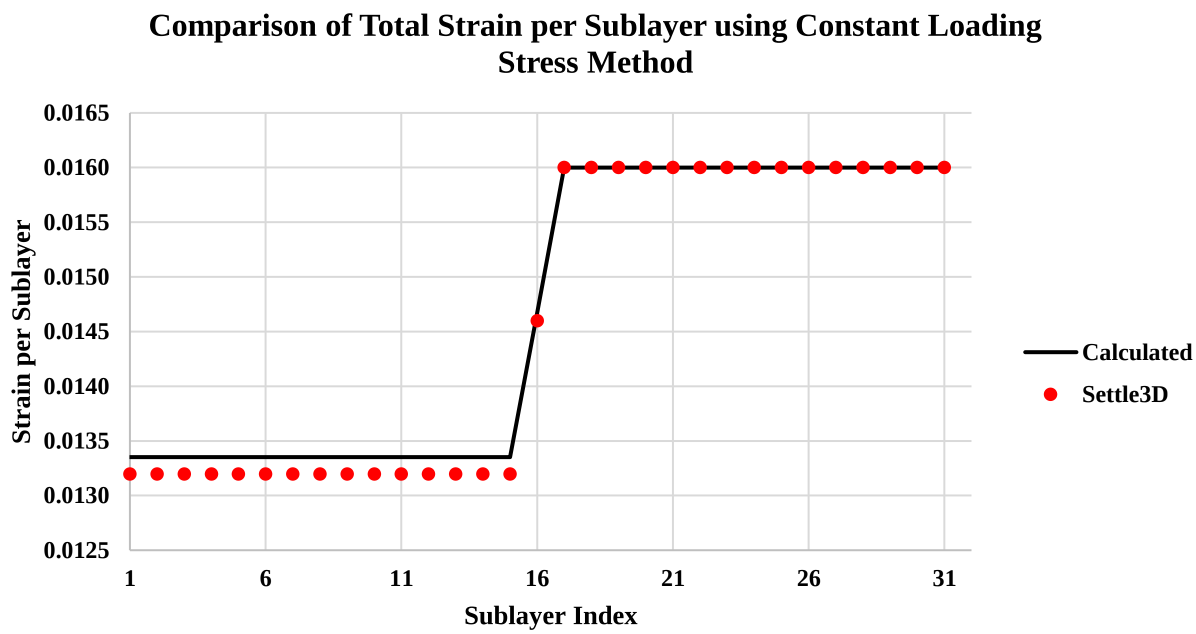
The implementation of the vibro-compaction feature **decreased the total immediate settlement by approximately 9%** dropping from 32 cm without any ground improvement to 29.2 cm after vibro-compaction. The following figure summarizes the difference between the theoretical calculations of settlement and the Settle3D output values.

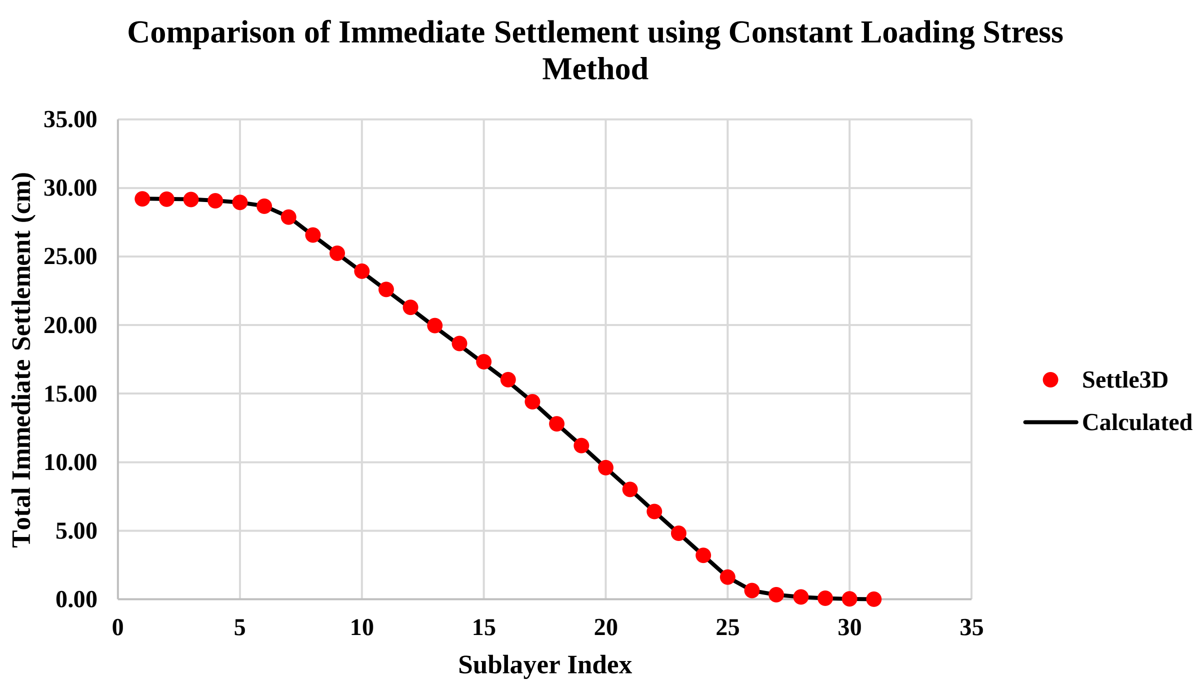
Table 1: Settle3D Output Values for Vibro-Compaction

Index	Depth	Loading Stress	Total Settlement	Total Strain	Modulus of Elasticity (kPa)
1	0	80	29.20	0.01	
2	0.02	80	29.17	0.01	
3	0.04	80	29.14	0.01	
4	0.1	80	29.06	0.01	
5	0.2	80	28.93	0.01	
6	0.4	80	28.67	0.01	
7	1	80	27.88	0.01	
8	2	80	26.56	0.01	
9	3	80	25.24	0.01	
10	4	80	23.92	0.01	
11	5	80	22.60	0.01	
12	6	80	21.28	0.01	
13	7	80	19.96	0.01	
14	8	80	18.64	0.01	
15	9	80	17.32	0.01	
16	10	80	16.00	0.01	
17	11	80	14.40	0.02	5000
18	12	80	12.80	0.02	5000
19	13	80	11.20	0.02	5000
20	14	80	9.60	0.02	5000
21	15	80	8.00	0.02	5000
22	16	80	6.40	0.02	5000
23	17	80	4.80	0.02	5000
24	18	80	3.20	0.02	5000
25	19	80	1.60	0.02	5000
26	19.6	80	0.64	0.02	5000
27	19.8	80	0.32	0.02	5000
28	19.9	80	0.16	0.02	5000
29	19.96	80	0.06	0.02	5000
30	19.98	80	0.03	0.02	5000
31	20	80	0.00	0.02	5000

Table 2: Theoretical Values for Vibro-Compaction

Index	N60	Equivalent Modulus of Elasticity (kPa)	Strain	Error in Strain	Settlement	Error in Settlement
1	39.42	5991.69	0.01	-0.01	29.22	-0.08%
2	39.42	5991.69	0.01	-0.01	29.19	-0.08%
3	39.42	5991.69	0.01	-0.01	29.17	-0.08%
4	39.42	5991.69	0.01	-0.01	29.09	-0.08%
5	39.42	5991.69	0.01	-0.01	28.95	-0.07%
6	39.42	5991.69	0.01	-0.01	28.69	-0.06%
7	39.42	5991.69	0.01	-0.01	27.88	-0.03%
8	39.42	5991.69	0.01	-0.01	26.55	0.03%
9	39.42	5991.69	0.01	-0.01	25.21	0.09%
10	39.42	5991.69	0.01	-0.01	23.88	0.16%
11	39.42	5991.69	0.01	-0.01	22.54	0.24%
12	39.42	5991.69	0.01	-0.01	21.21	0.33%
13	39.42	5991.69	0.01	-0.01	19.87	0.43%
14	39.42	5991.69	0.01	-0.01	18.54	0.54%
15	39.42	5991.69	0.01	-0.01	17.20	0.67%
16	39.42	5991.69	0.01	-0.01	15.87	0.83%
17			0.02	0.00	14.40	0.00%
18			0.02	0.00	12.80	0.00%
19			0.02	0.00	11.20	0.00%
20			0.02	0.00	9.60	0.00%
21			0.02	0.00	8.00	0.00%
22			0.02	0.00	6.40	0.00%
23			0.02	0.00	4.80	0.00%
24			0.02	0.00	3.20	0.00%
25			0.02	0.00	1.60	0.00%
26			0.02	0.00	0.64	0.00%
27			0.02	0.00	0.32	0.00%
28			0.02	0.00	0.16	0.00%
29			0.02	0.00	0.06	0.00%
30			0.02	0.00	0.03	0.00%
31			0.02	0.00	0.00	


Comparison of Total Strain per Sublayer using Constant Loading Stress Method
Strain per Sublayer
0.0165
0.0160
0.0155
0.0150
0.0145
0.0140
0.0135
0.0130
0.0125
1
6
11
16
21
26
31
Sublayer Index
Calculated
Settle3D


Comparison of Immediate Settlement using Constant Loading Stress Method
Total Immediate Settlement (cm)
35.00
30.00
25.00
20.00
15.00
10.00
5.00
0.00
0
5
10
15
20
25
30
35
Sublayer Index
Settle3D
Calculated

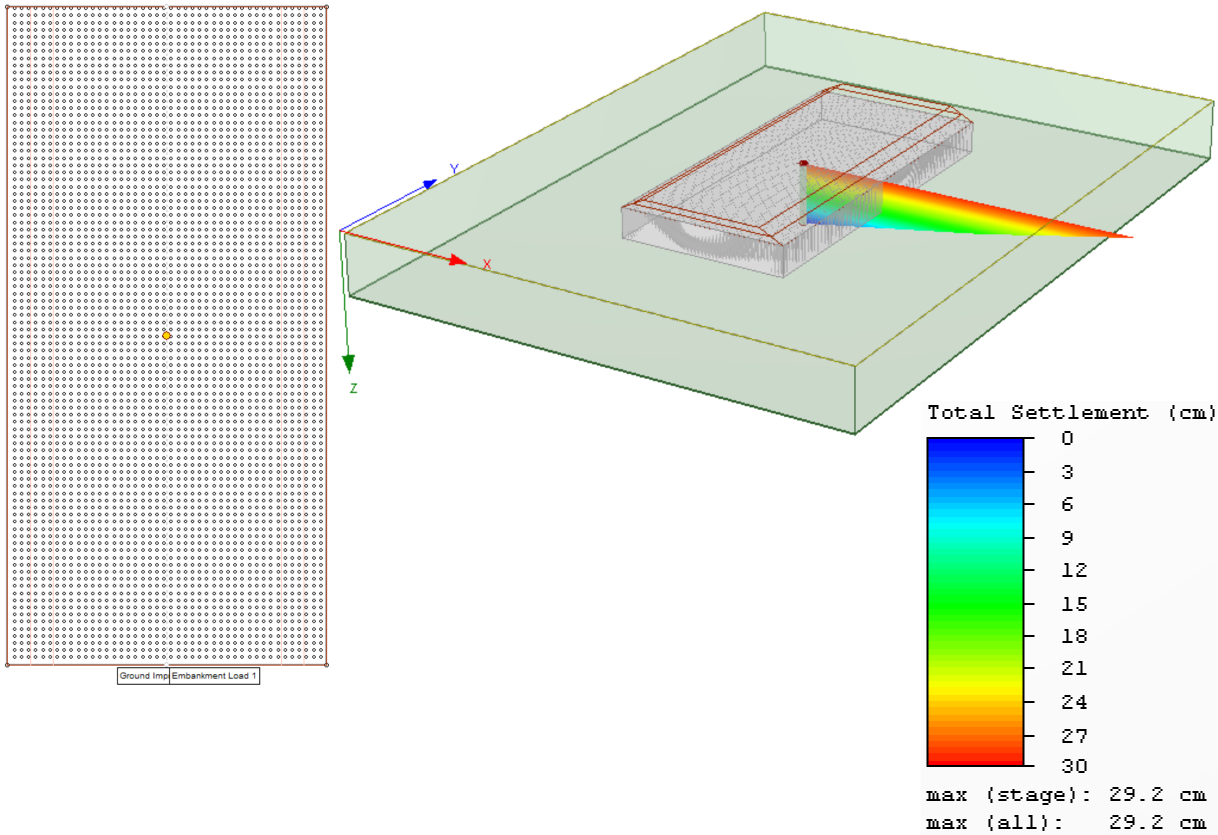


Figure 1: Settle3D Model after Vibro-Compaction using Constant Stress Method for Stress Computations

Case 2: Boussinesq Stress Method

The implementation of the vibro-compaction feature using the Boussinesq method to calculate stresses **decreased the total immediate settlement by approximately 9%** dropping from 30.4 cm without any ground improvement to 27.6 cm after vibro-compaction. The following figures and tables summarize the differences between the theoretical calculations and the Settle3D output values.

Table 3: Settle3D Output Values for Vibro-Compaction (using Boussinesq's Stress Method)

Index	Depth	Loading Stress	Total Settlement	Total Strain	Modulus of Elasticity (kPa)
1	0	79.99	27.59	0.013	
2	0.02	79.99	27.57	0.013	
3	0.04	79.99	27.54	0.013	
4	0.1	79.98	27.46	0.013	
5	0.2	79.98	27.33	0.013	
6	0.4	79.98	27.07	0.013	
7	1	79.96	26.27	0.013	
8	2	79.89	24.96	0.013	
9	3	79.78	23.64	0.013	
10	4	79.61	22.32	0.013	
11	5	79.37	21.01	0.013	
12	6	79.06	19.71	0.013	
13	7	78.68	18.41	0.013	
14	8	78.21	17.11	0.013	
15	9	77.67	15.83	0.013	
16	10	77.05	14.55	0.014	
17	11	76.35	13.02	0.015	5000
18	12	75.59	11.50	0.015	5000
19	13	74.76	9.99	0.015	5000
20	14	73.88	8.51	0.015	5000
21	15	72.94	7.04	0.015	5000
22	16	71.96	5.59	0.014	5000
23	17	70.94	4.16	0.014	5000
24	18	69.89	2.75	0.014	5000
25	19	68.81	1.37	0.014	5000
26	19.6	68.15	0.54	0.014	5000

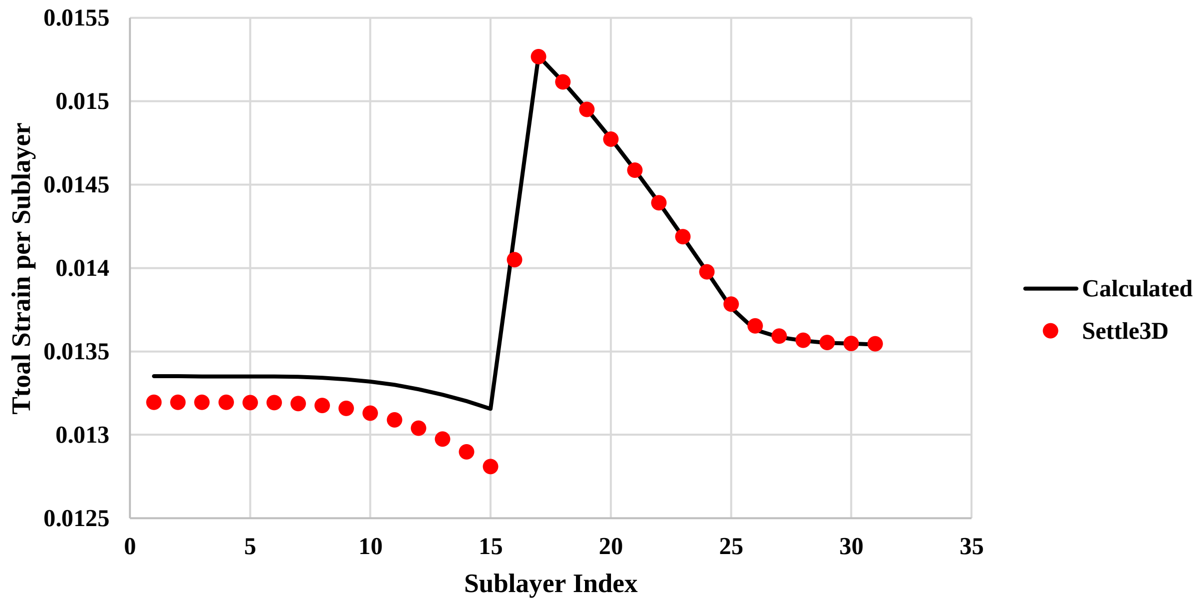
27	19.8	67.93	0.27	0.014	5000
28	19.9	67.82	0.14	0.014	5000
29	19.96	67.75	0.05	0.014	5000
30	19.98	67.73	0.03	0.014	5000
31	20	67.71	0.00	0.014	5000

Table 4: Theoretical Values for Vibro-Compaction (using Boussinesq's Stress Method)

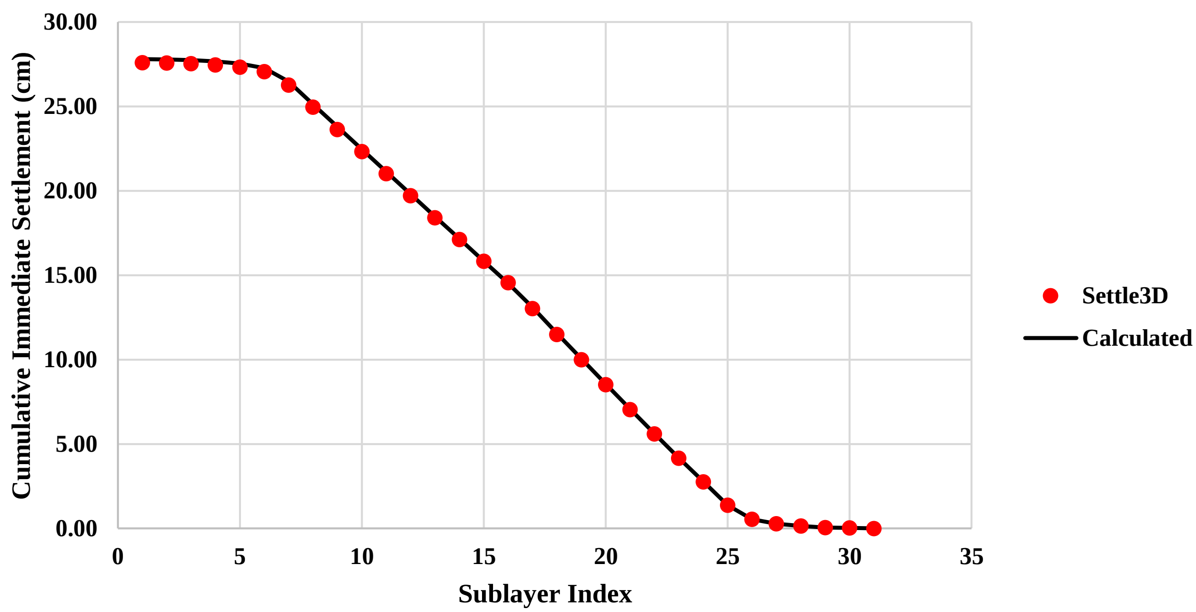
Index	N60	Equivalent Modulus of Elasticity (kPa)	Strain	Error in Strain	Settlement	Error in Settlement
1	39.42	5991.20	0.013	-1%	27.80	-1%
2	39.42	5991.18	0.013	-1%	27.78	-1%
3	39.42	5991.17	0.013	-1%	27.75	-1%
4	39.42	5991.12	0.013	-1%	27.67	-1%
5	39.42	5991.04	0.013	-1%	27.54	-1%
6	39.42	5990.84	0.013	-1%	27.27	-1%
7	39.41	5990.01	0.013	-1%	26.47	-1%
8	39.40	5987.57	0.013	-1%	25.13	-1%
9	39.37	5983.37	0.013	-1%	23.80	-1%
10	39.33	5977.01	0.013	-1%	22.47	-1%
11	39.27	5968.14	0.013	-2%	21.13	-1%
12	39.19	5956.51	0.013	-2%	19.80	0%
13	39.09	5941.95	0.013	-2%	18.48	0%
14	38.98	5924.35	0.013	-2%	17.15	0%
15	38.84	5903.71	0.013	-3%	15.83	0%
16	38.69	5880.06	0.014	-1%	14.52	0%
17			0.015	0%	13.10	-1%
18			0.015	0%	11.57	-1%
19			0.015	0%	10.06	-1%
20			0.015	0%	8.56	-1%
21			0.015	0%	7.08	-1%
22			0.014	0%	5.63	-1%
23			0.014	0%	4.19	-1%
24			0.014	0%	2.77	-1%
25			0.014	0%	1.37	0%
26			0.014	0%	0.54	0%
27			0.014	0%	0.27	0%
28			0.014	0%	0.14	0%
29			0.014	0%	0.05	0%

30		0.014	0%	0.03	0%
31		0.014	0%	0	

Comparison of Total Strain using Boussinesq's Stress Method



Comparison of Total Settlement using Boussinesq's Stress Method



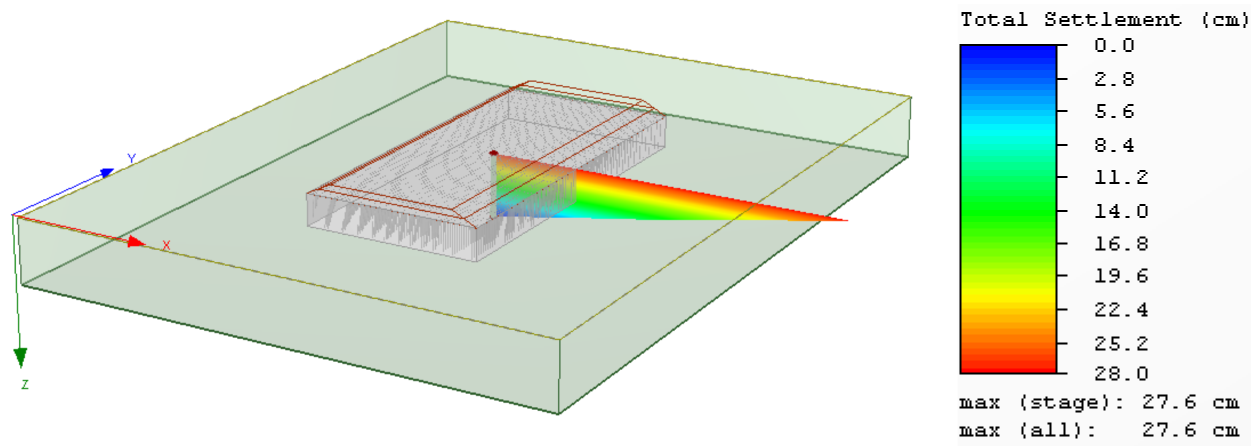


Figure 2: Settle3D Model after Vibro-Compaction using Boussinesq Stress Method for Stress Computations

Case 3: Westergaard Stress Method

The implementation of the vibro-compaction feature using the Westergaard method to calculate stresses **decreased the total immediate settlement by approximately 10%**, dropping from 23.2 cm without any ground improvement to 20.9 cm after vibro-compaction. The following figures and tables summarize the differences between the theoretical calculations and the Settle3D output values.

Table 5: Settle3D Output Values for Vibro-Compaction (using Westergaard's Stress Method)

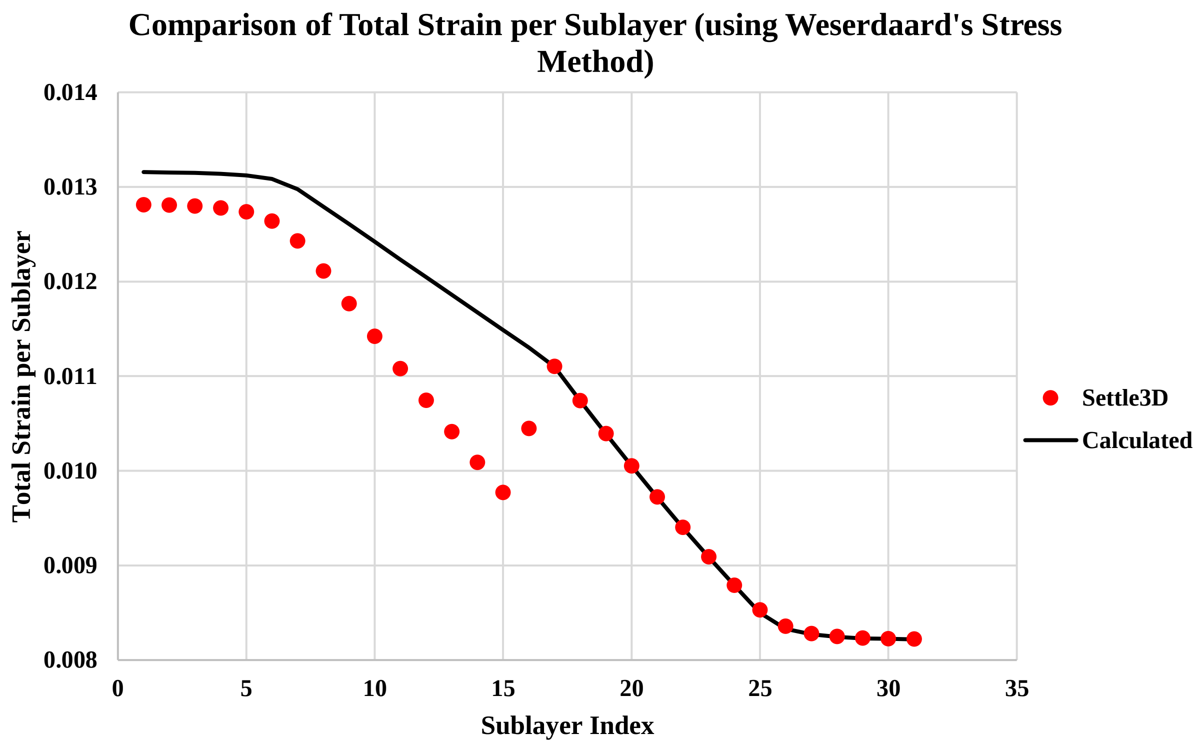
Index	Depth	Loading Stress	Total Settlement	Total Strain	Modulus of Elasticity (kPa)
1	0	77.69	20.86	0.013	
2	0.02	77.64	20.83	0.013	
3	0.04	77.60	20.81	0.013	
4	0.1	77.47	20.73	0.013	
5	0.2	77.26	20.60	0.013	
6	0.4	76.83	20.35	0.013	
7	1	75.55	19.60	0.012	
8	2	73.42	18.37	0.012	
9	3	71.31	17.17	0.012	
10	4	69.22	16.01	0.011	
11	5	67.16	14.89	0.011	
12	6	65.12	13.80	0.011	
13	7	63.12	12.74	0.010	
14	8	61.15	11.72	0.010	
15	9	59.22	10.72	0.010	
16	10	57.34	9.76	0.010	
17	11	55.49	8.63	0.011	5000
18	12	53.70	7.54	0.011	5000
19	13	51.95	6.48	0.010	5000
20	14	50.25	5.46	0.010	5000
21	15	48.60	4.47	0.010	5000
22	16	46.99	3.52	0.009	5000
23	17	45.44	2.59	0.009	5000
24	18	43.94	1.70	0.009	5000
25	19	42.49	0.84	0.009	5000
26	19.6	41.65	0.33	0.008	5000

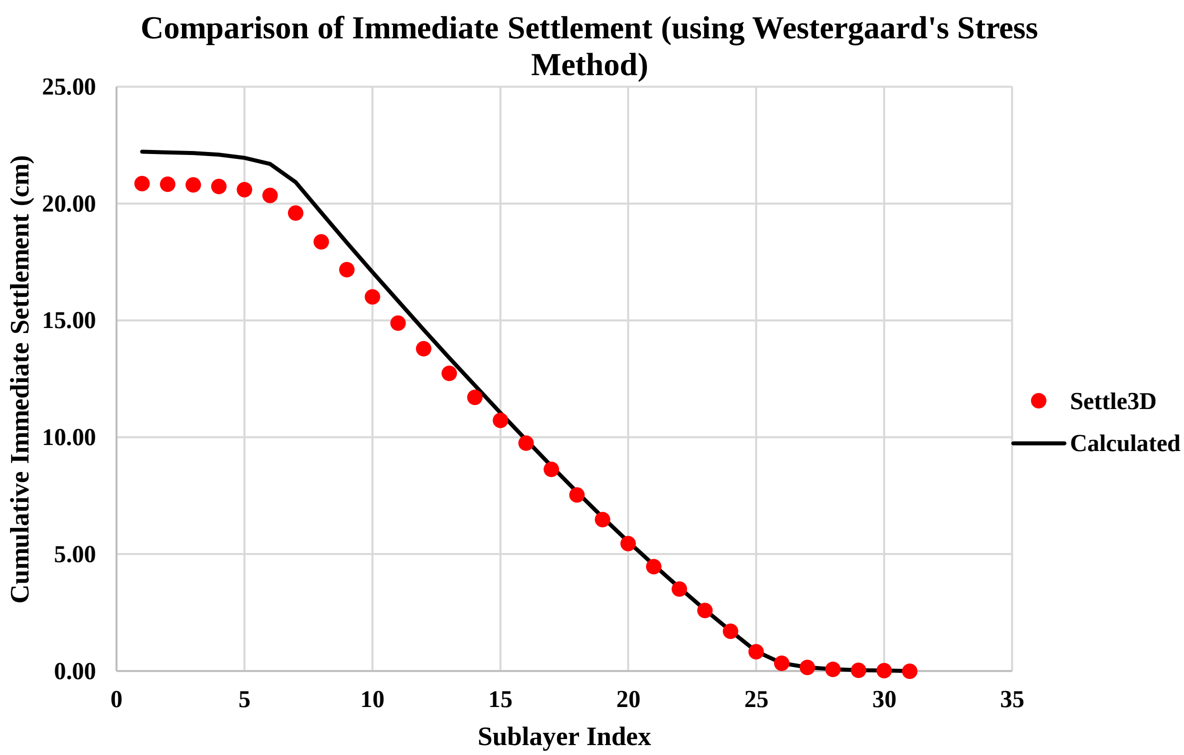
27	19.8	41.37	0.16	0.008	5000
28	19.9	41.23	0.08	0.008	5000
29	19.96	41.15	0.03	0.008	5000
30	19.98	41.12	0.02	0.008	5000
31	20	41.09	0.00	0.008	5000

Table 6: Theoretical Values for Vibro-Compaction (using Westergaard's Stress Method)

Index	N60	Equivalent Modulus of Elasticity (kPa)	Strain	Error in Strain	Settlement	Error in Settlement
1	38.85	5904.39	0.013	-3%	22.22	-7%
2	38.84	5902.76	0.013	-3%	22.19	-7%
3	38.83	5901.14	0.013	-3%	22.17	-7%
4	38.79	5896.25	0.013	-3%	22.09	-7%
5	38.74	5888.10	0.013	-3%	21.96	-7%
6	38.63	5871.78	0.013	-3%	21.69	-7%
7	38.31	5822.62	0.013	-4%	20.91	-7%
8	37.77	5740.12	0.013	-5%	19.61	-7%
9	37.22	5657.04	0.013	-7%	18.33	-7%
10	36.67	5573.55	0.012	-8%	17.07	-7%
11	36.12	5489.80	0.012	-9%	15.83	-6%
12	35.57	5405.95	0.012	-11%	14.61	-6%
13	35.02	5322.15	0.012	-12%	13.40	-5%
14	34.47	5238.55	0.012	-14%	12.22	-4%
15	33.92	5155.29	0.011	-15%	11.05	-3%
16	33.37	5072.50	0.011	-8%	9.90	-1%
17			0.011	0%	8.77	-2%
18			0.011	0%	7.66	-2%
19			0.01	0%	6.59	-2%
20			0.01	0%	5.55	-2%
21			0.01	0%	4.54	-1%
22			0.009	0%	3.57	-1%
23			0.009	0%	2.63	-1%
24			0.009	0%	1.72	-1%
25			0.008	0%	0.84	-1%
26			0.008	0%	0.33	0%
27			0.008	0%	0.17	0%
28			0.008	0%	0.08	0%
29			0.008	0%	0.03	0%

30		0.008	0%	0.02	0%
31		0.008	0%	0	





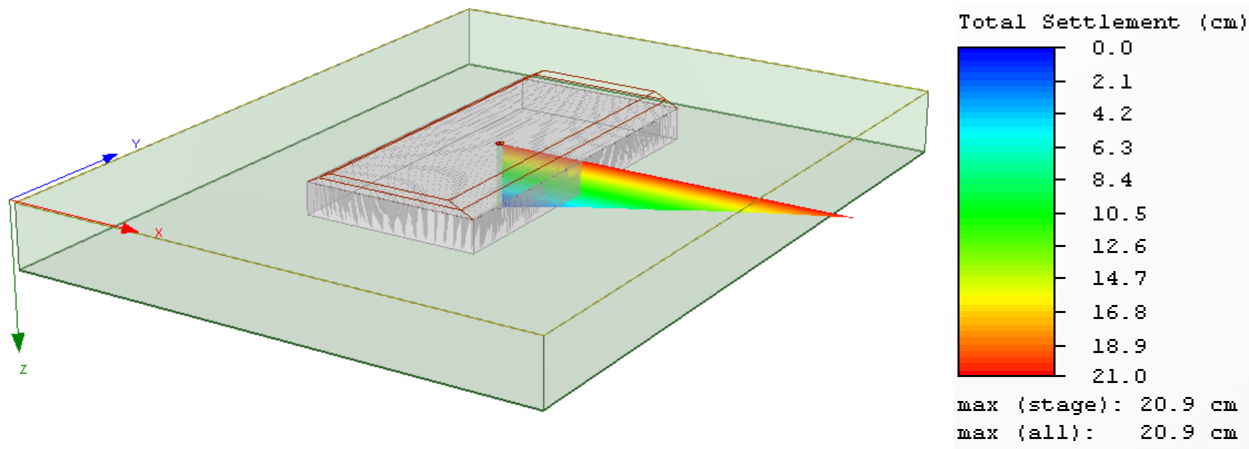


Figure 3: Settle3D Model after Vibro-Compaction using Westergaard Stress Method for Stress Computations

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Cubrinovski, M., and Ishihara, K. (1999). "Empirical Correlations between SPT *N*-Values and Relative Density for Sandy Soils," Soils and Foundations, Vol. 39, No. 5, pp. 61-92.

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