GROUND IMPROVEMENT CE: 632

Case Study 02: Ground Improvement using Pre-loading with prefabricated vertical Drains

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Introduction

- A container yard has been constructed at Chittagong Port, in Bangladesh. This site was located on the bank of the Karnafully river beside the Bay of Bengal in the Indian Ocean.
- The site covered an area of 60700 m2 and was designed to support load of 56 kPa.
- The geotechnical investigation of site revealed the presence of a soft to very soft clayey silt/silty clay layer at depths of 0 to 3.5 m below grade causing a settlement of around 200 to 450 mm throughout 1 to 5.5 years.
- A ground improvement work of pre-consolidation with the help of prefabricated vertical drain and preloading was designed and carried along with monitoring before construction of yard to minimize settlements during service period.

Subsurface conditions

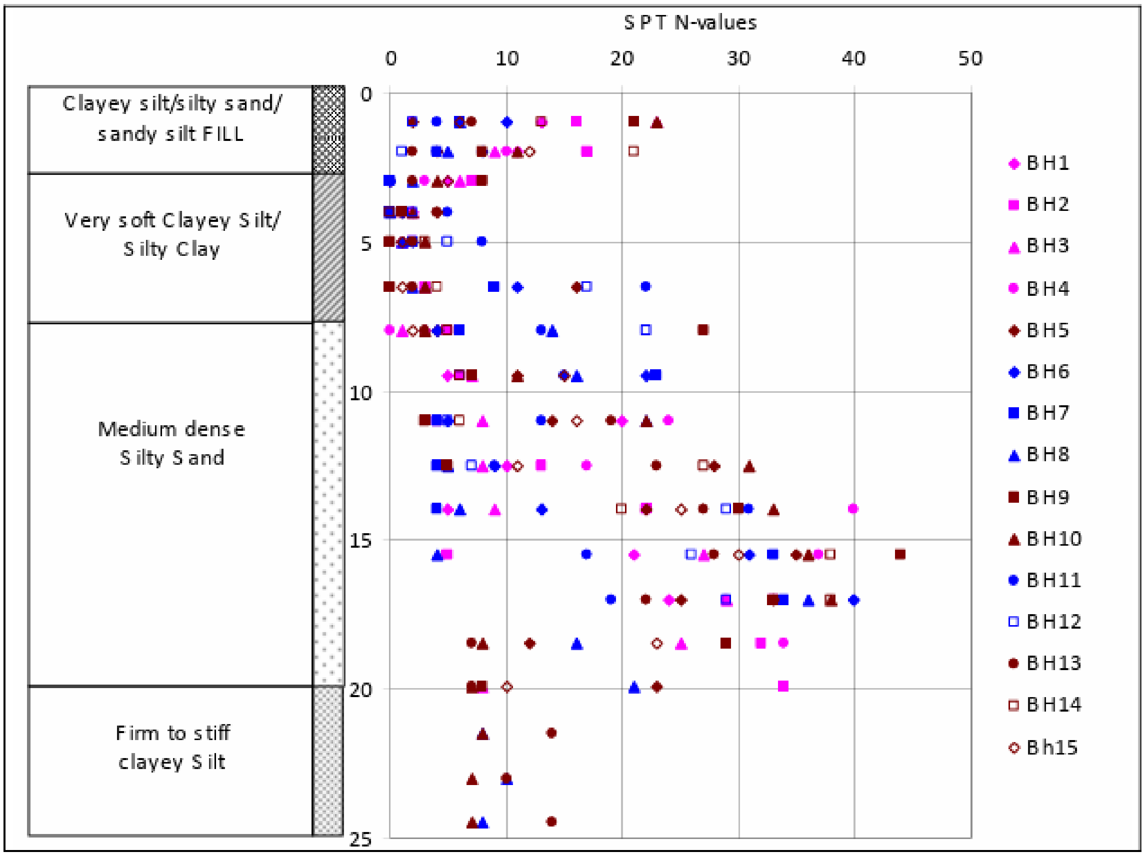
- The site for the container yard (Port Park area) is a tidal plain at a narrow strip between Chittagong hilly uplands and the Bay of Bengal. The surface geology of the site is mainly governed by shallow sea water and the floodplain activities of the river Karnafully and its tributaries
- The subsoil includes very soft to firm silty clay or clayey silt and fine-grained silty sand with some decomposed materials near the ground surface.

Figure 1: General ground profile along with SPT N-values (Ashutosh sutra Dhar et al. (2005))

Layer no.	Name of Soil	Thickness of layer
1	Light brown clayey silt/ Brown silty sand/ sandy silt	3.5 m
2	Very soft clayey silt/ silty clay	3-7 m
3	Medium dense silty sand	10-12 m
4	Firm to stiff clayey silt	5 m

- Table 1 : Layers of soil at site of project (Ashutosh sutra Dhar et al. (2005))

- From total of 15 boreholes, disturbed samples were extracted by using split spoon sampler during SPT



tests and undisturbed samples were retrieved from cohesive layers by pushing Shelby tubes.

Groundwater at site was located at depths of 0.3m to 3.4m below ground level.

Physical & Index properties of cohesive soil	Range
Water content	30-57%
Liquid limit	32-57%
Plasticity index	9-25%
Specific gravity	2.71-2.77
Bulk unit weight	20-23 kN/m3

Table 2 : Tests performed for determining properties of cohesive soil (Ashutosh sutra Dhar et al. (2005))

Laboratory tests

Physical and Index Properties

- Below physical and index properties of cohesive soil is tabulated,

Table 3 : Values of Physical & Index properties of cohesive soil (Ashutosh sutra Dhar et al. (2005))

- Based on index property tests, the subsoil in layer can be described as “low plasticity clayey silts” or “silty clay”

Name of test	Desired outcomes
Specific gravity test	Classification of soil as per USCS and Index properties
Atterberg limit test	
Wash sieve analysis	
Laboratory vane shear test	Shear strength of cohesive soil
Triaxial Test – CU & UU	
1-D consolidation test	Consolidation properties
CD Direct shear test	Shear strength of non-cohesive soil

Undrained shear strength

- In this section undrained shear strength values of silty clay/clayey silt are mentioned in following table

Test	Values
Vane shear test	26 kPa
Unconsolidated Undrained test	30 kPa

Undrained shear strength of cohesive soil from different tests (Ashutosh sutra Dhar et al. (2005))

- Based on values of undrained strength, soil can be described as “Very soft” to “soft”.

Compressibility and Permeability Parameters

- From nine shelby tubes retrieved from silty clay or clayey silt layer, the soil was used to determine the values of parameters by performing 1-D consolidation tests.

- The pre-consolidation pressures were less than ground stresses under the container yard, the coefficient of consolidation in the compression range was used for design of yard. The design value of coefficient of vertical consolidation estimated to be 7.5 m^2/year.
- The coefficients of vertical and horizontal permeability were estimated to be 0.047 m/year and 0.073 m/year ued in the design of drains.

Parameters	Range
Compression index	0.3
Recompression index	0.05 to 0.07
Initial void ratio	1.28
Preconsolidation pressures	30-50 kPa
Coefficient of vertical consolidation	2-21 m^2/year
Coefficient of horizontal consolidation	12-70 m^2/year
Coefficient of vertical permeability	0.032 -0.063 m/year
Coefficient of horizontal permeability	0.047 -0.095 m/year

- *Compressibility & permeability parameters of cohesive soil (Ashutosh sutra Dhar et al. (2005))*

Consolidation Settlements

- The classical one-dimensional consolidation theory of Terzaghi (1943) was used for calculation of consolidation settlements due to full design load (56 kPa) and time for consolidation.
- The maximum settlements due to design load of container yard were calculated to be 450 mm for 7 m thick layer and 200 mm for 3m thick layer of compressible soil.
- With the consolidation coefficient estimated from laboratory tests, the time required for 90% consolidation was estimated to range from 1 year to 5.5 years for 3m and 7m layers of soft soil, respectively.
- Preloading with vertical drains was considered and designed to accelerate the consolidation process.

Chapter 2: Ground Improvement

Design Assumptions

- Vertical drains are used to allow drainage in horizontal direction over a much shorter drainage path so that consolidation can take place in a shorter period of time.
- The theory of consolidation by radial drainage and by combined radial and vertical drainage is available in literature written by Barron (1948) and Hansbo (1960).
- The effects of vertical drains are analyzed by idealizing it as equivalent circular drain. An annular zone, called smear zone, is considered in soil surrounding the drain to account for the disturbace caused by installation of drain. The permeability of smear zone in vicinity of drain is reduced compared to native soil due to installation disturbance.
- The conventional design procedure for vertical drains provided by Hansbo (1979) and Holtz et al. (1987) is used for container yard project in Chittagong port.
- The diameter of smear zone ds is assumed as 3dw to examine smear effect in the design of the container yard. The smear effects can significantly reduce the permeability and coefficient consolidation. Thus, the value of coefficient of permeability of smear zone is considered as same as coefficient of vertical permeability for smear effect in design vertical drains.
- Also, the value of coefficient of horizontal consolidation can be less than coefficient of vertical consolidation due to smear effect. For design of ground improvement method for focused project work Cv = Ch was assumed.
- The presence of thin drainage seams or layers within silt/clay formation, may accelerate significantly the consolidation process. The presence of such layer was not considered during design in order to obtain upper bound value of time for consolidation.
- A settlement monitoring program was considered to observe consolidation was considered to observe consolidation with time so that the effects of acceleration (or deceleration) of consolidation can be incorporated during the construction (surcharge can be removed whenever consolidaiton is completed).

Design of vertical drains

- Maximum thickness of soft layer which was 7m was considered for design. Vertical drains were designed to install down to depth of approximately 9m below ground level to cover full depth of soft clay layer.
- The different options of vertical drains examined with time for 90% consolidation and cost are

Option	Consolidation Time (days)	Approximate Cost (Taka/ft^2)
(1) 200 mm diameter sand drain @ 1.5 m c/c in a square pattern	80	50
(2) PVDs (width = 100 mm, t = 4 mm) @ 1.0 m c/c in a square pattern	48	65
(3) PVDs (width = 100 mm, t = 4 mm) @ 1.5 m c/c in a square pattern	124	30

mentioned in the table below :

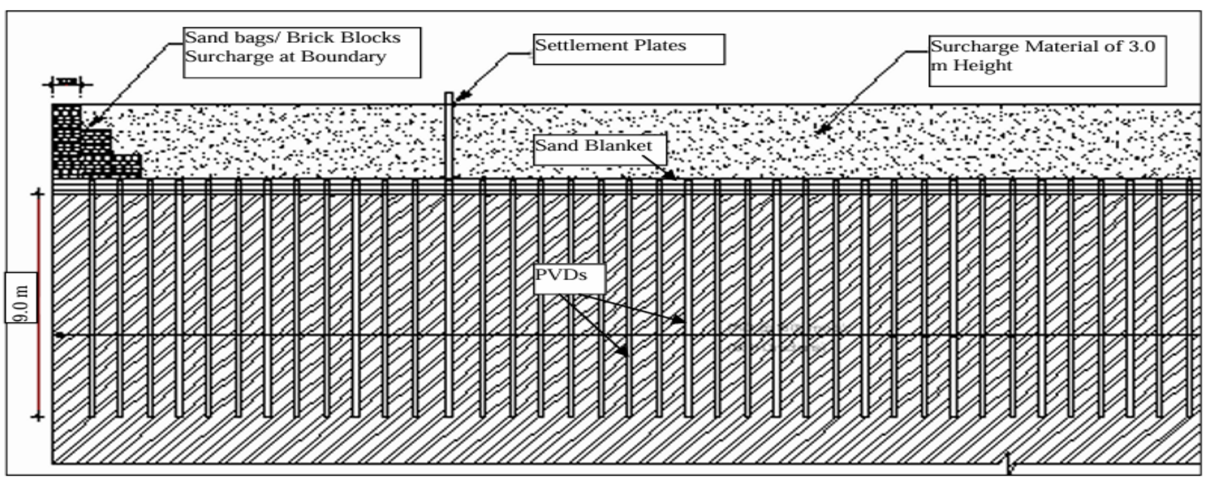
Different drainage options with 90% consolidation time & cost (Ashutosh sutra Dhar et al. (2005))

- Apparent opening size (AOS) of filter should be large enough to provide sufficient permeability, yet small enough to prevent fine particles of soil from entering filter and drain. The permeability of filter is expected to be larger than permeability of surrounding soil by at least one order of magnitude from consideration of clogging effects. Permeability of specified PVD (6310 m/year) was around 105 times greater than permeability of soil (k_h = 0.073 m/year). To prevent the penetration of fine particles, the design criteria given by Carroll (1983) was followed

Method of Construction:

- The construction of the ground improvement work involved preparation of the existing ground, placement of local sand to raise ground level where required, placement of a drainage blanket of coarse sand, installation of Prefabricated Vertical Drains (PVDs), and then pre-loading. Considering the large area (60700 m^2) of the container yard, the ground improvement work was accomplished in three segments with each segment consisting of approximately 20200 m^2.
- An approximately 150 mm thick local sand layer was first placed over the leveled ground after stripping of topsoil and unsuitable materials in order to attain the required grade for the container yard. The layer of the local sand was compacted using vibratory rollers to obtain a relative density of approximately 85%.

- A drainage blanket layer of 450 mm consisting of coarse sand placed over local sand to facilitate draining of water to be collected by PVDs and to compensate the settlement expected due to consolidation.
- During the placement of drainage blanket, the lower 250 mm of drainage blanket was placed before installation of PVDs to provide working platform for PVD installation and remaining layer placed after installation to allow drains to discharge into sand layer,.
- PVD were installed using a mandrel that provided minimum subsoil disturbances. A hollow mandrel or sleeve was advanced through the subsoil using vibratory, constant load, or constant rate of advance methods. The mandrel combined with the anchor had a maximum projected cross-sectional area of 70 cm^2. The anchor was used to remain in place at the bottom of the PVD when the mandrel was removed after installation.
- Thirty settlement measuring gauges were placed over sand blanket to measure the rate and magnitude of the settlements. A settlement gauge includes a base plate and a stand pipe. The base plate of the gauge was placed on top of the leveled granular layer, while the elevation of the top of the stand pipe was monitored (using a Surveyor's level) to obtain the ground settlements



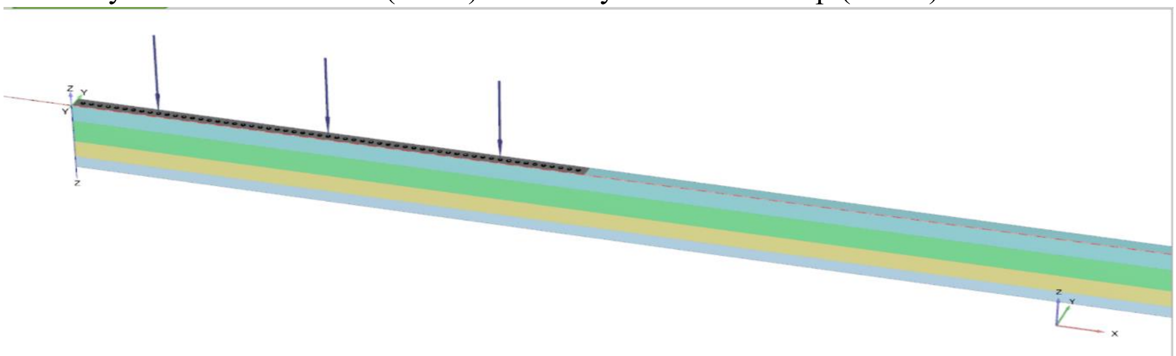
- Figure 2 : Detail of the ground improvement works (schematic) (Ashutosh sutra Dhar et al. (2005))

Chapter 3: PLAXIS analysis of the problem

Size and details of model

- Size of model = 60*2*25 m

- Location of borehole – (0 ,0 ,0)
- The PVDs were provided over length of 12m at 1 m c/c spacing.
- For application of surcharge, soil of density 18 kN/m^3 was considered and it was applied in the layers of 0.45m, 1.5m, 1.5m.
- Boundary conditions : The boundaries at XMin, XMax, YMax, YMin were ‘Normally fixed’. The boundary at bottom of model (ZMin) was ‘fully fixed’ and at top (ZMax) was ‘free’.



Soil layers in the PLAXIS-3D model

- Groundwater flow conditions:
- The boundaries XMin, YMin, YMax were ‘closed’ and remaining boundaries XMax, ZMin, ZMax were ‘open’.

Table 4 : Different soil layers with depth and soil model used for analysisGroundwater table considered at a depth of 3.0 m

Soil layer	Depth of layer	Soil model
1	0 to 3 m	Hardening soil
2	3 to 10 m	Soft soil
3	10 to 20 m	Hardening soil
4	20 to 25 m	Soft soil

Soil properties

Parameters	Layer 1	Layer 2	Layer 3	Layer 4
Drainage type	Drained	Undrained A	Drained	Drained
Unsaturated unit weight (kN/m^3)	16	11	17	15
Saturated unit weight(kN/m^3)	17	17	18	18
e_{init}	0.6	1.28	1.5	0.5
λ^*	-	0.057	-	0.05
κ^*	-	0.01142	-	0.01
Poisson’s ratio	0.2	0.3	0.15	0.15
Secant stiffness in standard drained	5000	-	7000	-

triaxial test (E_{50}^{ref}) (kN/m^3)				
Tangent stiffness for primary oedometer loading(E_{oed}^{ref})(kN/m^3)	5000	-	7000	-
Unloading/ reloading stiffness (E_{ur}^{ref})(kN/m^3)	15000	-	21000	-
Cohesion (kN/m^2)	5	30	1	30
Angle of internal friction	31	1	34	5
Dilation angle	0	0	3	0
Groundwater properties				
Classification Type	USDA	USDA	USDA	USDA
SWCC fitting method	Van Genuchten	Van Genuchten	Van Genuchten	Van Genuchten
Soil class (USDA)	Silt laom	Clay	Sand	Silt loam
k_x (m/day)	0.128	0.00128	1.28	0.108
k_y (m/day)	0.128	0.00128	1.28	0.108
k_z (m/day)	0.128	0.00128	1.28	0.108
Void ratio dependency (C_k)	None	0.2	None	None

Properties of soil used in the analysis

Phases used for analysis

Phases for analysis without Prefabricated vertical drains

Parameters	Initial phase	First construction	First consolidation	Second construction	Final consolidation
Activated volumes	All soil layers	All soil layers with surface load	All soil layers with surface load	All soil layers with surface load	All soil layers with surface load
Calculation type	K0 procedure	Consolidation	Consolidation	Consolidation	Consolidation
Loading type	Staged construction	Staged construction	Staged construction	Staged construction	Minimum excess pore pressure
Pore pressure calculation type	Phreatic	Phreatic	Phreatic	Phreatic	Use pressure from previous phase
Time interval (days)	-	2.0	40	2.0	-

Surface load (kN/m^2)	-	36.1	36.1	64.1	64.1
P-stop (kN/m^2)	-	-	-	-	6.41

: Phases generated for modelling the case study

Phases used for analysis with Prefabricated vertical drains

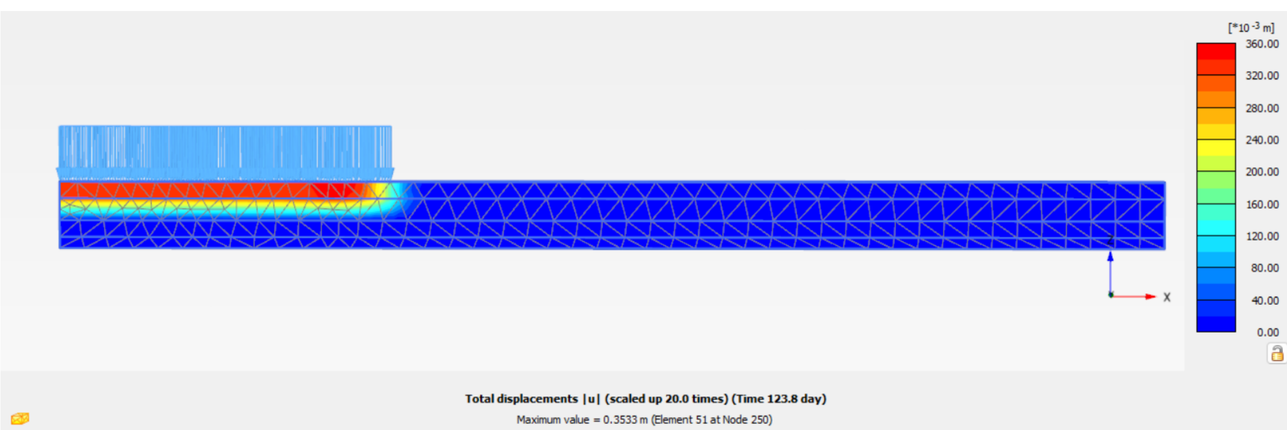
- All phases are generated in same fashion as for analysis without drains i.e. construction and then consolidation.
- For first construction phase, only sand blanket load of 250mm thick layer was applied and drains were activated. Then for second construction phase load equivalent to remaining 200 mm thick sand blanket was applied. The drains were kept on till final phase.
- All construction phases were having duration of 2 days and consolidation phase of sand blanket load application (first & second construction phase) was having also having same time interval.
- For consolidation phase after 1.5 m surcharge application (Third construction phase), time interval was 20 days.
- For final consolidation phase after final layer (1.5 m) of surcharge application, Excess was limited to 6.41 kPa.

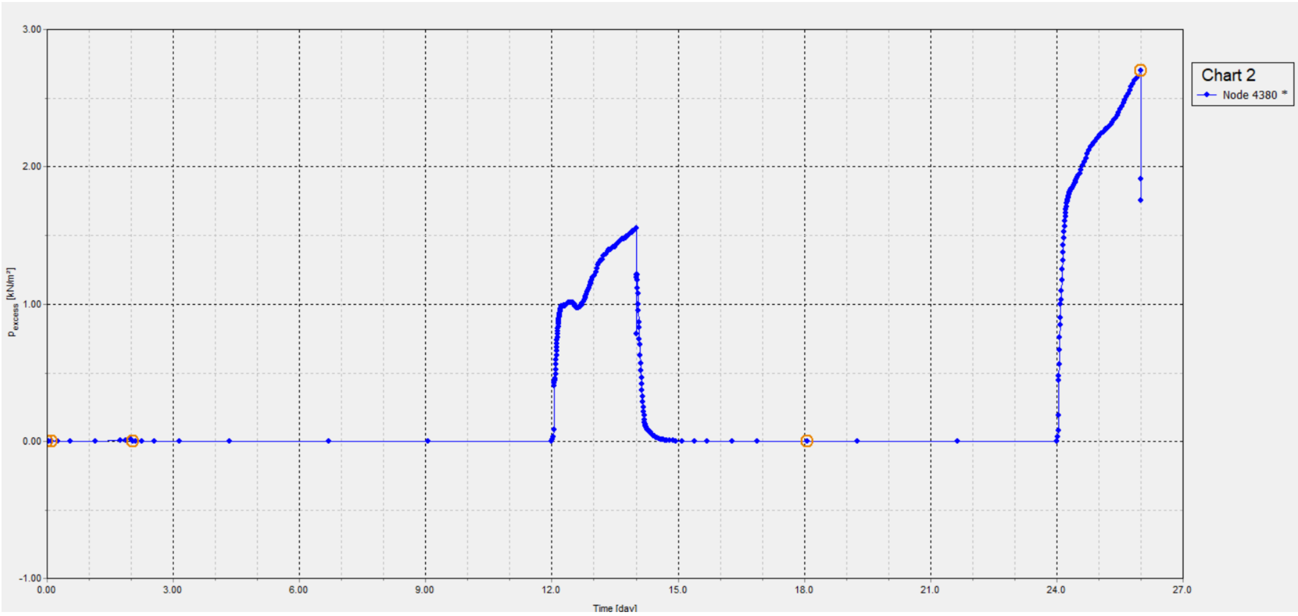
Calculation results

For analysis without the provision of PVDs

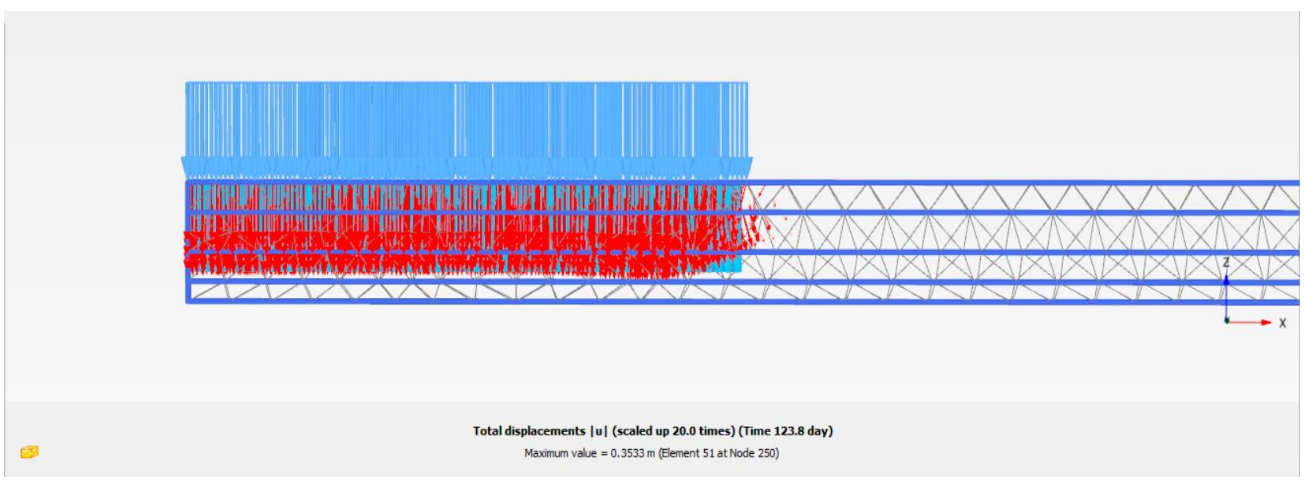
- Maximum settlement – 353 mm, Time taken for 90% consolidation – 123.8 days

Distribution of displacements in soil (Analysis with PVDs)

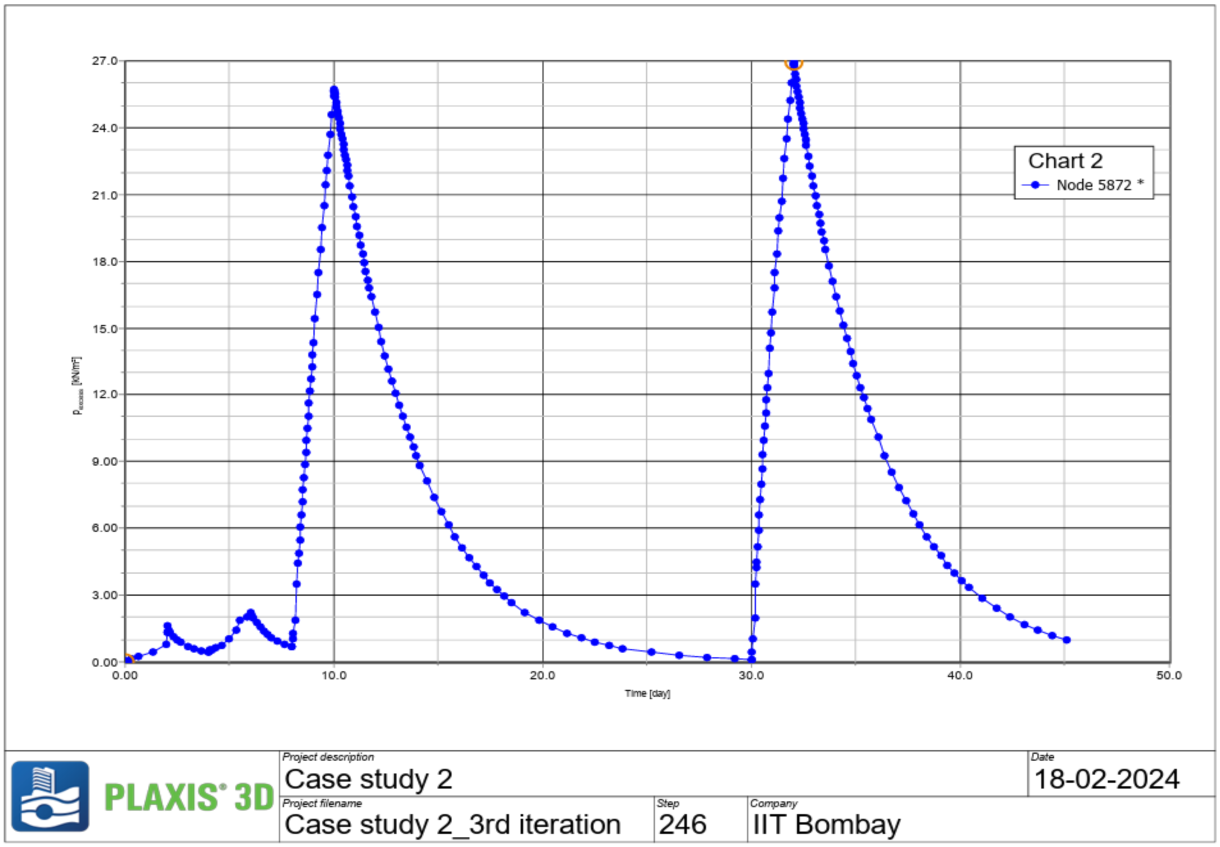




3.00
2.00
1.00
0.00
-1.00
p_{excess} [kN/m²]
0.00
3.00
6.00
9.00
12.0
15.0
18.0
21.0
24.0
27.0
Time [day]
Chart 2
Node 4380 *



Z
X
Total displacements |u| (scaled up 20.0 times) (Time 123.8 day)
Maximum value = 0.3533 m (Element 51 at Node 250)



Variation of excess pore pressure with time (Analysis without PVDs)

Conclusion

- Detailed laboratory investigation was useful for determining geotechnical design parameters which were used for analysis of consolidation and design of prefabricated vertical drains.
- Classical theories of consolidation and Hansbo theory of radial drainage was beneficial as calculated values or designs using these theories were giving satisfactory overlap with monitored readings.
- The consolidation time calculated by considering smear effect provided lower bound and by without consideration of smear effect provided upper bound.
- After accounting for smear effect, the assumptions made for coefficient of permeability and consolidation were satisfactory for container yard project.
- As vertical drain had very high discharge capacity as compared to required for consolidation, the effect of drainage congestion can be neglected.

- The installation of vertical drains reduced pre-consolidation time significantly. (from 1 to 5.5 years without vertical drains to about 50 days with PVDs.)

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