Prefabricated Vertical Drains to dissipate excess pore pressures during Dynamic Compaction of Clayey Sands with 30-45% Fines Content

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ABSTRACT: A proposed Electric Vehicle (EV) assembling facility, located in the Eastern Seaboard of Thailand, required soil improvement to enhance the mechanical properties of the clayey sands (SC). Albeit not the ideal soils for energy densification, Dynamic Compaction (DC) + Prefabricated Vertical Drains (PVD's) were chosen as the most suitable Soil Improvement technique to increase the strength of the soil and reduce the future differential settlements resulting from the loads onto the proposed slab-on-grade foundation structure. Given the presence of the water table within reach of the DC influence, and the high fines content of the soil (30% to 45%), PVD's in advance of DC were designed to quickly dissipate the excess pore pressures resulting from the dynamic compaction operations and hence, allow the continuation of the works without the risk of loss of strength in the soil and thus, reducing the dissipation times from 30 to 60 days (without PVD's) to about 2 to 4 days (with PVD's). Instrumentation of Cone Penetration Tests (CPT's), standpipe and vibrating wire piezometers were installed at the project. This paper focuses on the role of the PVD's as drainage elements for the quick bursts in pore pressure and the results are presented herewith.

KEYWORDS: Prefabricated Vertical Drains, Dynamic Compaction, Pore Pressure Dissipation, Soil Improvement, High Fines Content

1. INTRODUCTION

As automotive industry expansion continued to take place in the 90's and early 2000's in Thailand, (Warr, 2017) and the establishment of the deep-water port of Laem Chabang (120 km southeast from Bangkok) it led to the further investment and establishment of the Eastern Seaboard Economic Corridor (ESEC). Two decades into the 21st century, and as the world gradually shifts from fossil fuel energies to renewables, an increase in the demand of Electric Vehicles (EV) has pushed forward the necessity for available land within the Economic Corridor for EV companies to establish their assembly facilities.

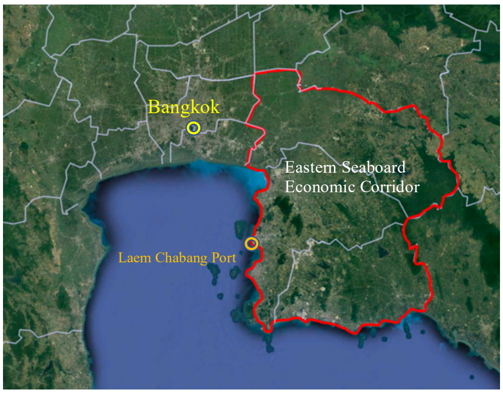


Figure 1 Google Earth Imagery depicting Thailand's ESEC and key locations

1.1 EV Plant Project

The EV Plant Project has a total area in excess of 400,000 m^2, located within the ESEC in a formerly rural land that has been turned into an Industrial Estate of *circa* 300 Ha. Between 2021 and 2022, the land was backfilled, mass graded and completed to meet the Industrial Park Developer's requirements. The EV Plant Project, within the Industrial Estate, is located in a topographical natural setting characterized by rolling hills ranging from an elevation as low as El. +84.0 (IND1975) *[all vertical elevations forward in this text are referred to this Datum]* to as high as El. +97.0m, featuring soil cuts as much as 4.0 m thick and fill in other locations as much as 9.0 m.

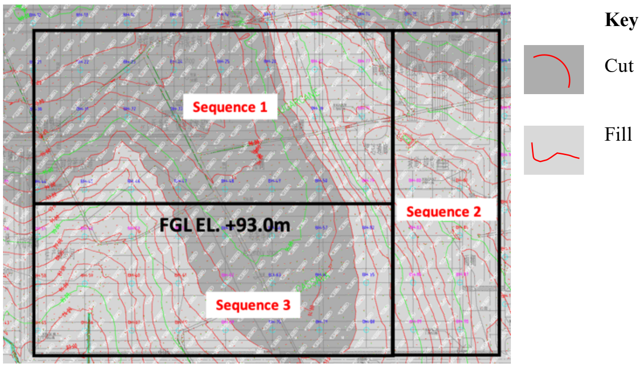


Figure 2 General Plan View of the EV Site

After been graded by the earth moving contractor, the plot of the EV Plant Plot was leveled at a Finished Ground Level (FGL) of El. +93.0m. The footprint of the buildings and main structures would occupy an area *circa* 130,000 m^2 (Rojana 2022). Notwithstanding the site being handed over to the Client, the subsurface layers lack the engineering properties (compaction, soil bearing capacity and settlement limitations) for industrial use, let alone for the support of Assembling Facilities, (i.e., Paint Shop, Welding Shop, etc.) required at the future EV Plant.

1.2 Necessity of Ground Improvement

The site was handed over to the Ground Improvement Contractor with the objective of enhancing the engineering properties of the soil, for both cut and fill areas underlying the FGL of EL. +93.00 m. As per the site investigation carried out after completion of the mass grading works, it was noticeable, albeit some areas of native material (cut) had substandard engineering properties, it was more prevalent the lower engineering properties were found in the areas where the contractor had already backfilled. The challenge was to arrive with a Soil Improvement method and solution that could deliver the compacting energy required to meet the density requirements; yet be mindful of the extremely high fines content that would be detrimental to the energy compaction effort. As pointed out by Han (2015), deep dynamic compaction is generally not recommended for clayey soil and high degree of saturation.

Figure 3 Soils and Overview at the EV Project site

An in-house design (CeTeau BV, 2022) was made by combining the energy delivered by the Dynamic Compaction to reach the underlaying low density layers along with a solution of Prefabricated Vertical Drains (PVD's), installed before the DC, to release the excess pore pressure mobilized by the DC loading. The key element consisted in installing the PVD's to reach the underlying high permeability layer (sandy layer with lower Fines Content at a depth ranging from 6.5m to 8.5m) so that the excess pore pressure could reach a shorter path to the PVD's and be released to the lower drainage layer. At some areas of the project, this lower layer was not present; hence, the excess pore pressure could be released directly up to the surface.

As pointed out by Slocombe (2013), efficient [Dynamic Compaction] treatment is achieved by attempting to provide as much improvement as quickly as possible, while recognizing that the response of the soils will dictate the speed of the treatment operations, and that was precisely the driving factor for the EV Plant Project.

2. SITE CONDITIONS

2.1 Soil Borings & CPT's

At handover and before improvement, the site was flat, leveled, filled in with native nearby soils that clearly appeared to be dry, clayey to silty sands with variable content of fines. Water content was in the vicinity or below the Plastic Limit (clayey samples).

Within the footprint of the EV project, more than fifty (50) soil borings were drilled, and samples were typically taken nearly continuously or every 1.5m in some cases (JLP Engineering Services, 2022). The depth of the borings ranged from 10 to up to 20 m with main Index geotechnical testing being performed, including Unit Weights, Atterberg Limits (where applicable) Moisture Content, Sieve Analysis, etc.

The soil could be characterized as Silty Sand (SM) to Clayey Sand (SC) but with very high fines content, ranging from 30% to as much as 50%+, and at times, some layers were turning into Sandy Silts (ML) or low plasticity Sandy Clays (CL) [Fines Content greater than 50%].

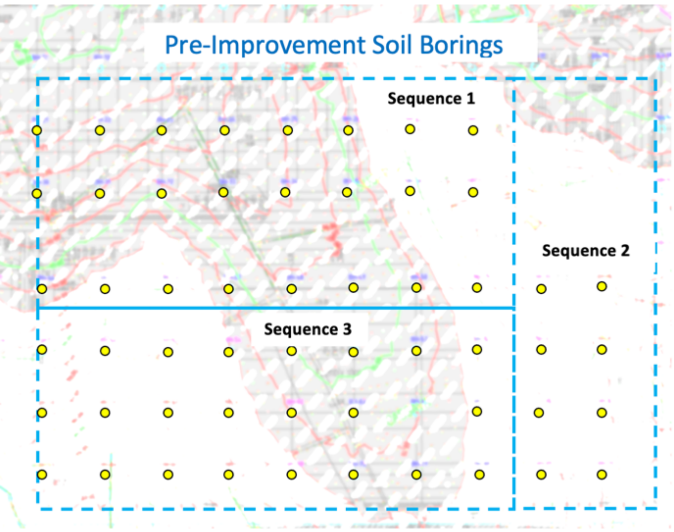


Figure 4 Plan view of Pre-Improvement Soil Borings

2.2 Water Table

According to the extensive site investigation campaign prior the start of the soil improvement works, water table (dry season) was established to a depth of between 4.5m to about 7.0m across the site.

2.3 Fines Content

Plots of Fines Content vs. Depth were produced and in them it was clear the trend of a FC with a moving average of around 40% with a standard deviation of +-10%. The highest fines content was observed mainly under the surfaced to a depth of about 1.0m and between 4.5 to 5.0m. One thing, and this was instrumental to recommending the PVD's in advance of the DC, was the fact the content of fines generally dropped at a depth of around 6.5 to 7.0, thus presenting a higher permeability layer at depth.

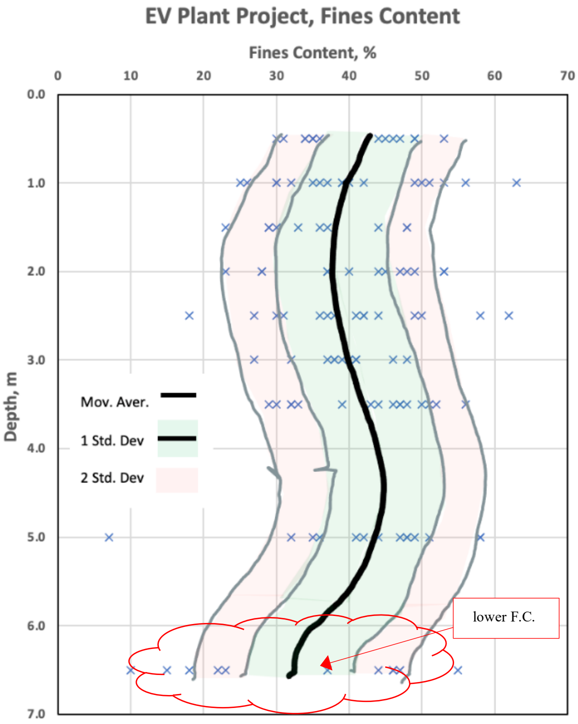


Figure 5 Fines Content profile of the site

Having accounted a good portion of the laboratory passing #200 sieve (Fines Content) the Frequency Distribution corresponded to:

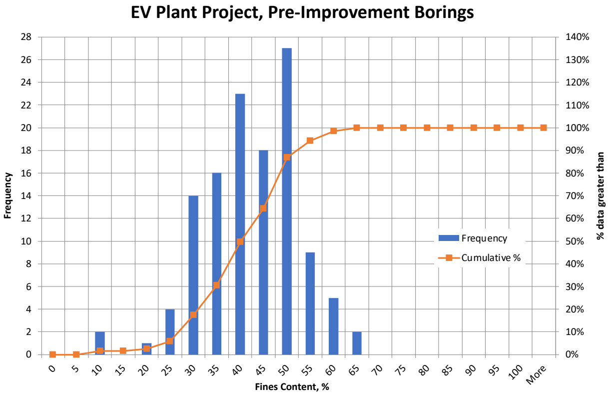


Figure 6 Frequency Distribution chart - Fines Content

50% of the data had Fines Content (FC) of less than 40%
15% of the data had Fines Content (FC) between 40% & 45%
25% of the data had Fines Content (FC) between 45% & 50%
10% of the data had Fines Content (FC) above 50%

That would essentially be laying out our solution to be more effective for about 65% of the soils and slightly less effective (Fines Content between 45% and 50%) for 25% of the soils, with 10% of the soil layers being technically "clays" and hence the solution, by definition, being marginally effective or inadequate.

3. DYNAMIC COMPACTION

Dynamic Compaction (DC) is one of the oldest methods for soil improvement. The DC method has been used successfully in projects with varying soil conditions and depths that is used to increase the density of the soil when certain subsurface constraints make other methods inappropriate.

3.1 Range of Suitable Soils

Although DC is favorable to many types of soils, it is certain that the effectiveness of the method diminishes with the increase in Fines Content. Trials are recommended to be undertaken to verify the effectiveness of the compaction with high fines content.

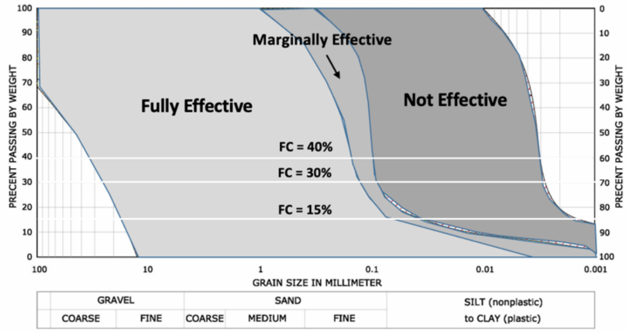


Figure 7 Suitability of soils for Dynamic Compaction

3.2 Equipment

The equipment for Dynamic Compaction consists of two elements, the crane, and the tampers. The tampers are available with different masses. The mass of tampers is in a range of 8 to 30 metric tons and the drop heights range from 5 to 30m (Lukas, 1995). Lighter tampers and smaller drop heights results in depths of improvement between 3.0 to 4.6m. Heavier tampers and greater drop heights are showing improvement depths up to 10m.

Figure 8 Crane and tampers for Dynamic Compaction

3.3 High-Energy Tamping

The process involves the dropping of a heavy weight repeatedly on the ground at regularly spaced intervals by means of crawler crane. The repeated application of the high energy impacts causes deep compaction in a soil mass.

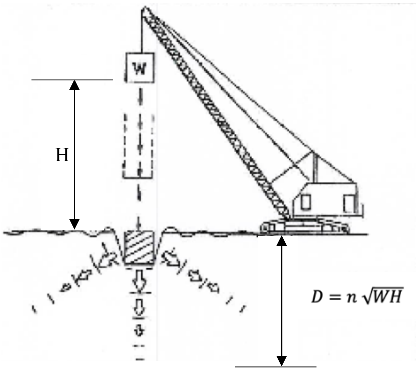


Figure 9 Depth of Improvement [from FHWA-SA-95-037]

Densification occurs by rearrangement of the soil particles or collapse of voids within the soil mass. The impact of the free fall creates stress waves that help in the densification of the soil. These stress waves can penetrate up to 10m. In predominately sandy soils, these waves create liquefaction that is followed by the compaction of the soil (Abramson, (1994).

The craters that are created by the tampers may reach depths up to 2m depending on the height and the mass of the tamper (Denies 2012). The degree of improvement of the soil is a function of following parameters: Tamper mass and drop height for required depth of improvement. The relationship between these figures is shown in equation below:

$$D = n\sqrt{WH} \qquad (1)$$

D = depth of improvement
n = empirical coefficient that varies from 0.3 to 0.6 and is primarily dependent on soil type
W = tamper weight in tons
H = drop height in meter

Applied Energy,

$$AE = \frac{NWHP}{S^2} \qquad (2)$$

AE = Applied energy per m^2
N = Number of drops at each specific drop point location
W = tamper mass
H = drop height
P = number of passes
S = Grid Spacing

It is common to perform the work in two or more phases or passes. The number of drops on one grid point location can be limited by the depth of the crater.

3.4 Low-Energy or "Ironing" Phase

After the "high-energy" tamping the "low-energy" or "ironing" phase is generally used to densify the crater backfill and the disturbed soil between the craters. During that phase the tamper is typically dropped from a height of 3-6 m.

4. PVD'S + DYNAMIC COMPACTION

PVD's are a soft soil technique whereby the drains are introduced to shorten the path of the water during a consolidation process. Typically, the soil's horizontal consolidation coefficient for horizontal flow, C_h, along with other design and project-specific parameters are needed to calculate the time required to reach a given percentage of consolidation. A common industry standard to determine consolidation parameters, including the time to dissipate the excess pore pressure which is important matter for this case, is to follow Barron's radial consolidation solution (1948) for sand drains, modified by Hansbo's (1981) to account for PVD's properties and geometry, so that design is being made to reduce the consolidation time from years (naturally occurring) to a matter of months (typically) with the PVD's, whereby, the load is applied by surcharge, vacuum consolidation, or a combination of both.

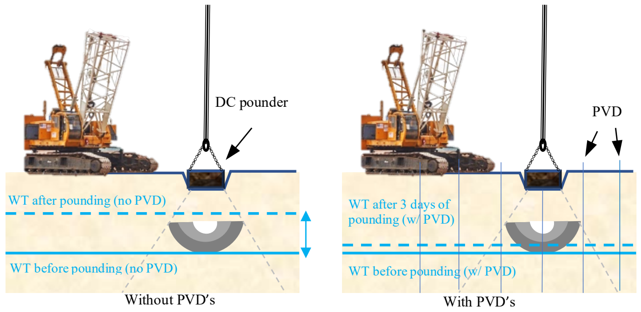


Figure 10 Sketch showing the difference between DC+PVD vs. DC only

For the case of the EV Project, the PVD's were designed to equally reduce the path of the water, yet not from a consolidation process, but from cyclic loading mobilized in the soil particles from Dynamic Compaction, and the resulting pore water pressure increase during tamping. Some authors call it Dynamic Consolidation for Clays (Slocombe, 2013), but in the case of the EV Plant Project, we were not really dealing with clays, but rather with sands with a significant fines content.

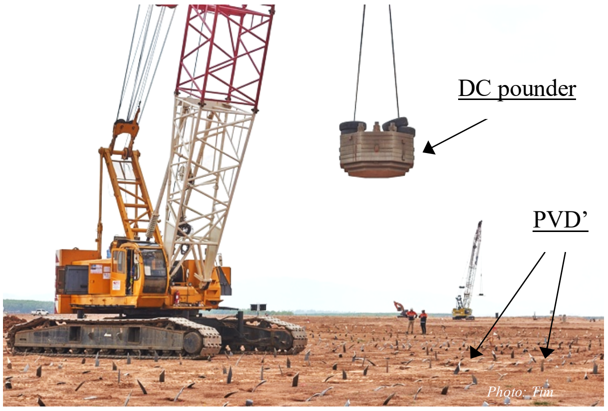


Figure 11 Dynamic Compaction works after PVD's are installed

4.1 Design Aspects

Barron's Hansbo formula (1981) could not be applied here as the application of the load was dynamic and cyclic and the formulae was developed for a low strain steady horizontal flow.

Figure 12 PVD draining through the surface during DC operations

Thus, bearing in mind the spacing for both the Primary and Secondary passes were 6 m (secondary pass is offset 3 m to target the points in between the primary pass), then the natural thing was to have a PVD design spacing that would be easy to layout and yet, achieve the main goal of accelerating the excess pore pressure dissipation from the Dynamic Compaction works; hence, a Trial would prove to be the best way forward to adjust the design grids. As a result, two (2) grids of PVD spacings were Trialed at the site: 1) one with PVD's at 3m spacing and the other one with 1.5m spacing (all of them in a rectangular fashion). The Trial area was chosen in the "fill" area with soil conditions representative of the rest of the site.

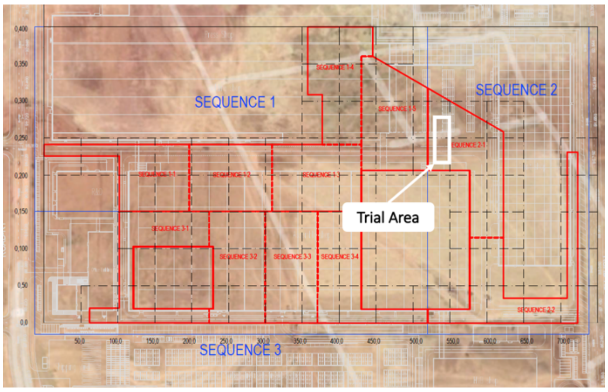


Figure 13 DC+PVD Trial Area (base drawing by Meinhardt (Thailand), 2022)

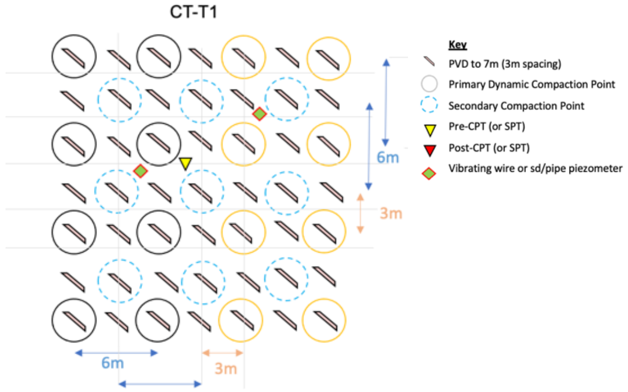


Figure 14 DC+PVD Trial Grids (PVD at 3.0 x 3.0m) - EV Project

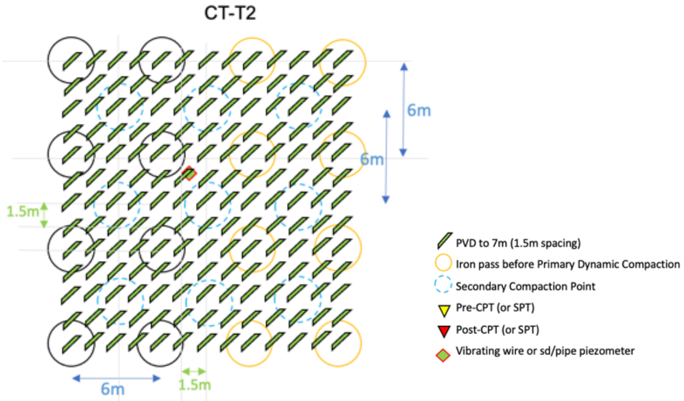


Figure 15 DC+PVD Trial Grids (PVD at 1.5 x 1.5m) - EV Project

4.2 Draining through underlying permeable layer

Densification of silty sand deposits containing high silt contents appears to be feasible only when these techniques are supplemented with wick drains Traditionally, field design of these approaches rely on site specific field pilot trials and/or past experience based on case histories (Thevanayagam, 2016).

For soft soils (consolidation problem), water plus air present in the soil pores, typically flow radially under the vertically downward pressure from the surcharge (in case of PVD + Surcharge) or radially inward pressure (when subject to PVD + Vacuum Consolidation). Once the difference in pressures is established, the water finds its way to the shortest path to reach the high permeability PVD, then escapes either to the surface (single drainage) or through the surface and a lower higher permeability layer (double drainage).

For the case of the DC + PVD for coarse grained soils, the geotechnical hazard is completely different (densification problem) but the ultimate effect (release of pore pressure) is the same. The difference in pressures is fast paced, dynamic and cyclic; hence, the role of the PVD is to serve as bridge to release the excess pore pressure and find its way out to a drainage layer. For the case of the EV Project, we focused the attention in draining through the underlying higher permeability layer present at a depth of around 6.5m to 8.5m, or else (when underlying drainage layer not present) to the surface.

4.3 Pore Pressure results from the Trials

Having installed the PVD's in the two (2) different grids, and prior installation of standpipe and vibrating wire piezometers, Dynamic Compaction works proceeded with the energy designed parameters. The area of the PVD grid of 3.0m spacing (CT-T1) showed a very slow pore pressure dissipation, nearly comparable to the case of No-PVD. On the other hand, the area where the PVD grid was 1.5m, there was a substantial reduction in the dissipation time of excess pore pressure. There were some instrument malfunctions and an attempt to install PVD's at 1.5m x 1.5m at the CT-T1 area, which proved to be ineffective, perhaps emphasizing the point that in order for the method of PVD+DC method to work, PVDs must be installed prior the beginning of Dynamic Compaction works.

The trials demonstrated the excess pore pressures were quicky dissipated in a matter of 2 to 3 days for the case where the PVD's were installed at 1.5m spacing prior the DC works whilst it showed a slow dissipation (about 35 days from day 7 until approx. day 42) on the areas where PVD spacing was 3.0m. It is important to note that once we realized the dissipation was slow in this Trial area, we went ahead and installed further PVD's to match the neighboring area. Nonetheless, the installation of those PVD's after the energy had already been delivered to the ground proved to be ineffective.

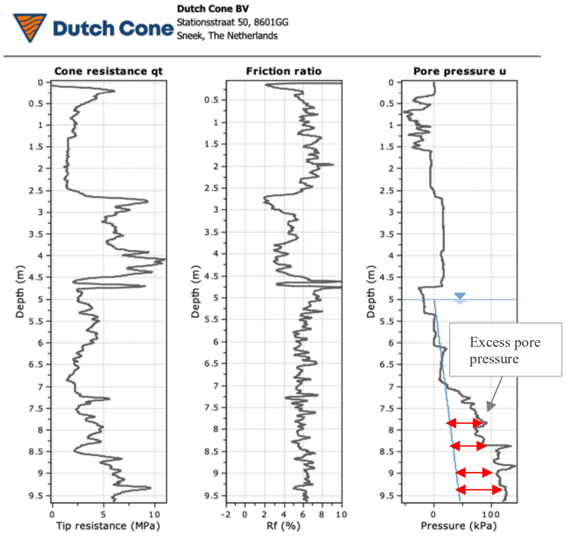


Figure 16 CPTU Log Post Pass 2 at EV Project

As shown in the above Post Improvement CPTU (Dutch Cone BV, 2023), the excess pore pressure remained below the depth of the PVD's (7m). Note the extremely high fines content by means of the Friction Ratio, R_f, with values between 4.0% and 6.0%. R_f is expressed as a percentage, of the sleeve friction resistance, fs, to the cone resistance, qt, both measured at the same depth (Lunne 2002, and Robertson, 2022)

$$R_f = \frac{fs}{q_t} \; x \; 100\% \qquad (3)$$

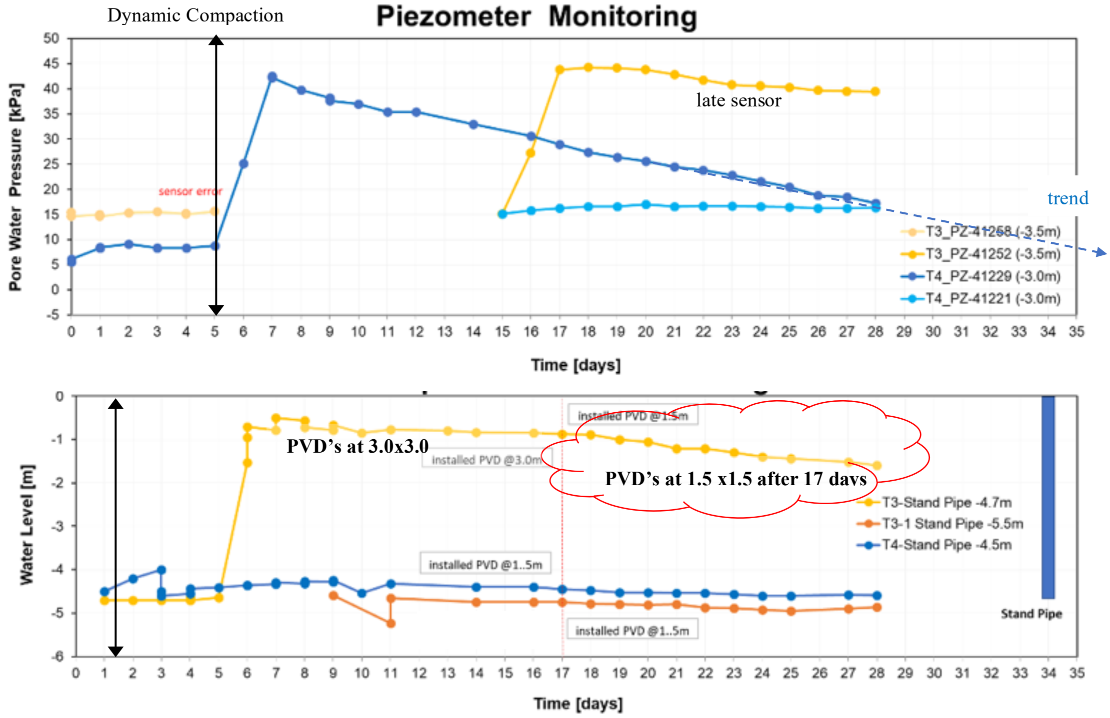


Figure 17 Piezometer readings at Trial areas

4.4 Construction Sequence & Observations

Following the results of the Trial, production works proceeded with the following general sequence:

1. *Advancing Pre-improvement CPT's (correlation between SPT & CPT to establish baseline);*
2. *Installing PVD;*
3. *Installing standpipe and vibrating wire piezometers*
4. *Undertaking Primary Pass of Dynamic Compaction*
5. *Monitoring of energy levels, crater depths, and vibrations at different distances;*
6. *Monitoring excess pore pressure dissipation;*
7. *Covering craters and mass grading;*
8. *Undertaking Secondary Pass of Dynamic Compaction on an offset grid;*
9. *Monitoring excess pore pressure dissipation;*
10. *Covering craters and mass grading;*
11. *Undertaking Low Energy or Ironing pass to ensure upper soils get the necessary compaction;*
12. *Grading;*
13. *Advancing Post-improvement CPT's to verify compliance of criterium;*

In some areas of the project, after Pass 1 or Pass 2, upper flow of water to the surface was observed; nonetheless, most of the areas (called Sequences in the EV Project) the water did not reach the surface. Most likely the areas of surficial flow coincided with the absence of lower drainage layer or being located in an area with high fines content throughout the whole soil column.

Figure 18 Detail of PVD in advance of Dynamic Compaction

Vibration monitoring was also undertaken at different stages of the project to establish a baseline of safe Peak Particle Velocity (PPV) and Frequencies within which no detrimental vibration could hamper other construction activities being taken place at the time of the Dynamic Compaction works, nor damage the integrity of other structures (i.e., road and box culverts already constructed at the boundary).

Through mid-progress of the works rainy season started; contrary to the believe the precipitation would significantly influence the dissipation times, indeed, it increased the piezometer readings, but influenced only marginally the dissipation by a few extra days.

Figure 19 Vibration monitoring during DC works

The data plotted proved the Peak Particle Velocity decay inversely proportional to the distance of the source of vibration (CeTeau, 2023).

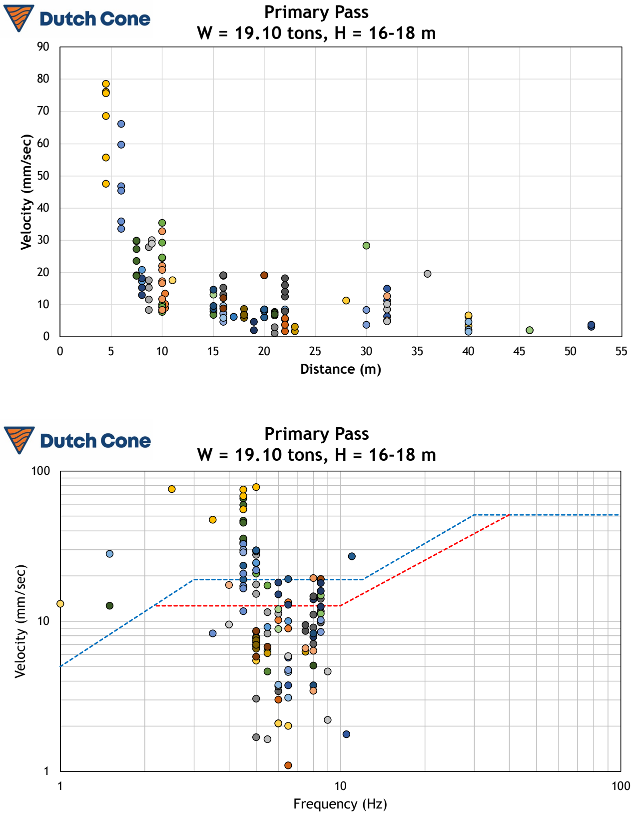


Figure 20 PPV vs Distance & vs. Frequency plots at the DC EV Project (Sinkind 1980, Alternative Blasting Level Criteria, US Bureu of Mines)

5. PIEZOMETER READINGS

5.1 Scope & description

Two types of piezometers were installed in the project site; (1) standpipe piezometer, which consists of a perforated pipe inserted into a borehole. This allows the water to enter the pipe, and the water level inside corresponds to the groundwater level, and (2) vibrating wire piezometer, which measures pressure through the resonance frequency of a vibrating wire. Changes in pressure affect the tension in the wire, subsequently altering its frequency. This change is measured and converted to a pressure reading.

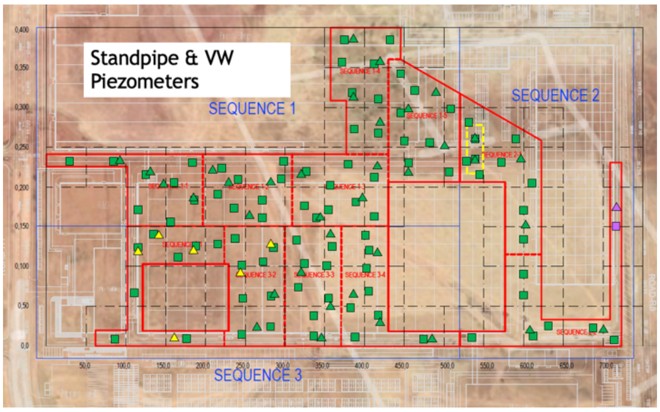


Figure 21 Plan view of Standpipe and Vibrating Wire Piezometers

A total of one hundred eighteen (118) standpipe piezometers were placed across the site, with one standpipe piezometer installed for every 1,250 m^2. These piezometers were installed at depths of -5.50m to -8.50m below the ground surface. Furthermore, a total of forty-nine (49) vibrating wire piezometers were installed, with one vibrating wire piezometer allocated per 2,500 m^2. The installation depth of these piezometers ranged from -2.50m to -7.00m, depending on the characteristics of the underlying soil layers.

5.2 Piezometer Readings area without PVD’s

A dedicated area within the project site, in which PVD’s were not installed, was chosen to monitor the piezometer levels.

The data of water levels vs. time was perfectly fitted to a logarithmic regression (R^2=0.988) although it could also have been fitted to a linear regression (R^2=0.94). Nonetheless, the data proved for the area without PVD’s and the soil mass having received Pass 1, Pass 2 and Ironing Pass, showed it required 65 days (from Day 17 until day 82) for the water levels to return again to the equilibrium.

The following were the observations:

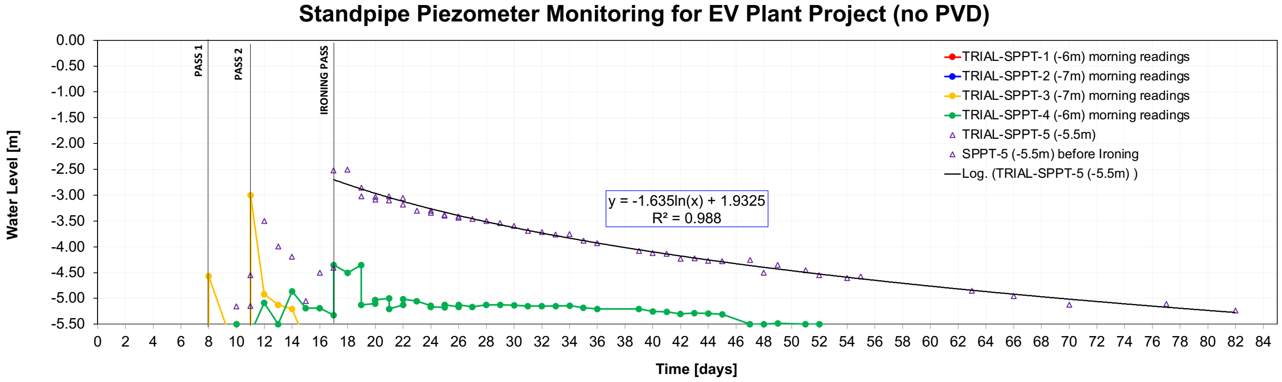
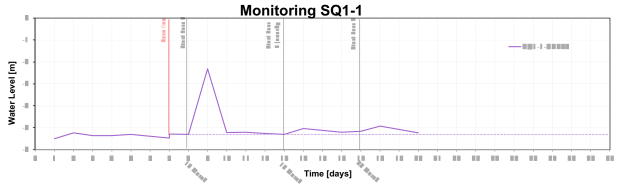


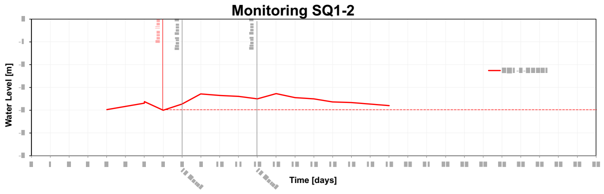
Figure 22 Piezometer readings Dedicated Test Area (Dynamic Compaction without PVD's)

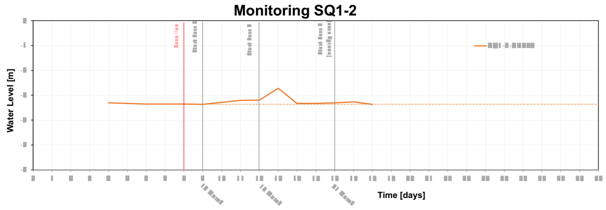
5.3 Piezometer Readings area with PVD's

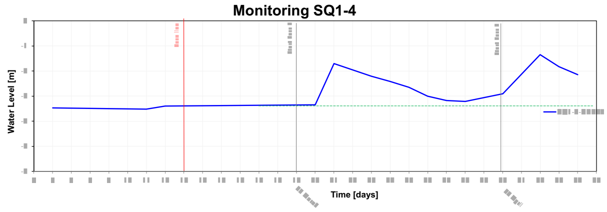
Several piezometer data from the production area of Dynamic Compaction plus PVD area are presented herein; vertical lines indicate the Pass 1, Pass 2 or Ironing Pass. As seen in most of the water levels recorded through the different areas (Sequences, SQ), excess pore pressure dissipated in less than 4 days after Dynamic Compaction energy tamping, enabling the continuation of the different passes without reduction of effective stress and loss of strength of the soil.

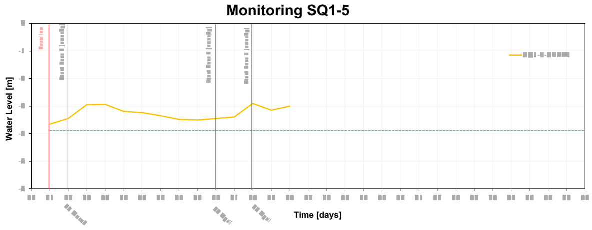
Figure 23 PVD Rig (foreground) and DC Rig (background) at the EV Project

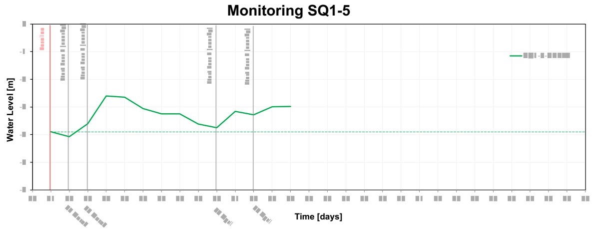


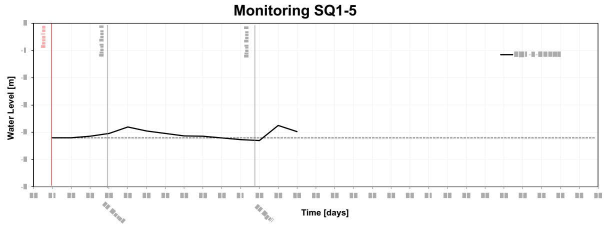


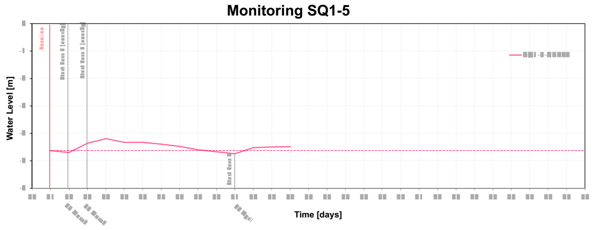












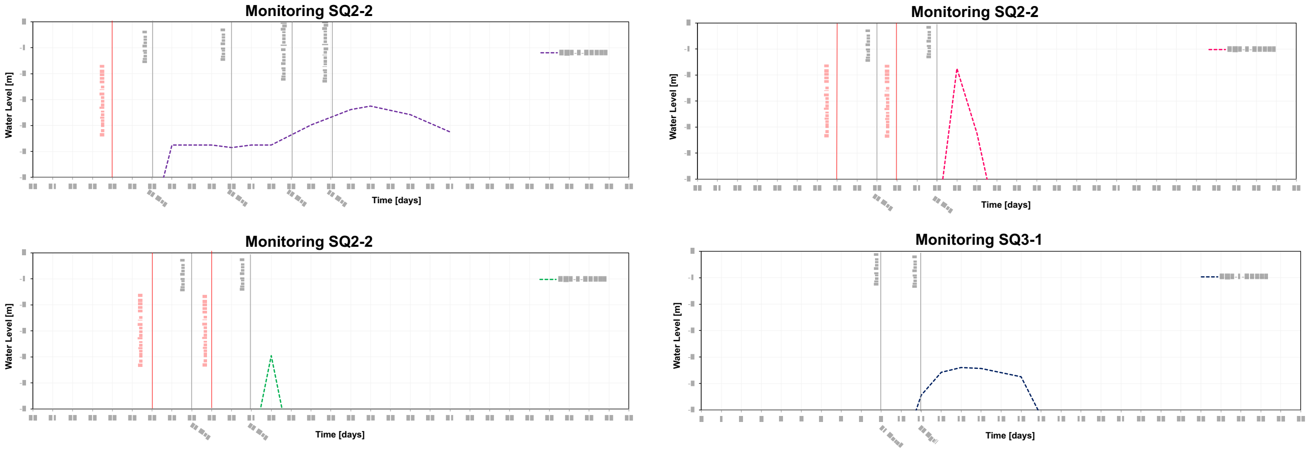


Figure 24 Standpipe Piezometer Monitoring (with PVD) EV Plant Project

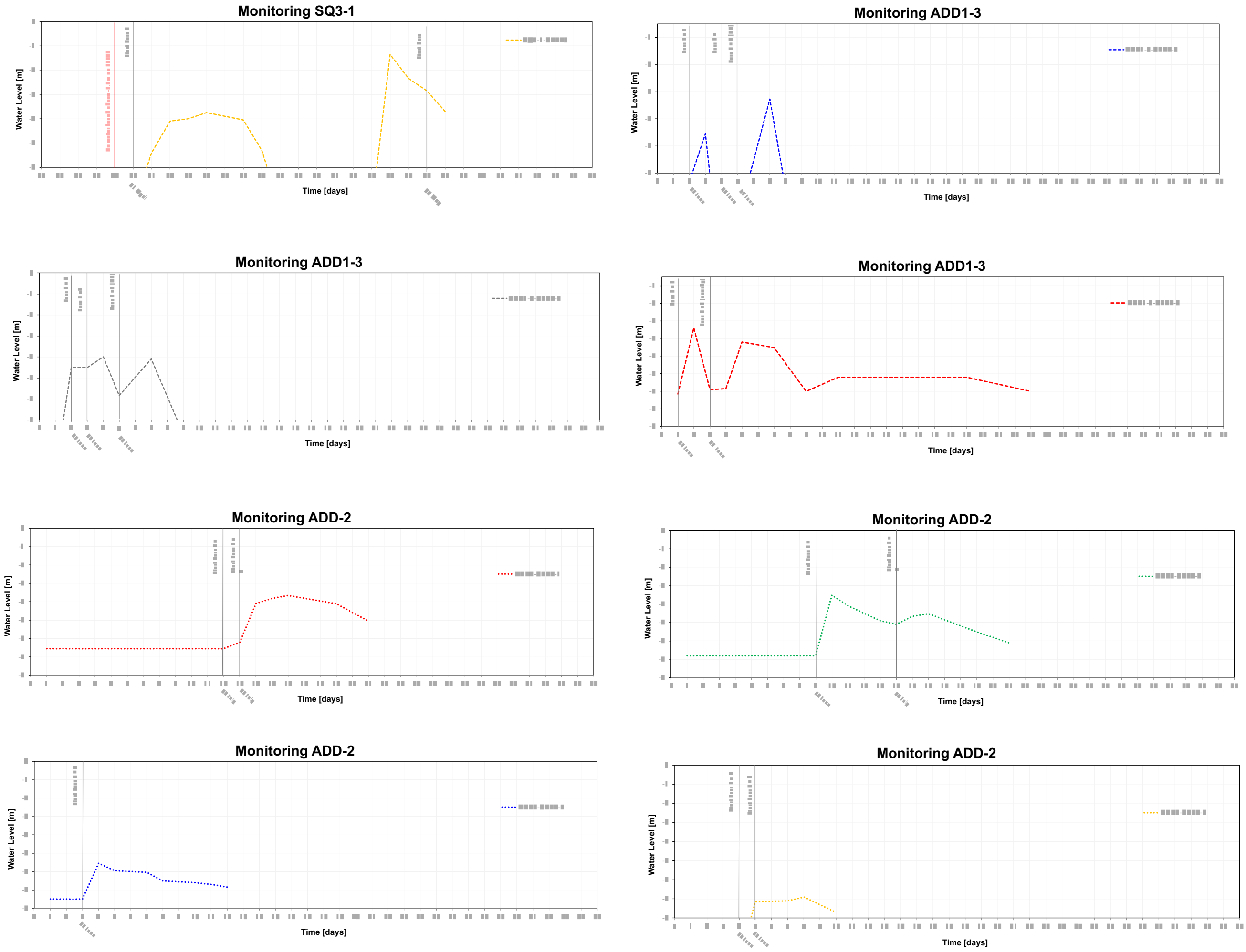


Figure 25 Standpipe Piezometer Monitoring (with PVD) EV Plant Project (continuation)

6. CONCLUSIONS AND RECOMMENDATIONS

Dynamic Compaction (DC) is a viable option to improve coarse grained soils, typically with fines content not exceeding 15% to 20% to obtain the maximum densification. Many DC projects across the world have shown the efficiency of the DC diminishes with the content of fines. When water table is within the influence of DC and FC is higher than 20%, pore pressures developed during tamping do not dissipate quickly enough, thus preventing the continuation of the compaction works due to loss of strength and reduction of effective stress. This study summarizes the advantages of employing Prefabricated Vertical Drains (PVD's) in advance of the DC to release the excess pore pressures.

Separate Trial Areas were carried out at the project, one Trial with two (2) different PVD spacing and another one without PVD's, showed after Dynamic Compaction, for the soil profile of Clayey Sands (SC) with average Fines Content of 40%, the following results:

No PVD's:	Dissipation time of 65 days
PVD's at 3m x 3m:	Dissipation time of 35 days
PVD's at 1.5m x 1.5m:	Dissip. time 2 to 4 days (max 6)

PVD's were designed to dissipate excess pore pressure (following DC works) onto an underlying higher permeability layer located to a depth encountered anywhere between 6.5m to 8.5m. In some areas at the site, this layer was not present and the PVD's evidenced surficial water flow; nonetheless, the PVD's in advance of the DC proved to be a very effective way to allow the development of all phases of tamping without hindering the progress of the compaction works.

Rain, as experienced through midway of the project onwards, influenced the piezometer readings as there was an increase in the water table due to precipitation; nonetheless, it made a small influence in the dissipation time (speed at which the levels returned to equilibrium).

It is very important to note, for the method of PVD+DC to work, the PV Drains must be installed prior to the cyclic loading of Dynamic Compaction. As proven in one of the Trials, it makes very little influence to install additional PVD's following the compaction works (even if the PVD's match the tight spacing of other areas) as the dissipation does not really change with the addition of further drains.

The traditional theory of Barron's Hansbo (1981) to estimate consolidation times could not be applied for coarse grained soils as the application of the load is dynamic and cyclic. The principles to apply here are more from the liquefaction theory with cyclic loading. Recommendation is made by the authors for further research to determine equations that could allow the more accurate design of the PVD spacing and parameters.

As pointed out by Thevanayagam (2016), densification of silty sand deposits containing high silt contents appears to be feasible only when these techniques are supplemented with wick drains. Traditionally, field design of these approaches relies on site specific field pilot trials and/or past experience based on case histories.

It is paramount to quality control the Dynamic Compaction works with pore pressure monitoring, vibration monitoring, measurement of crater depths, and subsidence of the overall ground level. Cone Penetration Tests with pore pressure measurement (CPTU), with about 200 tests performed, proved to be an invaluable tool have a continuous profile of the soil, before and after improvement, determine the Fines Content (indirectly by correlations) and monitor hydrostatic and excess water pore pressures.

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8. REFERENCES

Abramson, L. W. (1994). Soil Compaction and Consolidation. In Xanthakos, P. P., Abramson, L. W., & Bruce, D. A. *Ground Control and Improvement* (p. 234), John Wiley & Sons, Inc.

Barron, R. A. (1948) Consolidation of fine-grained soil by drain wells. *Trans. ASCE, 113 (2346) (1948).*

CeTeau BV (2022). DC+PVD- Design Approach *EV Plant Project,* December 2022.

CeTeau (Thailand) Ltd. (2023). *Additional 1 (DC+DR) 15 June 2023 TH.1258 –EV Plant Project, Dynamic Compaction & Replacement + Prefabricated Vertical Drains (PVD).*

CeTeau (Thailand) Ltd. (2023). *Field Analysis Report [All Sequences] May- July 2023 TH.1258 –EV Plant Project Dynamic Compaction + Prefabricated Vertical Drains (PVD).*

Denies, N., & Huybrechts, N. (Eds.). (2012). Recent Research, Advances & Execution Aspects of Ground Improvement Works. In *Proceedings of the International Symposium TC 211 IS GI-Brussels 2012* (Vol. 1).

Dutch Cone BV. (2023). *Final CPT Report [All Sequences] EV Plant Project.*

Google Earth Pro. (2015). Satellite view of 12°59'14.03" N; 101°19'03.39" E. Retrieved 2023.

Han, J. (2015). *Principles and Practice of Ground Improvement. John Wiley & Sons*.

Hansbo, S. (1981), Consolidation of fine-grained soils by prefabricated drains *Proc. 10th ICSMFE (1981).*

JLP Engineering Services Co., Ltd. (2022). *Soil Investigation (Reports Zone 1, Zone 2, Zone 3 and Zone 4).*

Lukas, R. G. (1995). *Geotechnical Engineering Circular No. 1 - Dynamic Compaction*, No. FHWA-SA-95-037. U.S. Department of Transportation - Federal Highway Administration.

Lunne, T., Powell, J. J. M., & Robertson, P. K. (2002). *Cone Penetration Testing in Geotechnical Practice*. Taylor & Francis Group.

Meinhardt (Thailand). (2022*). EV Factory Project- Layout and other drawings.*

Robertson, P. K., & Cabal, K. (2022). *Guide to Cone Penetration Testing* (7th Edition). Gregg Drilling LLC.

Rojana Industrial Park Public Co., Ltd. (n.d.) ROJANA PROJECT : NONGYAI.https://www.rojana.com/rojanaproject/0-8 NONGYAI

Siskind, D. E., Stagg, M. S., Kopp, J. W., & Dowding, C. H. (1980). Appendix B. - Alternative Blasting Level Criteria . In *Structure Response and Damage Produced by Ground Vibration From Surface Mine Blasting* (pp. 73–74), United States Bureau of Mines.

Slocombe, B. (2013). Dynamic Compaction. In K. Kirsch & A. Bell (Eds.), *Ground Improvement* (Third Edition). CRC Press, Taylor and Francis Group.

Thevanayagam, S., Veluchamy, V., Huang, Q., & Sivaratnarajah, U. (2016). Non-plastic silty sand liquefaction, screening, and remediation. *Soil Dynamics and Earthquake Engineering*, 91, 147–159. https://doi.org/10.1016/j.soildyn.2016.09.027

Warr, P., & Kohpaiboon, A. (2017). Thailand's Automotive Manufacturing Corridor. *ADB Economics Working Paper Series, No. 519*. https://doi.org/10.22617/WPS189284-2