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Vacuum preloading, an alternative soft ground improvement technique for a sustainable development

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Vacuum preloading, an alternative soft ground improvement technique for a sustainable development

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Abstract. Preloading with soil surcharging in combination with prefabricated vertical drain is one of the common methods used in improving high compressibility and low shear strength of soft soils, particularly in improving very soft to soft clay. One of the main issues of this technique is it requires a high volume of backfill material to apply the surcharging, hence, whenever the availability of the backfill material is scarce or remote, it becomes expensive. In such a case, vacuum preloading becomes one of the best options to be applied in alleviating the high compressibility and low shear strength of the soft clay layers. This vacuum technique also helps to create a sustainable environment as it omits the needs of a high volume of backfill material. Therefore, no hills cutting or ground excavation is required. This paper presents the difference between surcharging and vacuum preloading methods, the working principle, and installation of vacuum preloading. Case histories in improving the soft soils of in low land areas, a large residential located on high ground about 700m from sea level, and a highway construction projects are presented. The case histories revealed that proper application of vacuum preloading could effectively improve soft clays, be in a low land area or high ground area. The depth improved can reach as deep as 25m.

Keywords. Vacuum Preloading, Negative Pore Water Pressure, Surcharging, Preloading

1. Introduction

To increase the economic growth, in this early 21st century, Indonesia has been accelerating the development of infrastructures, from developing power plants, highways, airports, harbors to residentials. Many of those construction have to be built on marginal land, e.g. very loose to loose sandy soils, very soft to soft clays, and peats. In such cases, ground improvement schemes such as dynamic compaction, rapid impulse compaction, vibro-compaction have been implemented in mitigating the liquefaction potential of loose sands. Wooden or bamboo piles and raft system has been implemented to mitigate high compressibility problem of peats. Deep cement mixing or surcharging in combination with vertical drains are the main improvement scheme in increasing the bearing capacity and reducing the settlement problem of soft clays. Traditionally, to mitigate future settlement problem of any structures build over soft clays, surcharging in combination with vertical drains is adopted. However, this method needs a large amount of backfill material which requires hill cutting to obtain the backfill material, hence, it is not environmentally friendly. In this case, vacuum preloading becomes a better alternative as it requires no backfill material, it utilizes atmospheric pressure to pressurize and consolidate the soft clays before a structure is built. It is an environmental friendly solution to create a sustainable development by creating a stable and settlement-free foundation soils for the structures to be built over it. This paper presents the basic principles of the vacuum preloading, its differences with the traditional surcharging method, its installation method, and its monitoring system. Three case histories are discussed, the first one was on improving the foundation soils of a power plant project in a low land area, the second one was on accelerating the consolidation of a deep soft clay deposit in a large residential project, the final one was on the performance of vacuum preloading where it was applied in combination with surcharging to further accelerate the consolidation process in developing a highway project.

2. Vacuum preloading vs Surcharging

As the name implies, surcharging is a technique applied by placing a certain magnitude of load, generally around 1.3 times the anticipated working load on top of the soft clay to compress it up to a minimum of 90% degree of consolidation [1]. Soil backfill is generally used as surcharging material. Once the target consolidation is achieved, the surcharge is removed, and the planned structures are constructed. This way, future settlement of structures can be alleviated. By applying a surcharge, stress difference or anisotropic stresses within the soil is created and with this, if not carefully designed, comes the danger of excessive outward lateral movement, heaving, and slope failure. This case is schematically shown in Figure 1.

The vacuum preloading technique is applied by creating a vacuum system within the soft clay layer. When this vacuum is successfully created, the atmospheric pressure will act pressurizing the soft soils. Figure 2 shows the principle of vacuum preloading technique. The vacuum pressure within the soil body is created by pumping through an interconnected network of PVD (prefabricated vertical drain), horizontal filter pipes and sand blanket, forming a complete path for spreading the vacuum pressure and facilitating water flow. To create an effective vacuum condition within the target improvement area, an airtight isolation system which consists of geomembrane and the soft clay itself, is required. When there are sand lenses, a vertical slurry wall is required to cut off the continuous sand lenses or else the vacuum may not work. Figure 3 shows the whole configuration of the vacuum network.

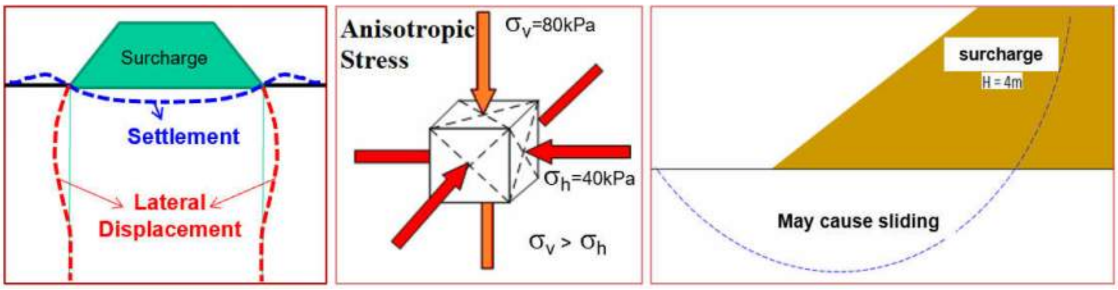


Figure 1. Stress difference or stress anisotropic in surcharging technique [2]

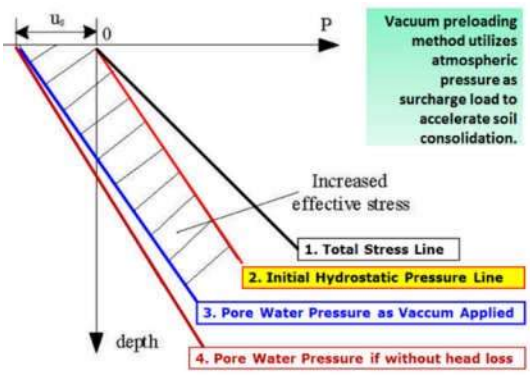


Figure 2. Principle of vacuum preloading [2]

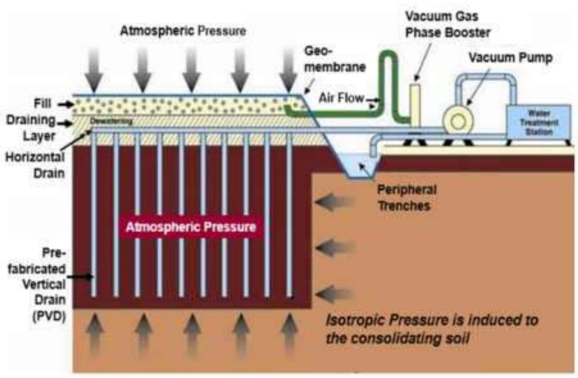


Figure 3. Configuration of the vacuum network [3]

In contrast with the surcharging technique, vacuum preloading created uniform or isotropic pressure (minimal stress difference) on the body of the soft soils as shown in Figure 4. Hence, there is no danger of outward lateral movement, heave, and slope failure. Generally, the vacuum system can induce a vacuum pressure in the order of 80% of atmospheric pressure to the soft soils being improved, which is equal to 81.06 kPa (1 atm = 101.325 kPa → 80% x 101.325 kPa = 81.06 kPa). If a unit weight of soil surcharge is 18 kN/m^3, the 80% of atmospheric pressure is equivalent to 81.06/18 = 4.5 m high of soil surcharge material.

From stress path point of view (Figure 5), in surcharging method, the relatively fast applied backfill (surcharge) on top of low permeability clay layer, undrained condition prevails, and positive excess pore water pressure is induced, which in turn reduces the mean effective stresses, p', in the soil, but increases the stress difference, q, the stress path will then follow an undrained path toward the failure line. On the contrary, in vacuum preloading system negative pore water pressure is induced in a uniform manner vertically and horizontally, hence it increases the vertical and the effective stresses uniformly, therefore, the mean principal stresses increases, p', while no deviatoric stress (stress difference), q, is induced. The stress path will then move horizontally with increasing mean principal stresses with no increase in stress difference, therefore, the distance to the failure line becomes farther away. This clearly explains that the risk of soil failure within the loaded area is eliminated.

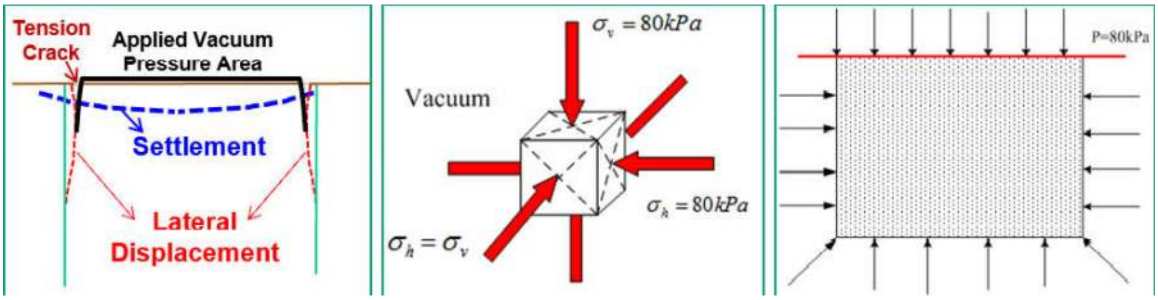
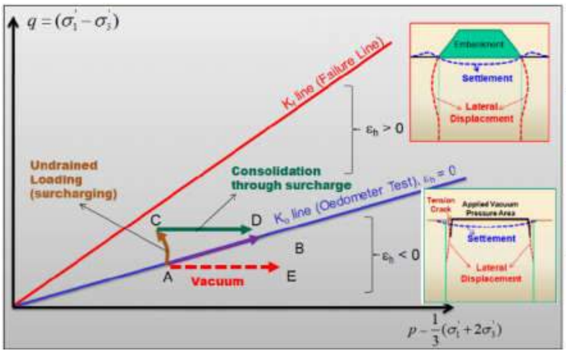


Figure 4. No stress difference or isotropic stress is imposed in vacuum technique [2]



Type	Total stress	Initial /boundary condition	Process	Effect
Vertical drain with surcharge	$\Delta\sigma\uparrow$	$\Delta u\uparrow$ σ'_o	$\Delta u \rightarrow \Delta\sigma'$	$\uparrow \sigma' = \sigma'_o + \Delta\sigma$ $(\Delta u \approx \Delta\sigma)$
Vacuum Preloading	σ	$u(soil)$ $-u^*(boundary)$ σ'_o	$u\downarrow$ $(\Delta u \approx -u^*)$	$\uparrow \sigma' = \sigma'_o + u^*$ $(\Delta u \approx -u^*)$

Remember Effective Stress Formula:

$$\sigma' = \sigma - u$$

Figure 5. Stress path difference of surcharging and vacuum technique [2]

It is clear that the main advantages of vacuum preloading over traditional preloading with surcharging system are:

- It eliminates the risk of slope failure since it applies a uniform pressure on the soil body (no embankment is built over the soft soils which means no stress difference is imposed over the soft soils),
- It requires shorter construction time as it does not need the mounting of backfill material,
- and hence practically no or much less earth moving equipment is required.
- It requires less consolidation time, as the vacuum system actively drained out the excess pore pressure and induced uniform pressure on the consolidating soil body.

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To create an effective vacuum system in the soft soil to be improved, the existence of high permeability granular material (e.g. free-draining sand and/or gravel layer) within the target improved area must be carefully investigated, because its existence will reduce the effectiveness of vacuum preloading system. When those free-draining material existed the following actions must be taken:

- The PVDs must not penetrate into the underlying granular material below the soft clay. Penetrating the PVDs into the granular material will pump out the water or air from within the granular layer. Therefore, a vacuum pressure cannot be effectively created.
- Whenever a thin sand layer exists within two soft clay layers, the sand layer must be isolated by providing bentonite slurry wall to contain the sand layers within the vacuum zone and separate it from the part outside the vacuum zone as shown in Figure 6.

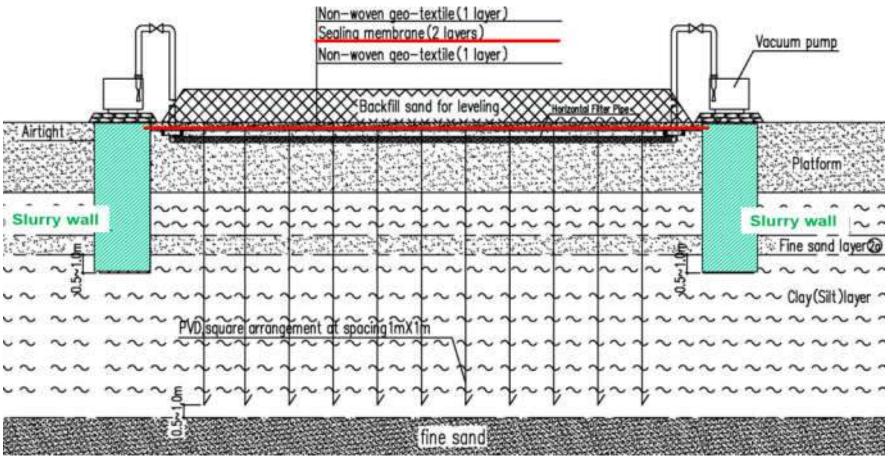

Figure 6. Slurry wall to seal-off sand lenses within the vacuum zone [4]

Basically, to successfully execute a vacuum preloading ground improvement scheme, three components must be properly provided, those are: drainage system, vacuum pump and sealing system as shown in Figure 7.

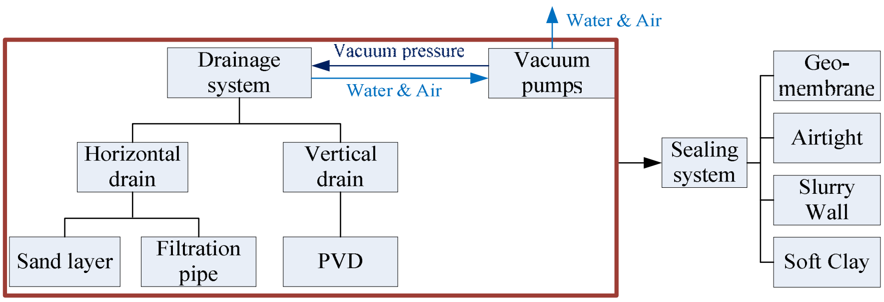

Figure 7. Three important components of vacuum preloading system [2]

3. Installation of vacuum preloading system

Generally, vacuum preloading ground improvement method is executed in the following steps:

- Step 1 – Prepare a working platform for equipment to safely access the job site. It is then followed by the installation of prefabricated vertical drains, also known as PVDs, and horizontal drains network within the target improvement area as shown in Figure 8. The horizontal drains are connected to PVC/HDPE piping system to a vacuum pump. The distance of the PVDs is determined by using Hansbo's formula [5, 6] and design guidelines written by Gouw [7, 8].
- Step 2 – Place 30-50cm thick sand layer on top of the PVD and horizontal drains network. Place geotextile on top of the sand layer. Finally, cover the whole target improved area with

geomembrane as presented in Figure 9. The sand layer and geotextile functioned as a protective layer to protect the geomembrane against punctured by any left-over sharp roots or stones. The geomembrane acts as a sealing system. To provide an effective airtight sealing system, at the perimeter of the target improved area, the geomembrane has to be anchored to a depth of around 80-120 cm and the trench created is either backfilled or filled with water as shown in Figure 10. When sand lenses/layers are encountered in within the soft clay layers, then an airtight slurry wall has to be installed around the perimeter to cut-off the sand lenses/layers (Figure 6)

- Step 3 – Connect the PVC/HDPE pipes placed underneath the sealing system are connected to the vacuum pump by flexible pipes (Figure 11).
- Step 4 – The vacuum pump is then started to pump out the water from within the improved zone and the vacuum pressure is monitored and maintained at around 80 kPa (Figure 12). Whenever necessary, to further accelerate the consolidation process, water that comes out sometime is pumped back and pooled on top of the improved area to act as a surcharge.

Figure 8. PVDs & horizontal drains installation

Figure 9. Geotextile & geomembrane installation

Figure 10. Anchoring geomembrane along the perimeter of target improve area

Figure 11. Connect the piping system to the vacuum pump

(a) Vacuum pump is started (b) Vacuum pressure monitor

Figure 12. Vacuum pump is started and the induced vacuum pressure is monitored

4. Monitoring system

In executing the vacuum preloading, a monitoring system is necessary, the most essentials ones are:

- Manometer to monitor the vacuum pressure induces below the sealing system.
- Settlement plate placed on top of the improvement area to monitor the induced settlement.
- Piezometer, generally vibrating wire piezometer is used, to monitor the pore water pressure within the improved zone.

Additional monitoring instrument that commonly used are:

- Extensometer or deep settlement probe to monitor the settlement of deeper soil layer.
- Inclinometer placed around the perimeter of the improvement area to monitor soil lateral movement.

Figure 13 shows the monitoring equipment. Any of the instrument protruding above geomembrane must be properly sealed as leakage will negatively impaired the performance of the vacuum system.

Figure 13. Monitoring instrument used in vacuum preloading

5. Case histories

5.1. Vietnam power plant project

A power plant project covering an area of about 25 hectares in South Vietnam was to be constructed on 16-30m depth very soft muddy clay layer. The very soft clay layer had a natural water content of around 58%, an initial void ratio of 1.594, and compression index 0.615. Vacuum preloading with PVD installed in 1.0 m x 1.0 m spacings and average depths of 26 m were employed to improve the soft soils. The vacuum pressure reading, typical settlement, the pore water pressure readings, and inward lateral displacement are presented in Figure 14.

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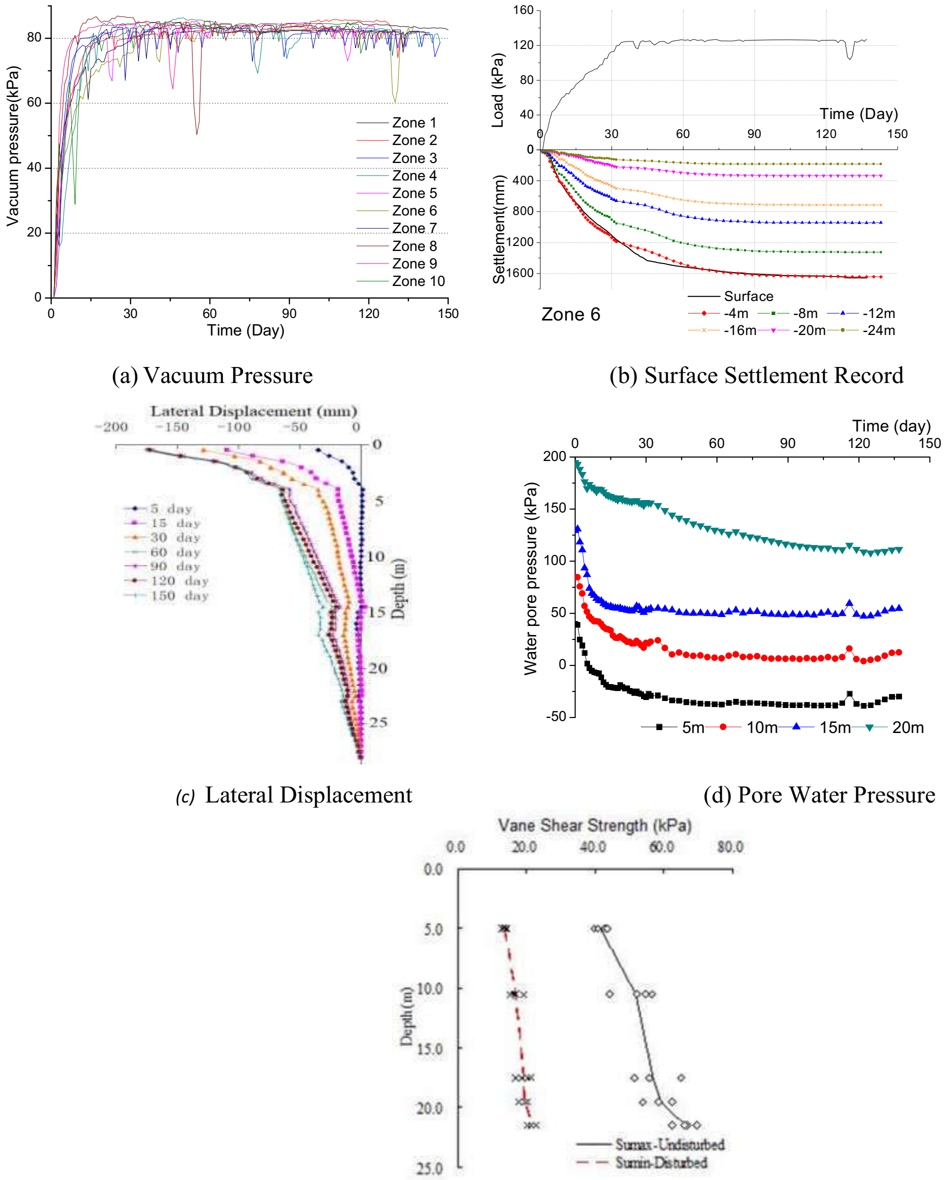

(a) Vacuum Pressure (b) Surface Settlement Record

(c) Lateral Displacement (d) Pore Water Pressure

(e) Undrained Shear Strength

Figure 14. Vacuum pressure, settlement and pore water pressure readings in Vietnam project [4]

The vacuum pressure record in Figure 14a shows that on average, vacuum pressures of around 80 kPa, were achieved in 8 to 30 days. After the vacuum preloading period of 117 - 150 days, typical ground surface settlement achieved slightly over 1600 mm and the soil layer at 24 m depth settled by around 200 mm (Figure 14b). These settlements correspond to a degree of consolidation over 90%. The maximum lateral displacement observed at ground surface was 176mm and it reduced to zero at a depth of around 28 m in the direction towards the improved area (Figure 14c) All piezometers placed 5, 10, 15 and 20 m below ground surface showed a reduction of pore water pressure by around 80 kPa. The pre and post vacuum preloading vane shear test showed that the post-treatment undrained shear strength increases by 2.5 to 3.0, even up to a depth of 20 m, the undrained shear strength increases by around 3 times (Figure 14e). These showed that the vacuum pressure can effectively improve the soil of up to at least 25 m depth.

5.2. Banten power plant project

A power plant project, located at Banten province in West Java island of Indonesia, was underlain by very soft to soft clay layer up to around 8 m depth. Vacuum preloading was adopted to improve the soft clay layer with PVD of 7.5 m long and 1.5 m triangular spacings. Figure 15a shows the pre-treatment undrained shear strength of the soft clay layer and Figure 15b shows the typical time settlement curve obtained. Figure 16 shows post-treatment cone penetration resistance increased by about 1.3 to1.5 times. Post vacuum water content was reduced from 100% to around 60%.

Figure 17 shows that before vacuum preloading an excavator could easily sink into the original ground and after vacuum preloading, the improved ground can be excavated with ease.

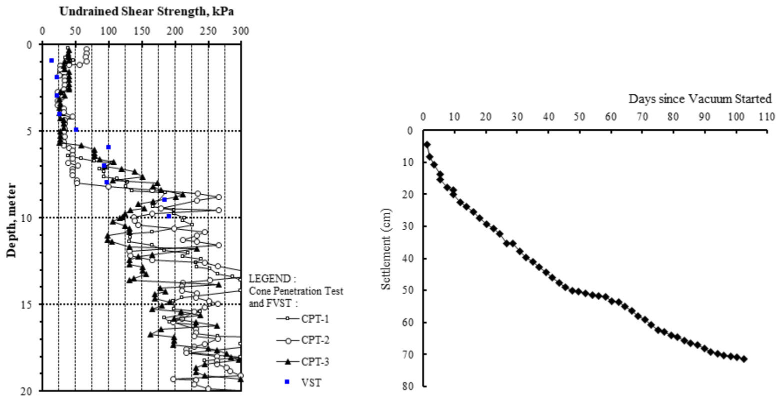

Figure 15. Banten project – (a) undrained strength and (b) settlement

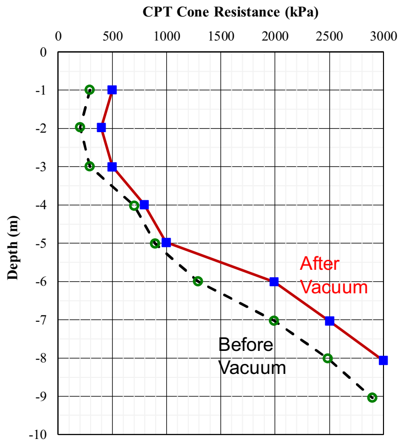

Figure 16. Banten project – pre and post vacuum cone penetration resistance

Figure 17. Pre-vacuum: excavator sank into soft clay, post vacuum: trenches were excavated with ease (courtesy of PT. Geotekindo)

5.3. Gedebage Bandung residential project

A vast housing complex is being built in Gedebage, a low land area at the outskirt of Bandung, the capital city of West Java province, Indonesia. This area is primarily underlain by very soft clay layer varying from 20 to 27 m thick. The clay layer has natural water contents that fall near or above their liquid limits, which vary within 100-200%, the liquidity indices are around 0.9 or more, indicating a very soft clay layer. The undrained shear strength is in the order of 15-25 kPa. To mitigate future settlement that could induce cracks and damages to the planned houses, ground improvement by vacuum preloading were tried out with 20 m long PVD of 1.2 m triangular spacings. Figure 18 shows typical vacuum pressure, time settlement, and piezometer readings.

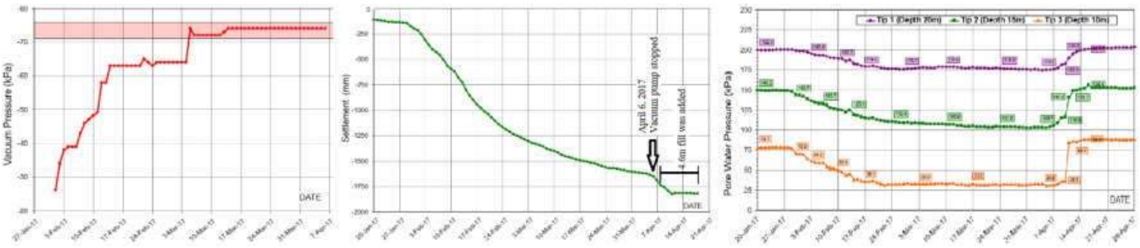

Figure 18. Gedebage, Bandung – vacuum pressure, settlement and piezometer typical readings

Despite the normal practice where vacuum pressure of around 80 kPa can be achieved, at this project the maximum vacuum pressure achieved was only in the order of 74 kPa. Being located in a relatively high ground, Bandung has an average atmospheric pressure of 93.8 kPa. With an effective vacuum pump of 80%, the effective vacuum pressure that can be exerted into the ground shall be around 80% x 93.8 kPa = 75 kPa. Therefore, it was concluded that the vacuum pressure of 74 kPa was acceptable. Apart from this lower vacuum pressure than normal, the vacuum data showed that it took 42 days to achieve 74 kPa. Generally, a vacuum of 80% atmospheric pressure can be achieved within two weeks. This rather long duration to achieve maximum vacuum pressure might be due to the existence of thin sand lenses at around 2.3-3m depths.

By employing Asaoka's method [9] on the recorded settlement data, it was found that the degree of consolidation achieved was in the order of U = 94%, as shown in Figure 19. Therefore, on April 6, 2017, i.e. 65 days after the application of vacuum or 24 days after the soil was subjected to a stable vacuum pressure of 74 kPa, the project director instructed the vacuum pump to be stopped. The decision was taken without considering piezometer data, if based on the pore water pressure data, it was found that the degree of consolidation achieved was only in the order of U = 80% (figure 20).

Judging from the fact that re-applying vacuum may take another 40+ days to achieve 74 kPa, to make sure 90% of consolidation was achieved, it was decided to apply soil surcharging of 4.6m high. Figure 21 shows the comparison of pre and post vacuum undrained shear strength derived from CPT tests. The post vacuum CPT test was performed on April 16, 2017, the undrained shear strength increases by about 3 to 4 times of its original values.

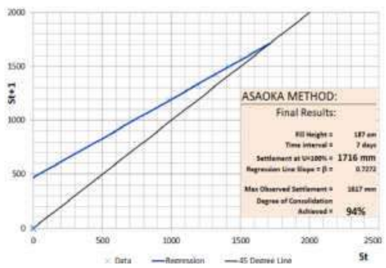

Figure 19. Asaoka's method gave U = 94%

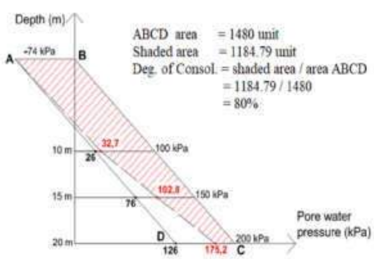

Figure 20. Piezometer data gave U = 80%

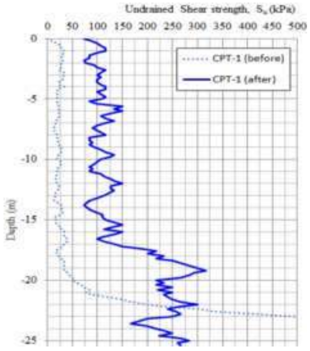

Figure 21. Pre vs post vacuum undrained shear strength

5.4. Trans Sumatra highway – Pematang section

The Pematang Panggang, Kayu Agung section in South Sumatra of the Trans Sumatra highway was built over 5-14 m thick soft clay. Vacuum preloading was applied with PVDs spacing of 1.0 m grid. To accelerate the construction process, once the vacuum reached 80 kPa, backfill material required to achieve the designed road elevation was placed on top of the vacuum area. It was observed that every time backfill was added the vacuum pressure dropped (Figure 22). This drop in the vacuum pressure is explainable. It is just like a person drinks a cup of water by sipping through a straw, at this moment suction or vacuum is applied inside the cup. At that instant, if the cup is pressed, water will rush out through the straw and suction inside the cup will drop. In vacuum preloading, the moment external pressure is exerted by the placement of backfill, the vacuum pressure reduces, and pore water pressure increases. The numerical calculation is as follows: The instance an external backfill of 0.6m is applied, a pressure of 0.6 m x 18 kN/m^3 ≈ 11 kPa presses the soil, vacuum pressure subsequently drops by the same amount. The vacuum pressure chart in Figure 22 shows that the pressure is reduced from 80 kPa to 69 kPa, and all the pore water pressure readings increase by about the same values. Therefore, it is a normal phenomenon and it shall have positive effects in accelerating the consolidation process.

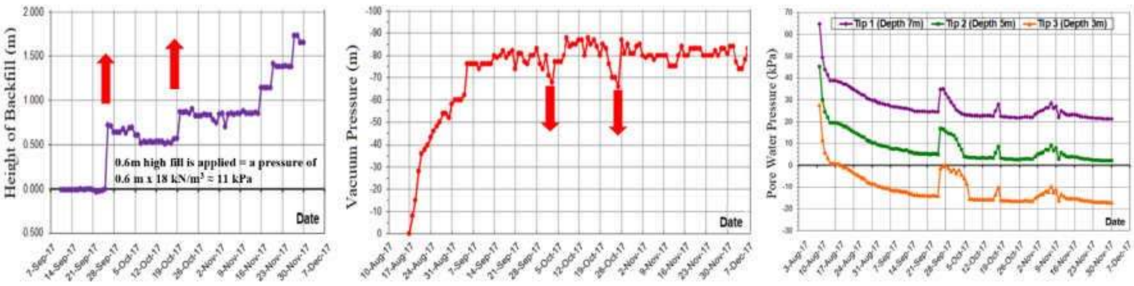

Figure 22. Typical monitoring data – Pematang Panggan, Kayu Agung, Trans Sumatra project

6. Concluding remark

Vacuum preloading is an effective method in improving soft clay layers. The post-construction settlement can be minimalized or even eliminated, and the bearing capacity of the original ground increases. The case histories presented showed that the technique could be applied both in low land where the atmospheric pressure is 1 atm (101.3 kPa) and high ground area where atmospheric pressure is in the order of 0.93 atm (93.8 kPa), post vacuum undrained shear strength can be increased by a factor of 1.5 to 4.0 times its original. The dropped of vacuum pressure when backfill or surcharge is added on top of the vacuum area is a normal phenomenon. The best way to evaluate the degree of consolidation achieved is by incorporating both settlement and pore water pressure data. Vacuum preloading technique practically requires no backfill materials, which means no terrain excavation nor cutting of hills is required to source for the backfill materials. Therefore, it is much more environmentally friendly compared to the traditional surcharging which needs large amount of soil backfill material. Vacuum preloading is also a sustainable method in developing over soft soils as it can mitigate future settlement of the structure built over the post vacuum ground.

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