# Analysis of soft soil lateral movement induced by vacuum preloading with finite element method

## Analyse du mouvement latéral du sol meuble induit par le préchargement sous vide avec la méthode des éléments finis

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ABSTRACT: Soil improvement is a construction method to reduce/eliminate post settlement. Soil improvement method for soft clay usually perform with installation of Prefabricated Vertical Drain (PVD) to accelerate consolidation process combine with preloading. Preloading could be in any form of loading, one of the methods is by vacuum preloading. In vacuum preloading, atmospheric pressure is used to create suction and squeeze excess porewater pressure out of soil. Deformation analysis that currently available for vacuum preloading is limited and usually come from soil preloading deformation. More advance analysis and model is necessary to understand soil behavior and deformation induce by vacuum preloading method. Especially around the perimeter of improvement area where the deformation profile is different. Vacuum preloading will create inward lateral displacement that usually occur as outward displacement in conventional preloading. Understanding this behavior is important to better estimate safety distance from vacuum preloading to avoid unfavorable damage to surrounding structure. Lateral deformation analysis is numerically modeled with Geostudio software. Analysis result show that the numerical model deformation and behavior match with monitoring data available. Based on this numerical model, significant movement (>5cm deformation) around vacuum preloading could be found until 20m away.

RÉSUMÉ: L'amélioration des sols est une méthode de construction pour réduire/éliminer les tassements postérieurs. La méthode d'amélioration du sol pour l'argile molle s'effectue généralement avec l'installation d'un drain vertical préfabriqué (PVD) pour accélérer le processus de consolidation combiné au préchargement. Le préchargement peut être sous n'importe quelle forme de chargement, l'une des méthodes est le préchargement sous vide. Dans le préchargement sous vide, la pression atmosphérique est utilisée pour créer une succion et extraire l'excès de pression interstitielle du sol. L'analyse de la déformation actuellement disponible pour le préchargement sous vide est limitée et provient généralement de la déformation de préchargement du sol. Une analyse et un modèle plus avancés sont nécessaires pour comprendre le comportement du sol et la déformation induite par la méthode de préchargement sous vide. Surtout autour du périmètre de la zone d'amélioration où le profil de déformation est différent. Le préchargement sous vide créera un déplacement latéral vers l'intérieur qui se produit généralement sous forme de déplacement vers l'extérieur dans le préchargement conventionnel. Il est important de comprendre ce comportement pour mieux estimer la distance de sécurité par rapport à la précharge sous vide afin d'éviter des dommages défavorables à la structure environnante. L'analyse des déformations latérales est modélisée numériquement avec le logiciel Geostudio. Les résultats de l'analyse montrent que la déformation et le comportement du modèle numérique correspondent aux données de surveillance disponibles. Sur la base de ce modèle numérique, un mouvement important (> 5 cm de déformation) autour de la précharge sous vide a pu être trouvé jusqu'à 20 m de distance.

KEYWORDS: soil lateral movement, vacuum preloading, vacuum consolidation, soil improvement, finite element method.

## 1 INTRODUCTION

Soil improvement or ground improvement is one of construction phase to optimize initial soil condition. Most popular and economical treatment for soft fine grain soil is with soil preloading method. Consolidation process will be induced by a temporary pre-loading that later will be replace by permanent construction load. Settlement expected to happen during improvement period to reduce/eliminate post settlement during operational period. (Stapelfeldt 2018; Han 1964)

Biggest limitation when using preloading method is the improvement time. Since permeability of clay is very low, soil improvement duration with consolidation process could take month to years to reach consolidation degree of >90%. To shorten the drainage length of water and reduce the consolidation duration PVD (prefabricated vertical drain) is installed to the ground. PVD usually installed with spacing between 0.7m to 1.5m. PVD will allow excess Pore Water Pressure (PWP) to flow radially and dissipate rather than vertically to the ground surface or other permeable layer to be able to escape the soil mass. Another limitation of soil preloading technique is when huge load expected during operational period, improvement load should also increase to mitigate the post settlement. Since bearing capacity of soft soil is limited to typical critical height of backfill height 3.0 to 3.5m before failure and also increment of soil shear strength happen gradually along with consolidation process, soil preloading process should construct stage by stage when the critical height is exceeded. this process will lead into longer construction duration and also cause another logistic problem of preloading material that need to be purchase and later remove. Under this condition, vacuum preloading method is introduced as a more economical alternative. Several applications of use of vacuum consolidation to improve soft clay has been reported (Chu et al 2008; Dam et al 2006; Indraratna et al 2005 & 2007)

Vacuum Preloading or Vacuum Consolidation Method is applied by creating a vacuum condition underneath ground with the help of prefabricated vertical drain and airtight sheet/geomembrane. In practice, vacuum preloading could provide preloading pressure from 40 to 90kPa depend on the site altitude and vacuum system efficiency. Vacuum preloading pressure could substitute equivalent of 3.0 to 5.0m height of soil fill. Vacuum preloading gains its most advantage if backfill material around construction site is limited and construction duration is limited.

Soil deformation around improvement boundary induce by vacuum preloading tent to move toward improvement area compare to soil preloading that usually induce outward lateral movement. Inward deformation will cause tension crack around vacuum preloading area (Chai 2005). Outward soil movement by soil preloading could be reduce by suction and inward movement produce by vacuum preloading (Indraratna 2007).

Since it produces difference soil deformation behavior compare with the traditional consolidation settlement analysis, this research intended to model soil deformation with a numerical approach using finite element method. Correct model of soil deformation around perimeter is important when there is important structure nearby improvement area. Excessive an unfavorable deformation to the surrounding structure can cause damage. Understanding this behavior and estimate influence area, is very important to avoid unnecessary damage on surrounding and design preventive action to reduce the movement.

## 2 METHODS

In order to get soil behavior outside improvement area, numerical model is used for this study. Finite Element Model (FEM) in this study will be built with help of Sigma/W-Geostudio software. Soil layer was modeled with Modified Cam Clay constitutive relationship. New compacted backfill will be model with Mohr coulomb soil model.

PVD will be model using a line element with hydraulic boundary condition. Spacing of PVD need to adjusted according to its equivalent influence area. Total water head along the hydraulic boundary element is input as equal to the hydrostatic water pressure head or ground water level, by doing so, when there is excess porewater pressure generate by backfilling, excess pore water pressure (PWP) will dissipate through this element inducing consolidation settlement.

In case of Vacuum Preloading, when pump is turn on and pressure applied to the ground, water pressure head input in the PVD will be defined at equivalent pressure head below hydrostatic pressure. Average vacuum pressure to the ground is estimate around 80kPa. During vacuum preloading process, height in the hydraulic boundary element will input 8m below ground water level. Differential pressure of 80kPa between boundary element and soil will generate excess pore water pressure and this PWP will dissipate though the boundary element inducing consolidation settlement inside improvement area. Several adjustments in soil parameter are needed to ensure that the soil behave as saturated soil throughout the process like VWCC is manually define so its didn't affect by change in suction also soil permeability is defined to neglected unsaturated permeability being used during consolidation process. Geometry model and meshing for Finite Element Model show in Figure 1.

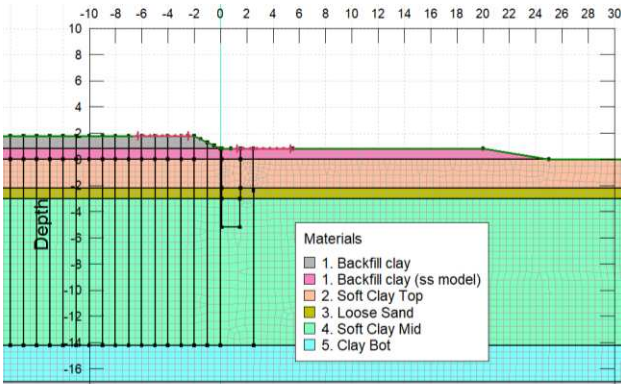


Figure 1. Finite Element Model

## 3 CASE HISTORY

Case history from improvement area that located in north-west of Jakarta, Indonesia will be used in this study. Vacuum preloading with membrane method has been applied in this area. During improvement there is no backfill perform in this area, hence preloading is only due to soil working platform fill and vacuum preloading load of 80kPa. In this location typical soft silty clay is found in the top soil layer with thickness from 10 to 25m with permeable sand layer intercalated in between this improvement layer. Permeable sand layer found around depth 7m from original ground surface and will be sealed prior to improvement. sealing method carry out by construction of slurry wall (clay mixture wall) to cut off and separate permeable layer inside improvement area to outside. This slurry wall is necessary to guarantee vacuum pressure can generate inside improvement area.

South-west part of the project is well monitored and chosen as case study location. Soil investigation result and stress history data from site record will be used to build a Finite Element Model that can well represent site condition on study area. Several inclinometers as show in Figure 2 located about 2.5m from vacuum preloading boundary will be used to verify FEM analysis. Based on inclinometer result at the end of improvement show in Figures 3, 2 from 3 inclinometer show that soil movement in the ground surface is around 80cm and the other 1 most likely is not long enough to be pinned in good bearing layer so collected data need to adjust with toe movement of the inclinometer. Beside inclinometer, nearest Settlement plate (Figure 4a) and vacuum gauge monitoring (Figure 4b) will be also used to verify FEM model. Vacuum gauge and settlement plate reading show that 150days is needed to finish soil improvement process, total 150days duration including 3times process need to be stop due to maintenance problem.

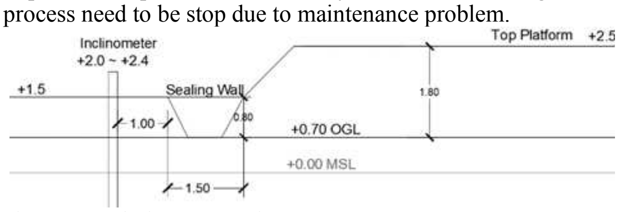


Figure 2. Analysis Cross Section

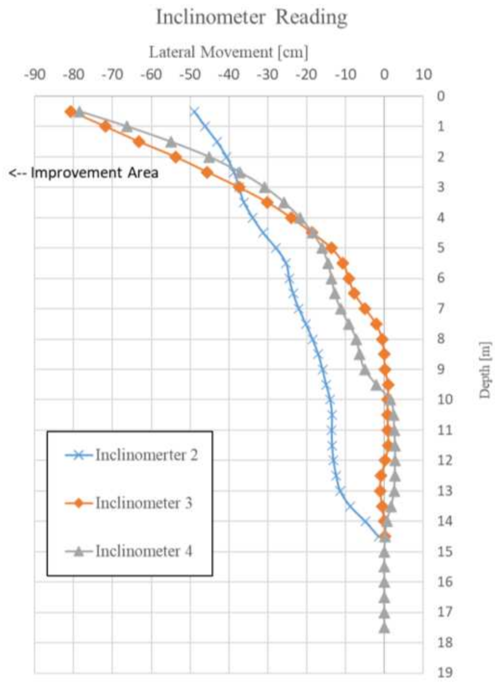


Figure 3. Inclinometer Monitoring Result

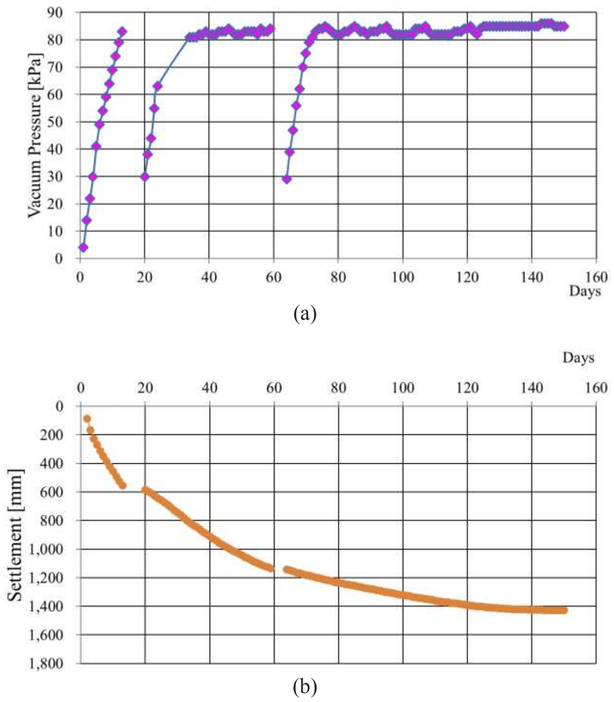

Figure 4. Vacuum Gauge (a) and Settlement Plate (b) Monitoring Result

Two CPTe point near the location (Figure 5 and 6) show soil condition below ground. From the lab test result and empirical correlation, soil parameter for FEM analysis could be found in Table 1 and Table 2.

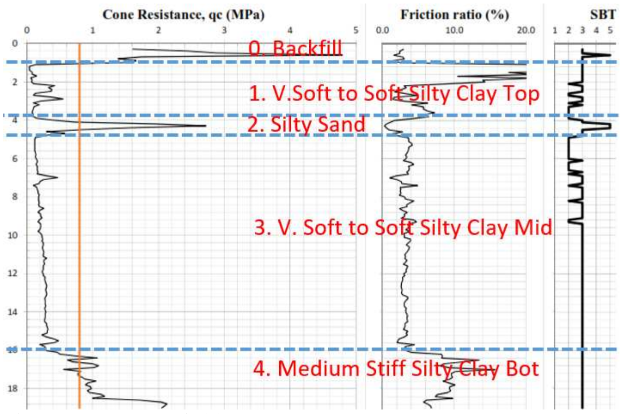

Figure 5. CPTe Result (1)

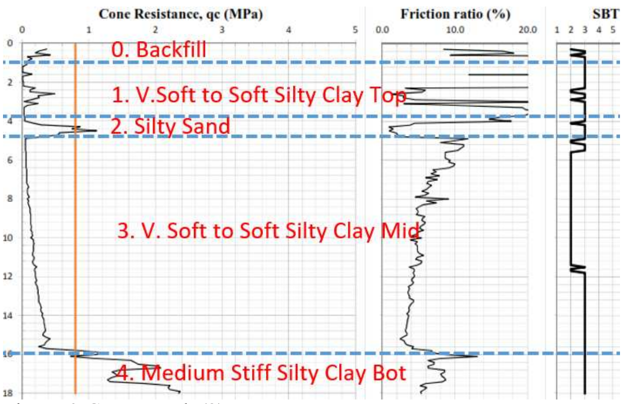

Figure 6. CPTe Result (2)

Table 1. Soil Parameter (1)

| Elev. | layer | $N_{SPT}$ | $\gamma$ [kN/m$^3$] | $\lambda$ | $\kappa$ | $e_0$ |
|---|---|---|---|---|---|---|
| - | Slurry Wall (Mud) | 1 | 13.0 | 0.50 | 0.08 | 3.0 |
| +1.8 to 0.8 | New backfill clay (MC) | 1 | 15.0 | | | |
| +0.8 to 0.0 | Old backfill clay (MCC) | 1 | 15.0 | 0.23 | 0.08 | 2.5 |
| 0.0 to -2.2 | v.Soft to Soft silty clay top | 1 | 14.0 | 0.45 | 0.08 | 3.0 |
| -2.2 to -3.0 | Silty sand (very loose) | 1-8 | 16.0 | - | - | - |
| -3.0 to -14.2 | v.Soft to Soft silty clay mid | 2 | 14.0 | 0.30 | 0.05 | 2.5 |
| -14.2 to -17 | Medium Stiff silty clay bot | 5-11 | 16.5 | 0.15 | 0.05 | 1.5 |

Table 2. Soil Parameter (2)

| Elev. | layer | c' | $\phi$' | E [kPa] | v' | $k_x$[m/s] | $k_x/k_y$ |
|---|---|---|---|---|---|---|---|
| - | Slurry Wall (Mud) | | 25 | | 0.4 | 3.0E-08 | 1 |
| +1.8 to 0.8 | New backfill clay (MC) | 35 | 25 | 5000 | 0.35 | 9.0E-10 | 2 |
| +0.8 to 0.0 | Old backfill clay (MCC) | 0 | 28 | | 0.35 | 9.0E-10 | 2 |
| 0.0 to -2.2 | v.Soft to Soft silty clay top | 0 | 28 | | 0.35 | 9.0E-10 | 5 |
| -2.2 to -3.0 | Silty sand (very loose) | 5 | 25 | 5000 | 0.3 | 1.0E-07 | 1 |
| -3.0 to -14.2 | v.Soft to Soft silty clay mid | 0 | 28 | | 0.35 | 1.2E-10 | 5 |
| -14.2 to -17 | Medium Stiff silty clay bot | 0 | 32 | | 0.35 | 1.2E-10 | 5 |

## 4 RESULTS

Before lateral deformation output is presented, monitoring data will be used to verify model. Comparation between analysis result with monitoring data for settlement could be found in Figure 7 and lateral movement in Figure 8. Analysis result show that FEM deformation have match with the actual monitoring data and represent actual site condition.

Deformation analysis result shows in Figure 9 to Figure 12. Significant ground surface settlement (>5cm) reach 15m from boundary and significant Lateral movement (>5cm) happen until 20m away from the improvement boundary. Based on this result, safety distance from vacuum preloading boundary could be set depending on the tolerance of structure or infrastructure in the surrounding to movement to movement. However, Tension crack behavior cannot be identified though the FEM model.

Excess PWP results at the end of vacuum preloading period show in Figure 13. Inside improvement area, at the soft clay layer excess PWP is 70-75kPa and outside improvement area its around 0 to 15kPa. This result show that vacuum preloading does not change water pressure outside improvement area. Permeability of clay material in the boundary is low enough that the pore pressure is not developed outside PVD influence zone. Deformation outside the improvement area is not happen due to change of water pressure underneath it.

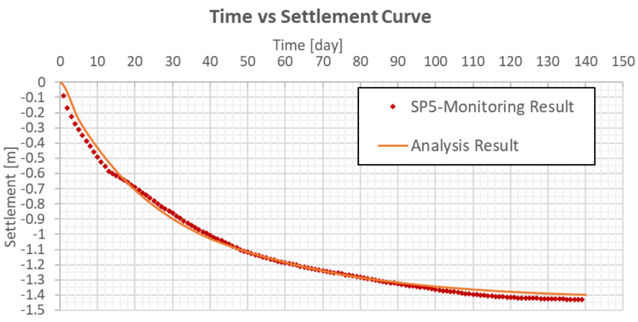


Figure 7. Back Analysis Result of Time Settlement Curve

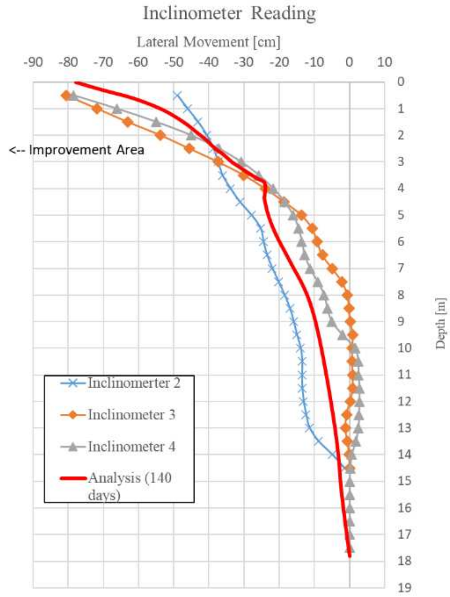


Figure 8. Back Analysis Result of Lateral Movement

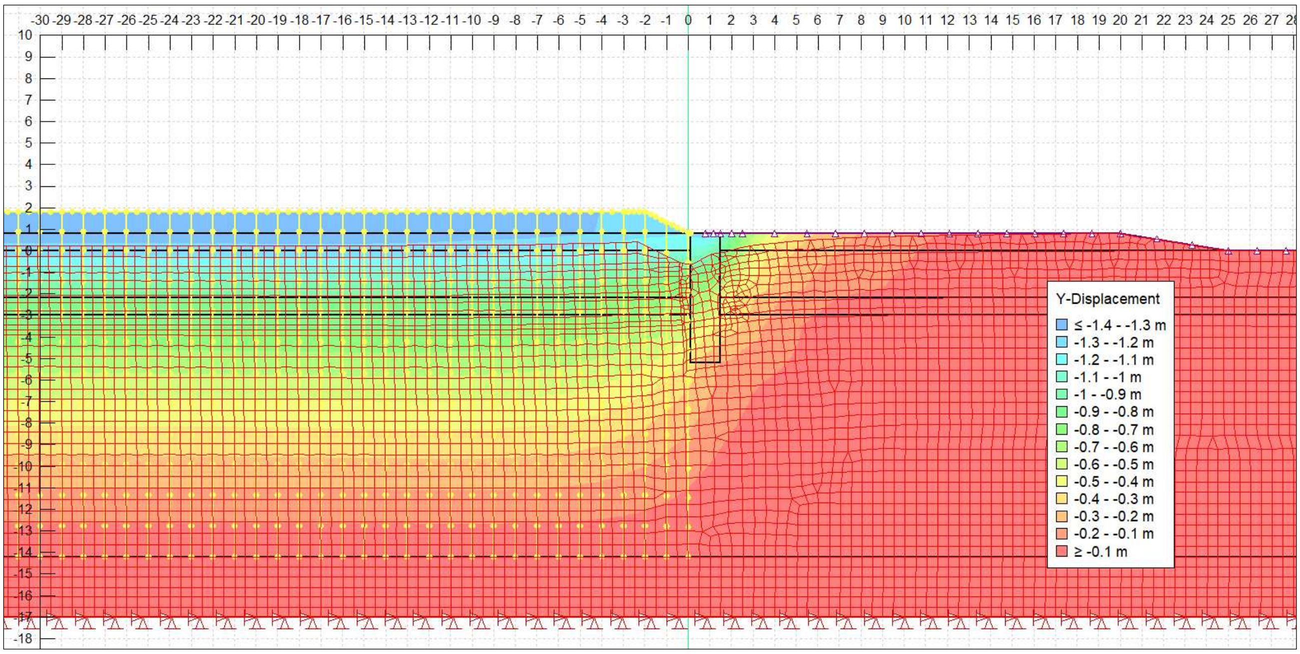


Figure 9. Settlement Analysis Result at The End of Vacuum Preloading Period

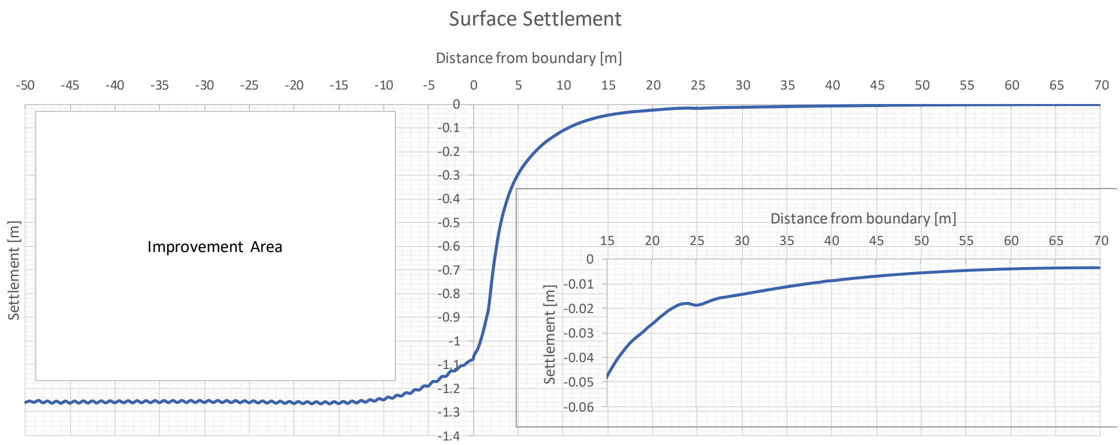


Figure 10. Settlement Profile on Ground Surface

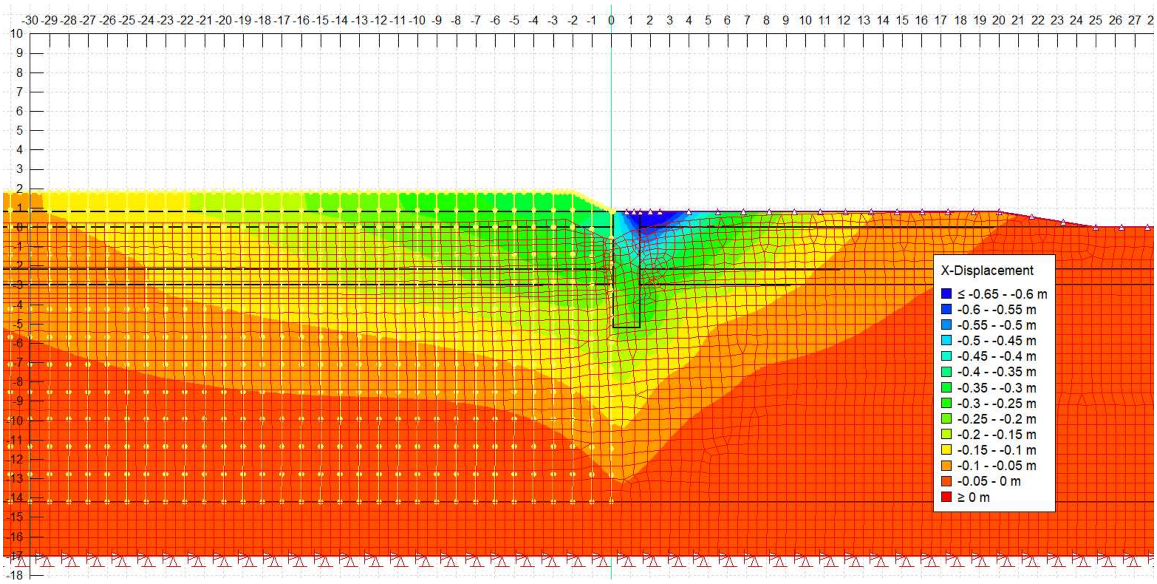


Figure 11. Lateral Movement Analysis Result at The End of Vacuum Preloading Period

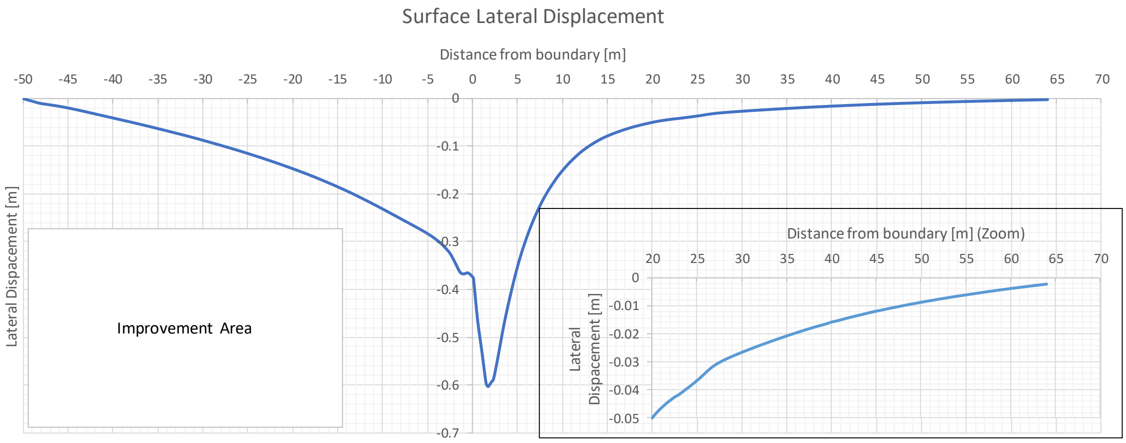


Figure 12. Lateral Movement on Ground Surface

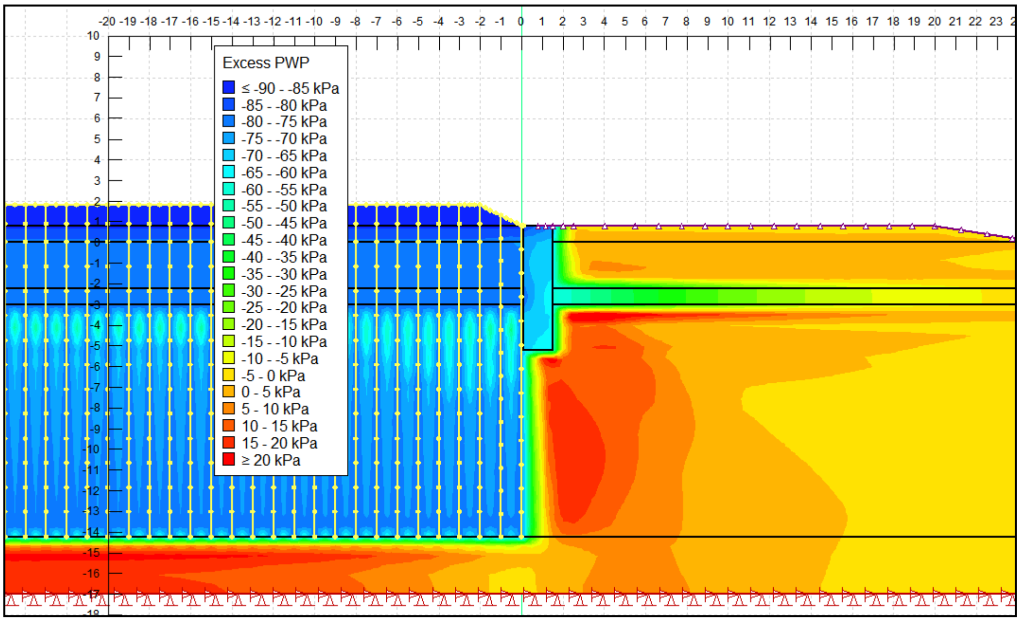


Figure 13. Excess Pore Water Pressure Result at The End of Vacuum Preloading Period

Mean effective stress (p') result show in Figure 14. Observation is made in line between 2 PVD model. Increment of effective stress is from estimate 70-80kPa.

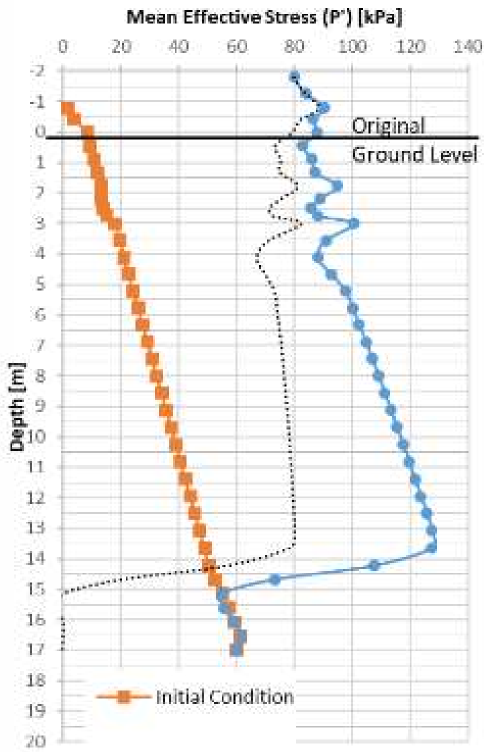


Figure 14. Mean Effective Stress Increment

## 5 CONCLUSIONS

Finite Element Model with suction head hydraulic boundary can simulate the behavior of vacuum preloading application fairly well. Deformation of soil in the surrounding of improvement area, can be predicted in advance and safety distance can be determined. Beside safety distance, additional measure to limit the lateral movement of the surrounding area also can be better plan in the design stage. In the case study presented, Significant ground surface settlement (>5cm) reach 15m from boundary and significant Lateral movement (>5cm) happen until 20m away from the improvement boundary.

Observed pore water pressure from the model at the end of vacuum preloading Inside improvement area is 70-75kPa and outside improvement area its around 0 to 15kPa.

Mean effective stress (p') in the observation point between vacuum drain show value of 70-80kPa. this value is equal to 87%-100% from vacuum suction (80kPa).

## 6 ACKNOWLEDGEMENTS

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