Necessity of Integrating Soil Treatment Systems in BIM from Design to Final Construction

mohamad mehdi pardsouie[1]

[1]Affiliation not available

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Introduction

The ironic phrase used by (Antoljak 2020) may be best to define the process of formation of BIM with reference to geotechnical engineering 'the BIM collaboration is increasingly being achieved via data stored in and shared in the cloud. Geotechnical data that has always been so much down to earth now needs to be looked up in the cloud'. BIM allows governments and Architecture/Engineering/Construction organizations to collaborate and transform any infrastructure asset into a computer model long before breaking the ground. Consequently, many conflicts can be identified and resolved in the model at a fraction of the cost it would require to correct the mistake in the field (Antoljak 2020). As reported by (Tawelian and Mickovski 2016) geotechnical engineers fully support the integration of geotechnical data into the BIM process, while the majority of them consider that this would provide significant cost and time savings in major infrastructure projects. (Valeria, Roberta et al. 2019) Successfully imported a big quantity of borehole data in BIM software which were lately used for the design of soil nail reinforcements. (Berdigylyjov and Popa 2019) Investigated the barriers of integration of geotechnical and structural data as a single BIM model. It was stated that one of the obstacles was that many geotechnical engineers are discouraged from sharing data for the fear of possible interpretive misuse. (Fabozzi, Biancardo et al. 2021) performed a "3D BIM to finite element model (FEM) to BIM analysis" for a tunnel excavation case study. By the completion of the analysis the fourth dimension for project management was also added to the numerical model. It was shown that the existing 3D FEM software's are not still mature enough for such complex systems and more improvement is necessary in this area. (Xu and Wang 2020) Used 3D geological modeling to conduct preliminary investigation of geotechnical survey results. (TUDublin and Brennan 2021) Conducted a case study on applying BIM for coastal infrastructure projects and proposed a potential of a 40 percent saving in capital budget. (Vaníček, Jirásko et al. 2021) State that by incorporation of BIM in geotechnical engineering along with 3D Geotechnical structure model, the necessary base for the future decision making would be created especially when some changes occur in the projects. (Goyal, Rai et al. 2022) Emphasized the revolutionary impact of BIM and transportation geotechnical engineering. (Bradley, Li et al. 2016) in a review highlighted the developing base of BIM for infrastructures from preliminary analysis to construction site and state that with the increasing complexity, Information uniqueness and governance requirements of infrastructure projects graph based technologies and distributed data environments are the way forward in meshing together and leveraging the vast amount of data produced by modern day architecture, engineering, construction, owner and operator Projects.

Soils with poor geotechnical properties, such as weak clays, require improvement technique applications. Surcharge preloading along with PVDs is a very common technique nowadays and can be seen nearly in all section from urban to industrial industry, expanding to any location regardless of undesirable ground condition where it might be weak pits or expansive and sensitive marine clays. Since clays and peats have very low hydraulic conductivities, PVDs which have high hydraulic conductivity and high bending strength, are widely used in soft subsoil improvement. PVDs alter the drainage pass from vertical direction to horizontal, and accelerate the primary consolidation of soft ground. The basic concept of preloading is the reduction of weak soils void ratio through consolidation by applying pressure on ground surface for a predetermined time period and then removing whole or a part of embankment for construction of a permanent super structure. . A key design feature of prefabricated vertical drains (PVDs) use is to accelerate consolidation and increase shear strength of the weak, fine-grained foundation soil(Stark, Ricciardi et al. 2018) but care should be taken in real assessment of real behavior of the embankment. In the case of shortage of time, supplementary methods such as vacuum preloading might be applied as well. In such a case preloading consists of combined vacuum and surcharge preloading. Because of excessive downward and lateral forces, PVDs should be very flexible in nature otherwise the drainage capacity would be decreased or lost and in such a case differential settlement is unavoidable. In recent years new generations of PVDs with higher discharge capacity and strength were introduced like (Fu and Chai 2020, Zhang, Chen et al. 2020). Overestimation and false assumptions in design are the main factors which lead to embankment failures in most of the reported cases (Tan and Liew 2000, Hayashi, Nishimoto et al. 2011, Stark, Ricciardi et al. 2018).

After preliminary site investigation and superstructure designation, based on project time schedule and cost, the soil treatment procedure is defined. Since such projects are often big-scale inherently, all parts from design to field executive operations are divided between different teams and smaller companies. Because of this inevitable division in responsibilities, there are always many clashes and inconsistencies between design offices and also between design sheets and field executive operations. This article discussed the importance of collaboration that should exist between structural and geotechnical designers and executive engineers. Two important items such as the infiltrated layer and the behavior of treated soil including PVDs in different phases of construction is discussed that is often neglected even in mega projects, and have the potential to become the reason for catastrophic failures in such projects.

Preliminary site investigation and superstructure design

After preliminary site investigation and determination of the overall project site plan, structural designers perform the preliminary designs of the super structure. Then the foundation is designed. Based on the configuration of footings, the required bearing capacity of the soil is determined and then the geotechnical engineers check the site preliminary site investigation report to check if ground improvement is necessary or not. If there would be weak clay stratums with high compressibility index and low bearing capacity, preloading or other soil remediation techniques is inevitable. Figure 1 shows a sample of such report that belong to Mekong test embankment in Vietnam (Nguyen and Pham 2012)

(Figure 1)

In this step the design and execution of soil remediation (here surcharge preloading) is often assigned to a third party. The preloading would be designed and executed in the field and meanwhile the superstructure designation would be finalized. All the designs are based on estimated parameters taken from preliminary site investigations like what is shown in figure 1 such as the soil profile, soils bearing capacity strength, underground water level and related probable fluctuations, drained and undrained shear strength, coefficient of soil reaction and etc. By the completion of preloading operation in the field, the unloading process would start and then the executive operation of superstructure would begin immediately. Now a question arises if all the preliminary assumptions that are the basis of the designations are valid. If not, what would be the consequences of these unrealistic assumptions.

Figure 2 shows an example of displacement of surface under the embankment (consolidation) resulting from preloading for a project in plane strain condition. In the first glance it is a normal displacement curve but the point is that other than displacement, it actually shows the volume of hydraulic fill that has been entered into the ground beneath the surface line. Hydraulic fill is a term that is used for any materials constructing embankment bodies and can be sand, clay and even reinforced geomaterials (Rowe, Taechakumthorn et al. 2008, Chu, Bergado et al. 2012).

(Figure 2)

New soil stratum

Figure 3 shows the schematic sequences of preloading and the new stratum that had been formed there in a finite element program (Geostudio Sigma/w). Figure 3a shows a FEM model based on a preliminary soil report. Figure 3b shows the embankment constructed on the ground. As it can be seen after the completion of consolidation, the new infiltrated layer is a part of soil stratification under foundation (figure 3c). The preloading process is shown in the FEM program to illustrate the power of FEM programs in such problems and great potential of geotechnical FEM software's which can be integrated in BIM. Figure 3d shows the PVDs that were installed under embankment to accelerate the consolidation process.

(Figure 3)

The main factor in determination of hydraulic fill is the availability of it and hence any material either with or without preferred engineering property would be used for the embankment body. It should be noted that nearly in most of the projects at grading phase, the upper organic soils are removed and usually replaced by a 0.5 m subgrade with the minimum compaction of 90 percent like the case history reported by (Debats, Scharff et al. 2013). In fact the infiltrated soil layer in some parts that has the settlement more than 0.5 m is a combination of two materials that is subgrade and upper hydraulic fill. Since the designation process of superstructures is finalized, none of the distinct characteristics of the new layer would be reflected in the designation. The soil underneath is treated by surcharge preloading along with PVDs but this new stratum is only under the pressure of hydraulic fill above it. Since the basis of calculated time for target consolidation time is only for layers existing in the preliminary geotechnical reports, in the case of high compressibility index or high water content or low shear strength, the infiltrated zone becomes the weak zone of embankment. The coefficient of soil reaction was computed based on a preliminary report and has a different value compared to existing soil layer and also the assumed underneath soil stress distribution is not valid anymore.

This issue can be investigated in 4 different cases as:

1. Issues and uncertainties in preloading phase
2. Issues and uncertainties in surcharge unloading process
3. Issues and uncertainties in superstructure construction phase
4. Issues and uncertainties after the completion of main structure It should be mentioned that there is no difference between embankment with or without reinforcement and all 4 cases are valid for both.

Issues and uncertainties in preloading phase

Embankments are usually designed with a factor of safety ranging from 1.1 to 1.5 (Han 2015) and therefore the pressure applied during the preloading is greater than the pressure that would be applied after the completion of superstructure. As a result of inclusion of PVDs a faster rate of fill placement would be applied compared to the condition without PVDs presence (Weech and Lister 2009). Regarding case 1, if the infiltrated layer doesn't have enough shear strength, with the increase of the embankment height, the shear stresses continue increasing. When the shear stress is equal to the soil shear strength, the soil yields and slip surfaces develop. When the slip surfaces are fully developed, the soil is no longer able to carry any additional load; therefore, the footing would collapse (Han 2015). Although footing collapse doesn't occur instantly in most of the cases, first shear cracks would appear on embankment surface as reported by (Stark, Ricciardi et al. 2018). Occasionally by the appearance of these cracks, the backfilling would be stopped.

Issues and uncertainties in surcharge unloading process

For case 2, since after the completion of the unloading process, a surficial heave happens, a small fraction of the infiltrated layer would be removed as well. For the case where expansive or any other problematic soil existed, the construction process can be delayed for treatment or complete removal and replacement of undesirable layers.

Issues and uncertainties in superstructure construction phase

Regarding case 3, since there is a completely new soil layer, the design procedure regarding "replaced zone" (Han 2015) should be applied for foundation bearing capacity and settlement requirements and not the common procedure which might have been applied without considering the real field situation. All the parameters including Depth of replaced zone, Length and width of replaced zone, Thickness of the replaced zone and Fill quality including strength and modulus of fill should be considered in the designation. The detailed design procedure and possible failure modes can be accessed from (Brown 2001) that are 1) general failure within replaced zone 2) punching failure through replaced zone 3) failure of distributed foundation 4) punching failure of replaced zone. The ultimate bearing capacities of the footing on the replaced zone for all the possible failure modes should be calculated based on the short-term and long-term strengths of the soil and fill. The minimum ultimate bearing capacity among all the calculated values should be selected for the design. If the minimum allowable bearing capacity is less than the applied pressure, the design parameters for the dimensions of the footing and dimensions and properties of the replaced zone should be adjusted until meeting the bearing capacity requirement(Han 2015). Since the foundation is situated above reclaimed land including PVDs (figure 3d), the constitutive model proposed by (Flessati, Di Prisco et al. 2020) can give a reasonable outlook of foundation behavior.

Issues and uncertainties after the completion of main structure

For case 4, if the infiltrated layer is susceptible to liquefaction or expansion (because of expansive clays), necessary considerations should be accounted for by the designers. The foundations that are situated on treated soil with PVDs are inherently susceptible to differential settlement as a result of soil anisotropy, smear zone, partial penetration of PVDs, secondary consolidation, unsaturated soil consolidation and the existence of layers with high compressibility in great depth (Paveenchana and Arayasiri 2009, Long, Bergado et al. 2013, Jang, Chung et al. 2014, Da Silva, Justo et al. 2017, Zhuang, Wang et al. 2017, Abouhashem, El-Gendy et al. 2021). If the effects of an infiltrated layer don't be considered in the design process, the possibility of differential settlement increases drastically.

As a result of the presence of PVDs under infiltrated layers, especially in the case of permanent road embankments, the analysis of bearing capacity of the foundation should be checked considering the unsaturated soil with negative pore pressure as discussed by (Fredlund, Rahardjo et al. 2012). The existence of PVD under the foundation changes all the known governing equations, and till now short and long-term behavior of such treated soils under different conditions and scenarios(static and dynamic loads, severe climate change, underground water fluctuations and etc.) have not been investigated. As a general recommendation, since there are numerous unknown parameters regarding the behavior of saturated and unsaturated zones related to PVDs inclusion, it is wise for the designers to use higher safety factors especially in the case of sensitive and very sensitive structures. Sand layers and sand lenses are very common in preliminary site investigation reports. Both the potential of liquefaction and cycling softening (Chu, Stewart et al. 2008) should be checked by designers especially in areas with high seismicity.

Design and executive recommendations

Based on four cases that were discussed the following design and executive recommendations might be considered by office and field engineers as:

1. For finalizing the foundation and superstructure design, field and lab reports after the compilation of ground reclamation operations should be considered.
2. For geo-materials that would form the embankment body and especially the first layers that would infiltrate to ground (in the case the foundation is on the ground), special considerations should be taken by both geotechnical and structural engineers.
3. Field engineers should strictly follow the quality control (QC) checklists that have been provided by the designers and don't underestimate the embankment as an impermanent structure.
4. Plate load test before and after compilation of soil treatment operation, is a must for soil treatment systems regardless of the size of the project. The quantity and location of the tests should be determined and referred by designers in QC checklists.

5. Since the short-term and long-term behavior of PVDs is still unknown especially under earthquakes and there is possibility of further settlement as a result of excess pore pressure formation under dynamic loads (Han 2015), in areas with high potential of seismicity, consideration should be taken by designers especially for sensitive and very sensitive structures. If there is such a case, performance based design might be an option.
6. Soil bearing capacity should be checked for unsaturated state. Since till now there is no research about short-term and long-term behavior of soils including PVDs, it is wise to use higher factors of safety based on engineering judgment.
7. Sand layers and sand lenses are very common in preliminary site investigation reports. Both the potential of liquefaction and cycling softening should be checked by designers especially in areas with high seismicity.

The necessity of incorporating soil treatment system in BIM

The importance of the existence of BIM may not be better understood considering all the cases that were discussed here. All the projects including ground treatment are from big scale to mega scale, and collaboration between all staff participating from the preliminary design to final landscaping is a must. By applying BIM capacity in the project, the necessary base for collaboration between engineers in various fields is provided to avoid such design and executive faults. It was shown that even a simple false assumption can lead to costly remediation works that on the other side has the potential to cause a considerable delay in the project. The operational costs associated with BIM implementation in small to medium companies, was the main obstacle in BIM growth in the past but with the fast growing of awareness regarding the benefits of the existence of such systems, nowadays it is viewed as an investment instead of unnecessary cost. Unfortunately unlike architectural and structural cases, the entrance of geotechnical engineering in BIM platforms was and still is very slow and apart from its deterministic role in main construction parameters, it is like a newborn infant in BIM.

All the leading companies that were active in the geotechnical engineering software industry started incorporating their products in BIM for the past decade, although it seems there is a long way to see a geotechnic-structure-architecture BIM platform as complex and efficient as it exists for architecture- structure.

Ground parameters obtained from preliminary site investigation have a deterministic effect on the design of the structure and even a little change in their quantity is equal to tons of bar and concrete. On the other hand exactly the same is true for structural design parameters compared to geotechnical parameters. The basis of designs for each party is the parameters that are announced by the other party, as there is a connecting chain between them. If soil treatment would be necessary, the importance of the selection of the right soil parameters amplified greatly as shown in previous sections. Since soil treatment alter the geotechnical property of site completely, along with raw data obtained in the field, lab and log reports, profiles and sections, interpolated 3D models and geotechnical analytical models (Antoljak 2020) that should be linked and stored in BIM database, soil treatment FEM analyses and precise site and lab reports after the compilation of treatment process should also be stored and linked with special obsession.

Conclusion

This article followed two main objects: First, a case is presented in full technical detail and the importance of permanent collaboration between different parties is shown, and second, the importance and necessity of the existence of a system like BIM is illuminated, as in big and mega projects with thousands of design and report sheets, such a close link is if not impossible but is very hard to be attained. In the case of weak collaboration it is obvious that both the time and final cost would be increased drastically. The objective of this study was illumination of this matter and only a small case was discussed. A BIM basis that includes a complete geotechnical-structural-architectural framework can greatly ease the necessary collaboration between related parties and reduces a considerable amount of project cost and time. 3D Geotechnical FEM softwares with capability of communication of data between related programs are an inseparable part of the near future

BIM integrated systems.

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FIGURE DISCRIPTIONS:

Figure 1: A sample of preliminary site investigation report after (Nguyen and Pham 2012)

Figure 2: Surface settlement under surcharge embankment simulation in a FEM software

Figure 3: Schematic FEM (a) existing ground before soil treatment (b) surcharge embankment on the ground (c) infiltration of the embankment in ground due to the consolidation (d) PVDs installed in soil treatment system

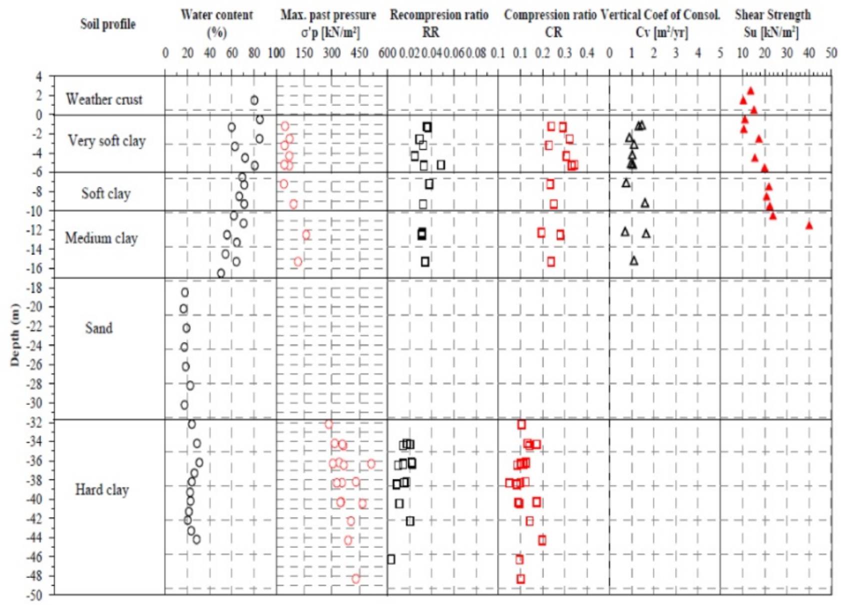


Figure 1

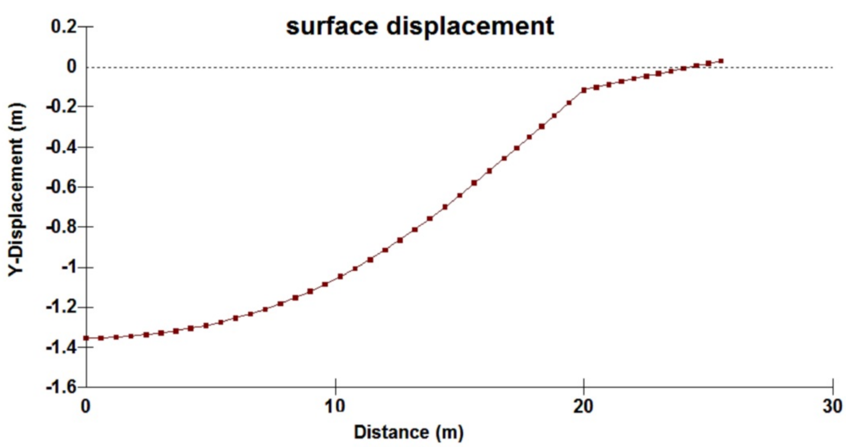
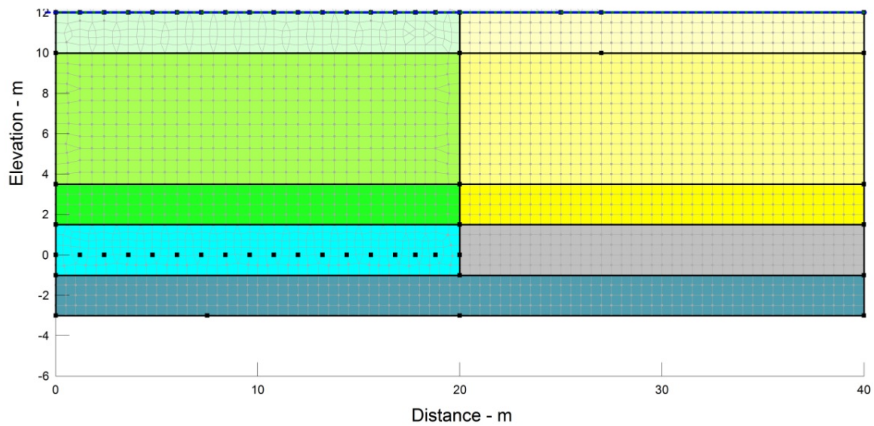


Figure 2



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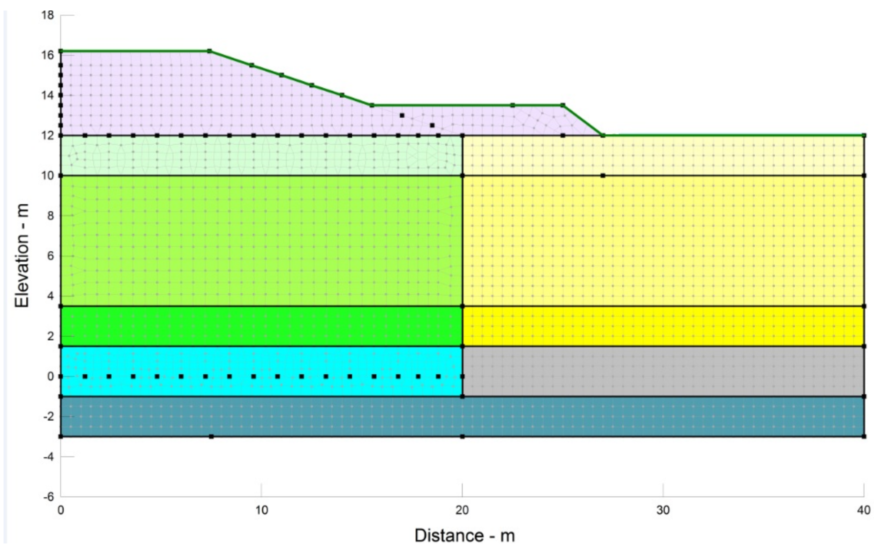

Figure 3b

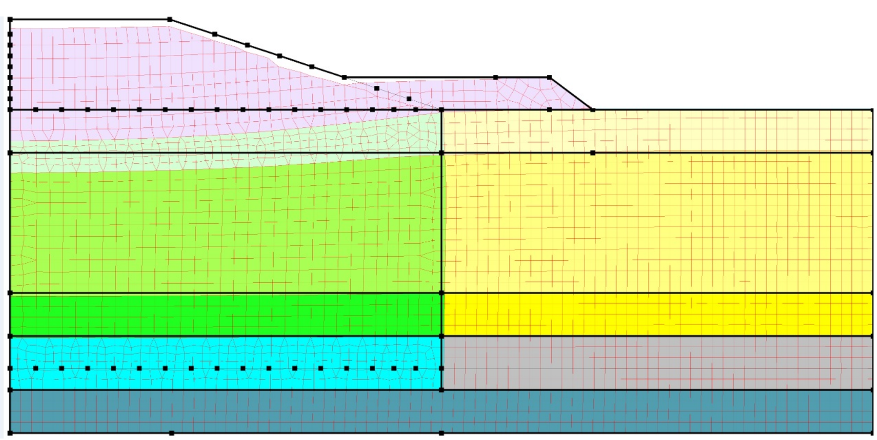

Figure 3c

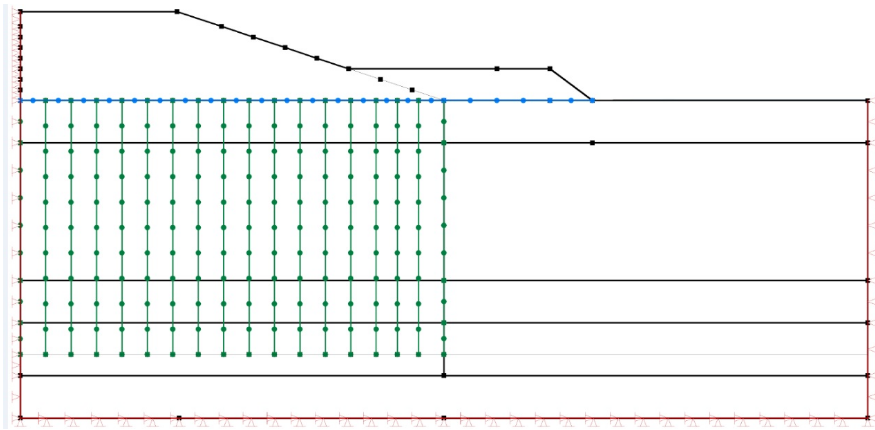

Figure 3d