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2D numerical modeling of sand compaction pile in soft soil under railway embankment

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ABSTRACT: Performance of SCP improved ground has been studied using software aided 2D & 3D Finite Element (FE) models. A challenge in modeling of 3D practical scenario in 2D model was solved utilizing simulation of drainage path in 2D plane. A new method for simulation of drainage path in 2D model was proposed, keeping the replacement ratio and diameter of SCP unchanged. The result from analyses indicated that proposed method of equivalent 2D idealization of 3D problem simulated both consolidation and stability.

1 INTRODUCTION

Embankment construction on soft soil requires ground improvement. Sand Compaction Pile (SCP) is one the many methods of ground improvement. Sand Compaction Pile (SCP) improved ground is a 3D problem. To accurately simulate the behavior of SCP improved ground in a Finite Element (FE) model, it is preferable to model it as a whole system. However, finite element calculations with discrete modelling of granular piles in 3D are very complicated and time consuming. For routine analysis and design, it is not feasible. Therefore, 2D analysis is easy, cheaper and less time consuming. But, modelling 3D practical problem in 2D model is challenging. Schweiger & Gab (2006) gave an overview about issues in modelling of stone columns and simplifications, when a full 3D analysis is not performed. Simplification of model geometry as well as parameters is often needed. These modifications of parameters vary depending on the type of analyses performed.

For consolidation analysis of ground improved by granular pile (GP), analytical methods developed so far using concept of a "unit cell", wherein a circular domain of influence of GP is analyzed. Assuming that each unit cell works independently and all strains within the soil mass occur in the vertical direction only (Barron, 1948; Hansbo, 1981). This assumption of no lateral displacement is not reliable particularly for the case of embankment on soft ground. Schweiger and Pande (1988) introduced an "equivalent material" model of improved ground for 2D plane strain analysis where "Equivalent material" is modeled with the "equivalent parameters" of strength and stiffness. But flow parameters were not considered. Therefore, their model only analyzed undrained or fully drained cases.

It is necessary to convert the spatial flow in actual case into the laminar flow in 2D plane strain model for consolidation analysis. Shinsha et al. (1982) attempted to do so and introduced converted permeability based on the assumption that the required time for 50% degree of consolidation in both scheme (actual case and 2D model) are equal. Later, Cheung et al. (1991) concluded that Shinsha's method should be used with caution as it shows higher pore pressures in 2D model.

Asaoka et al. (1991) transformed (SCP) into a number of sand walls for analysis of undrained failure of embankment. Similarly, Bergado and Long (1994) have proposed an approach for 2D modeling of GP, where GP is transformed into continuous walls with the same spacing as that of the actual case considering area replacement ratio (a_s) is same for both scheme. Therefore, the thickness of the wall in 2D model is smaller than the diameter of GP in actual case.

Recently, Weber et al. (2009) represented 3D stone column grids in 2D model as a series of parallel trenches. Stiffness as well as permeability was adapted in order to model the deformation behavior and drainage conditions for consolidation correctly. All these models deal with consolidation analysis solely.

In this research, authors have developed a 2D idealization of 3D SCP improved ground problem. It can be used as consolidation analysis as well as stability analysis. This study consist a series of 2D and 3D numerical analysis to justify the developed idealization.

2 PROPOSED 2D IDEALIZATION OF 3D PROBLEM

SCP is 3D in field. This becomes a rectangular trench when it is modeled in a 2D space. Therefore, geometric distortion occurs. To overcome this distortion, and model actual case in 2D, this method is developed. Basic idea behind developing this method is to combine a consolidation analysis 2D model and a stability analysis 2D model. For consolidation 2D model, conversion of soil permeability is necessary. And for stability analysis, conversion of physical and mechanical properties of soil (such as stiffness) are important. Combining these two, this proposed method is developed.

Firstly, for consolidation settlement of soil, it requires appropriate drainage condition or permeability of soil. When a 3D SCP improved ground is simulated in 2D model, due to the changes in geometry, area of SCP and surrounding soil is changed. Therefore, drainage condition is changed as well. The permeability must be adapted to represent the modified drainage condition. Hird et al. (1992) and Indraratna & Redana (1997, 2000) recommended how to perform a conversion of permeability.

In this developed method, permeability is not converted from 3D to 2D, rather practical drainage path is simulated in 2D model. Assumption is made, if drainage path in actual case and in 2D model is equal, then time required to pore pressure dissipation will be equal. Therefore, consolidation settlement behavior of field can be simulated in 2D model.

To minimize variable parameters from equation, area replacement ratio (a_s) and SCP diameter (d_w) of actual field is kept similar in 2D model. Therefore, the spacing of the SCP must be adapted for 2D model. Area replacement ratio a_s can be expressed as follows:

$$a_s = (d_w/D_e)^2 \quad (1)$$

here, d_w = diameter of SCP

D_e = effective diameter of equivalent circle

According to Rixner et al. (1986), D_e can be defined as follows,

$$D_e = 1.05 \, . S \quad (2)$$

here, S = Spacing of SCP in field/design

Further, the maximum travel distance (i.e. drainage path) of pore water in 3D model d_t, can be expressed as follows,

$$d_t = (D_e - d_w)/2 \quad (3)$$

Now, the spacing of SCP in equivalent 2D consolidation model S_m, can be written as

$$S_m = 2d_t + d_m \quad (4)$$

This will ensure the same drainage path in 2D model, where d_m = width of SCP trench in equivalent 2D stability model and a hypothetical PVD is modeled in between two SCP trenches as shown in Figure 2.

Now, to keep equivalent vertical stiffness in 2D model, area replacement ratio was kept unchanged. In 2D model, area replacement ratio and S_m are related as follows,

$$d_m = S_m \, . a_s \quad (5)$$

In Equation (4) and (5), S_m and d_m are two unknowns. By solving these two equations width and spacing of SCP trenches are found. Therefore, the area replacement ratio and diameter of SCP is unchanged.

One limitation of this method is that it does not consider smear effect of SCP installation. In this paper, several 2D and 3D models have been analyzed, to verify the applicability of this developed method. Analysis and results are presented in the following sections.

3 FE MODEL FOR ANALYSIS

3.1 *2D model (using proposed method)*

Both the 2D and 3D Finite Element (FE) calculations is performed using the software PLAXIS with 10 node element. The Hardening-Soil Model is used for Sand and Embankment material, Soft Soil Model is used for Clay. Embankment is 3m high, 6m wide crest and side slopes are 1:2 (V:H). Subsoil is 10 m soft clay underlain by dense sand. Embankment is symmetric, so only one half is modeled (the right half is chosen). SCP of 300 mm diameter and spacing 1500 mm, (a_s= 0.04) is considered. Deformation and ground flow boundary conditions are applied for symmetric condition. Ground water is defined at the toe RL of the embankment at the initial phase of analysis.

For 2D analysis, SCP is modeled as rectangular trench. The width of the trench is equal to the diameter of the SCP. But, the distance between trenches is calculated using the developed method. Calculating Equation (1-5), following values were obtained;

S_m = 2646 mm

d_w = 300 mm

a_s = 0.04

Therefore, mathematically the maximum drainage path is (2646-300)/2 =1173 mm, which is almost double the maximum drainage path at field. So, a line drain in between two sand trenches is modeled. So the drainage path in 2D model is 1173/2 = 586.5 mm. FE 2D model with mesh is shown in Figure 1.

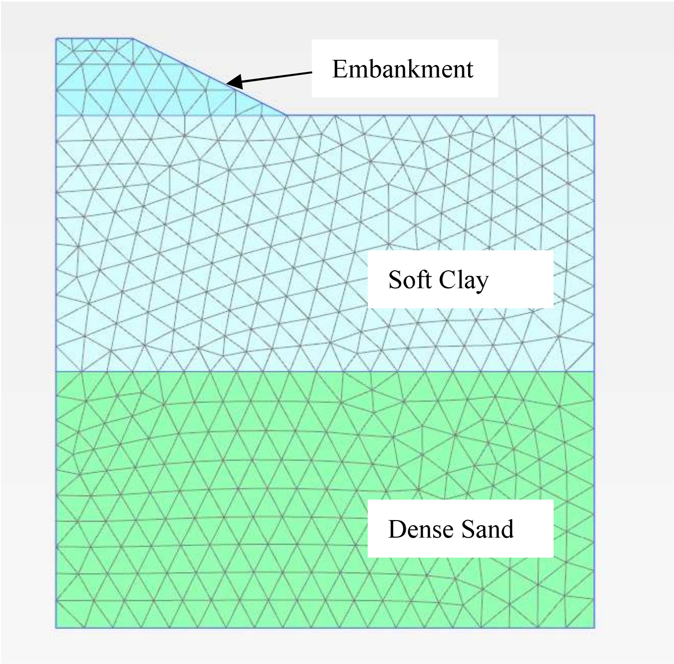

Figure 1. FE model showing mesh (coarseness factor: 1.0)

2D model of SCP is shown in Figure 2. SCP is modeled as trench of 300mm width, spaced at 2646mm, and vertical line drain in between trenches to simulate drainage path.

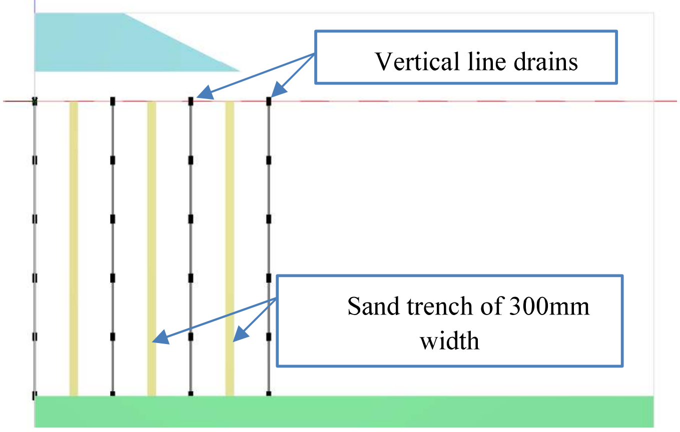

Figure 2. SCP modeled as trench; width = SCP dia, Spacing = S_m

3.2 *3D FE model*

3D model of the same embankment section is modeled using PLAXIS 3D to verify developed 2D idealization. SCP diameter 300mm and spacing 1500mm is used. Material property in both 2D and 3D analyses. Material properties used in analyses are discussed below. Figure 3 shows SCP in 3D model.

3.3 *Materials*

Properties of the materials used in 2D and 3D model, are shown in Table 2. In these analyses, clay permeability is very high which is not realistic. This is used to verify the developed method only, not to predict settlement or consolidation period accurately.

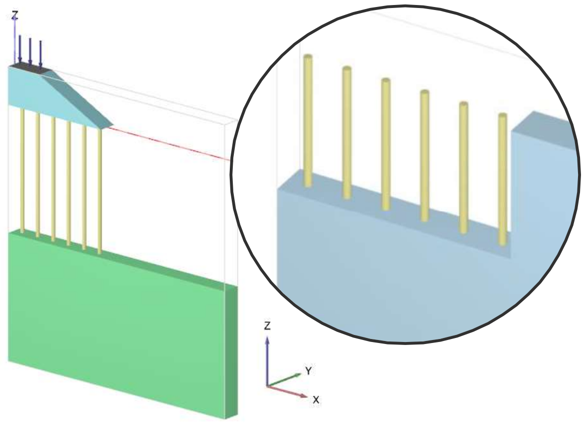

Figure 3. SCP model in 3D; cylindrical shaped SCP in close-up view

Table 2. Properties used for in model

Material	Unit weight (kN/m^3)	Effective Young's (E') (kPa)	Initial void ratio	Eff. cohesion c' (kPa)	Phi' (°)
Embankment Sand	19	25,000	0.50	01	30
SCP	18	35,000	0.50	01	30
Sand (dense)	20	35,000	0.50	01	33
Very Soft Clay	17	--	1.00	25	00

3.4 *Mesh*

Analyses are performed using two types of mesh. First, using coarseness factor 1 for all soil materials and 0.5 for structural loads. Second, coarseness factor of soil materials and SCP is reduced to 0.50 and 0.25 respectively and 0.5 for structural loads.
Global fine mesh is used on top of that. Analyses with the second mesh type is denoted as refined mesh (refn. Mesh) analysis. Figure 4 shows two types of mesh used in this study.

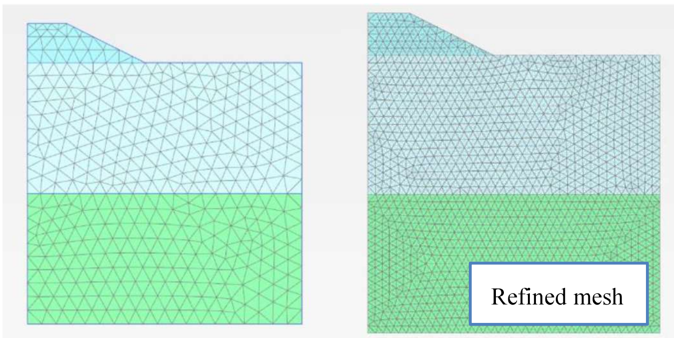

Figure 4. Two types of mesh used in analysis

4 RESULTS OF THE ANALYSES

Without ground treatment the embankment settles mainly vertically with some rotation around the embankment toe and with slight heave in front of the embankment toe. Figure 5 shows settlement pattern of the base of the embankment. Figure 5 shows settlement profile of the base of the embankment.

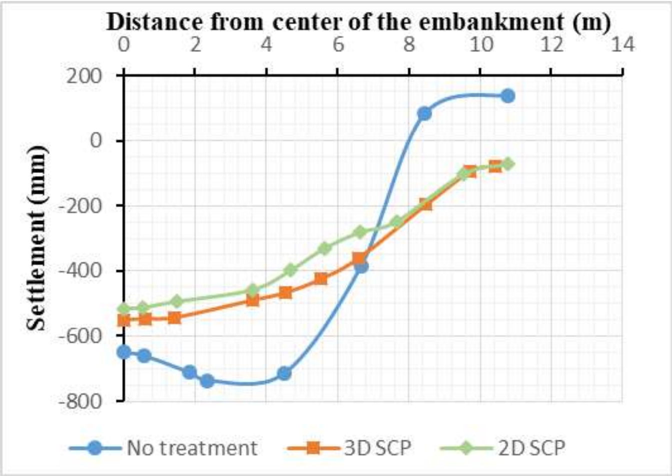

Figure 5. Settlement profile of the base of embankment; corresponding to 95% consolidation state

From Figure 5 it is clear that effect of SCP installation on vertical settlement can be modeled using developed 2D model. Though 3D SCP model result differs slightly with 2D model. The maximum settlement using 3D SCP is 550 mm and using 2D model is 515 mm. This difference can be minimized if mesh is refined in both cases. Figure 6 shows the same plot for refined mesh analyses.

Settlement of the center of the embankment is shown in Figure 7-8. It is found that ground improved using SCP yields 15% improvement in settlement over untreated ground. For untreated ground, total settlement at base corresponding to 90% consolidation is 650 mm.

From Figure 6 and Figure 8, it is clear that mesh size has significant impact on 2D analysis result.

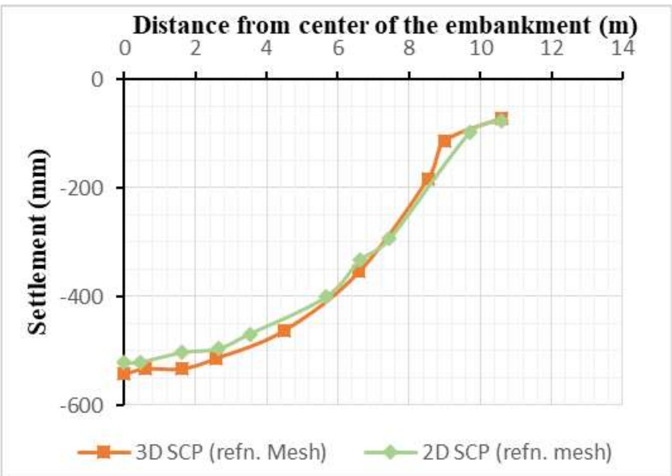

Figure 6. Settlement profile of the base of embankment; using refined mesh (coarseness factor reduced); corresponding to 95% consolidation state

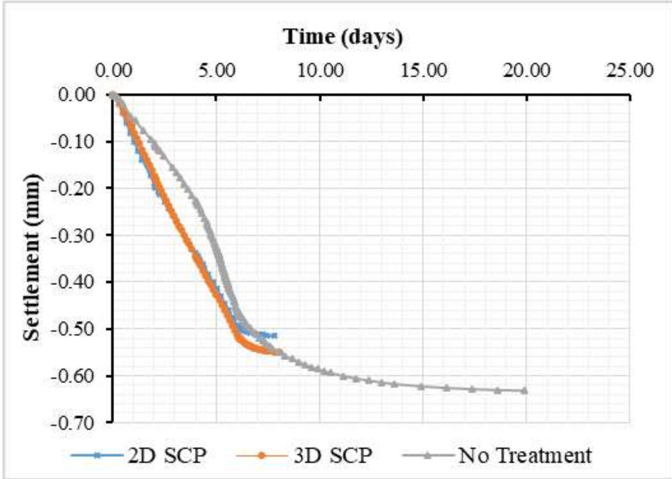

Figure 7. Settlement at the center of the base of embankment; corresponding to 95% consolidation state

Figure 7 shows that improved ground settles less than untreated ground. And settlement curve is similar for 2D model and 3D model. Note that, 95% consolidation is done within a month which is not realistic in case of soft clay. As mentioned earlier, this is due to high permeability of clay in model. This settlement values are just to identify the effectiveness of the developed method.

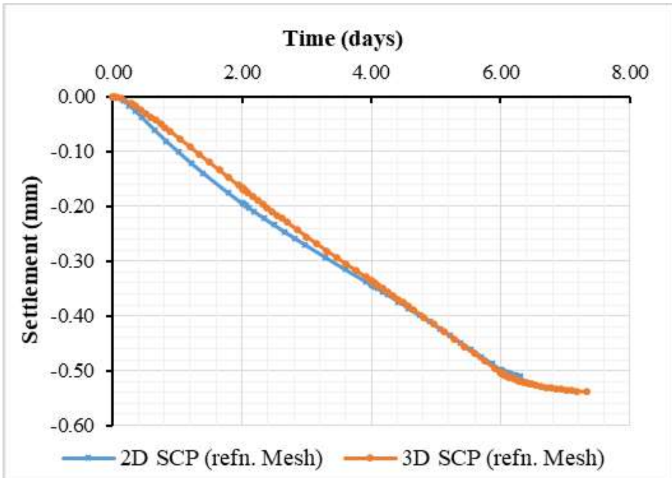

Figure 8. Settlement at the center of the base of embankment section; using refined mesh (coarseness factor reduced); corresponding to 95% consolidation

Figure 8 shows that when mesh is refined further, settlement curve using 2D model and 3D model is almost similar.

Rate of pore water dissipation under embankment using 2D model is found to be similar to 3D model. Figure 9 shows excess pore pressure vs time graphs. From these graphs it is noted that, time required to dissipate pore pressure is almost similar in both 2D and 3D models. But maximum excess pore pressure is lower in 2D model. And the value is almost one-third of the value of 3D model.

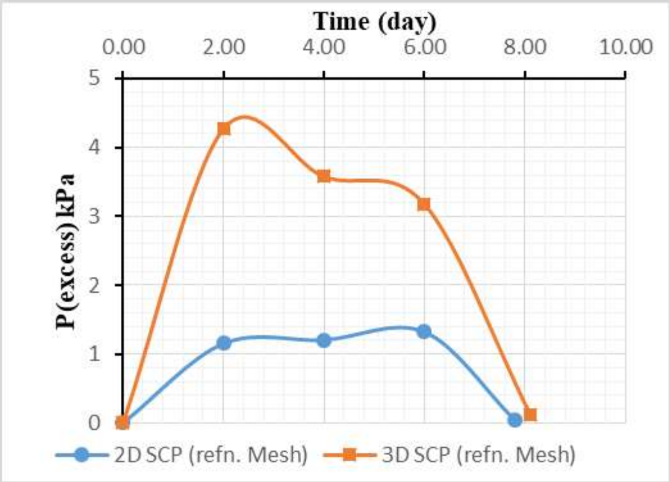

Figure 9. Excess pore water pressure dissipation over time (at center of clay layer)

Along with consolidation analysis, stability of embankment is also checked. In PLAXIS, stability during embankment construction can be checked. As per reference manual of PLAXIS, factor of safety, SF is defined as following

$$SF = \ (available\ strength)/(strength\ at\ failure) \tag{7}$$

$$SF = \ \sum M_{sf} \tag{8}$$

In order to find out stability of embankment, safety factor $\sum M_{sf}$ is calculated using PLAXIS. $\sum M_{sf}$ vs incremental displacement is plotted for both 2D and 3D analysis. Figure 10 shows similarities between 2D and 3D model. Difference between the two $\sum M_{sf}$ values is extremely marginal.

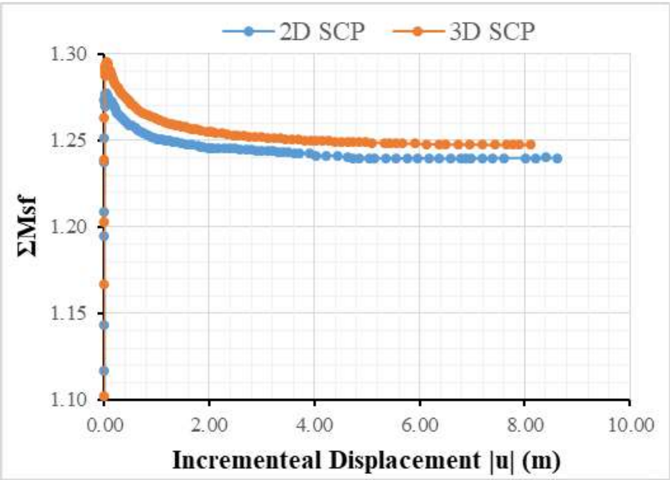

Figure 10. Stability analysis of embankment using 2D and 3D model

Further, using refined mesh for both analysis, $\sum M_{sf}$ vs incremental displacement is plotted again. And this time, there is no difference between the two models. Figure 11 shows $\sum M_{sf}$ vs incremental displacement using refined mesh.

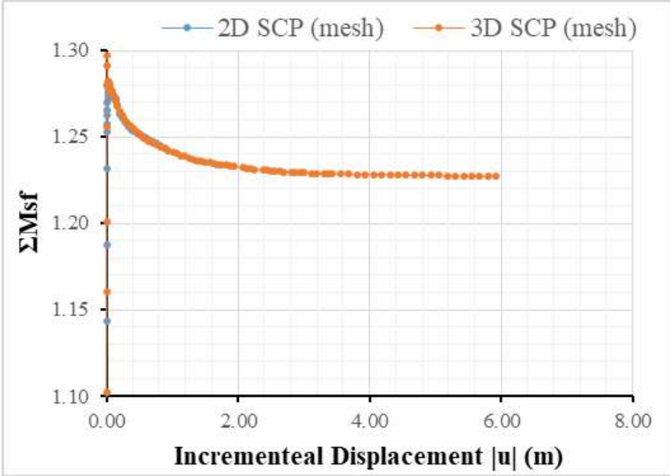

Figure 11. Stability analysis using refined mesh shows no significant difference between 2D and 3D model

Further, effect of plastic points on total settlement is checked for both 2D and 3D model. Figure 12-13 shows plastic points at the last phase of analysis. Comparing these two figures, failure points are found to be similar in both case.

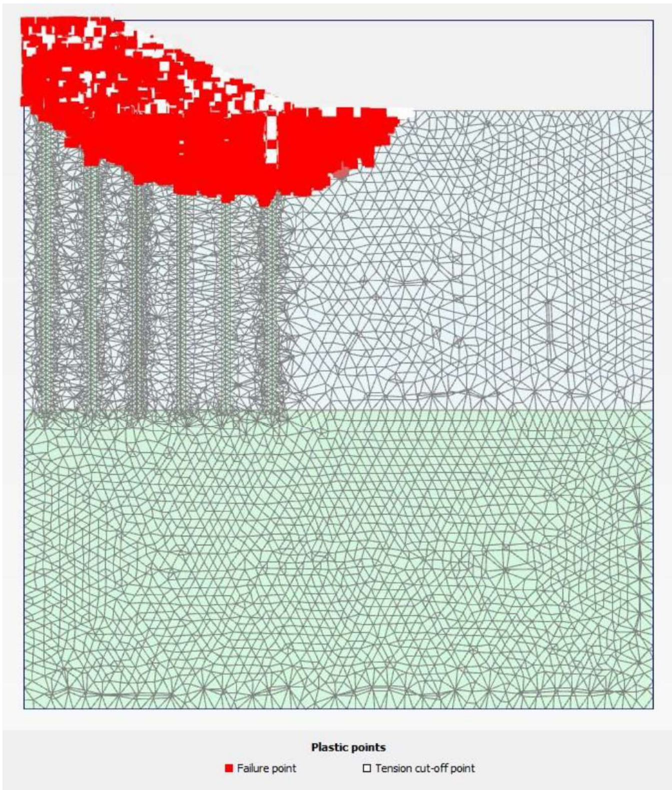

Figure 12. Plastic points for 3D SCP model showing Failure points and Tension cut-off points

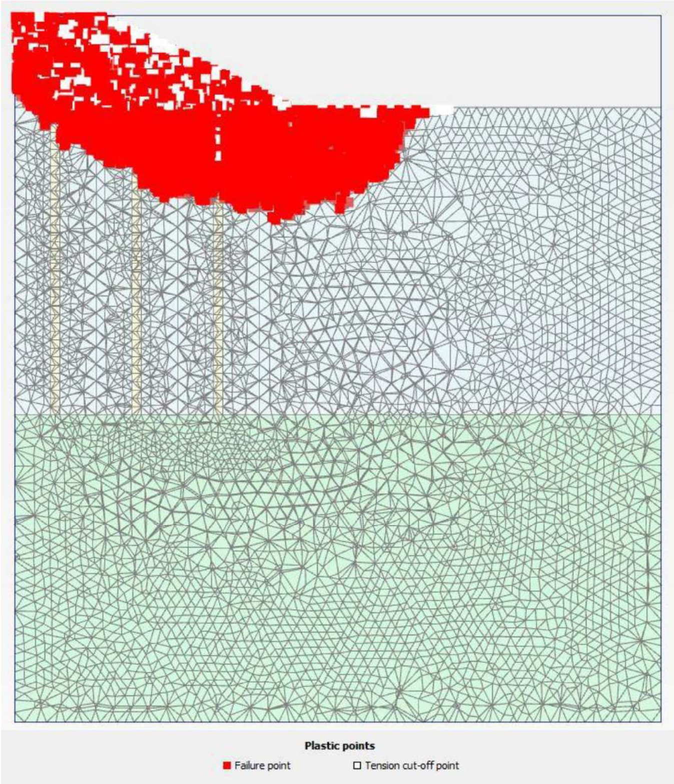

Figure 13. Plastic points for 2D SCP model showing Failure points and Tension cut-off points

5 CONCLUSIONS

The analyses performed in this study are to justify the developed method of 2D idealization. Comparing the results of 2D and 3D models and observations, following conclusive remarks can be drawn:

1. Considering performance of developed model in consolidation settlement, the proposed method seems to work; compared to 3D model
2. Using developed 2D idealization, pore water dissipation rate is found to be similar to 3D model, but maximum pore water pressure is found one-third of the 3D model. Reason is unknown, further studies are required to identify and mitigate this problem.
3. Stability of embankment, during construction and after construction is checked, developed method performs similar to 3D model.
4. The proposed method is developed considering triangular distribution of SCP; thus only applicable to triangular distribution pattern
5. It does not require permeability adaptation; rather it is based on the simulating maximum drainage path.
6. This method only requires a few equations and conversion of stiffness parameter of granular pile material to develop a 2D model

Further studies may be conducted on this considering smear zone and changing few more parameters.

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