Application of 3D Numerical Simulation of Sand Drain Element to Soft Soil of Guangzhou-Zhujiang Highway, China

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Abstract: The behavior of sand drain was estimated so that the size of very large load-pressure could be eliminated by changing the configuration of the sand drain elements into sand wall. A 3D mathematical model was formulated to transform the configuration of a sand drain into a sand wall to minimize or eliminate the excessive stress and primary settlement on the road base. This was barely considered in the past. According to soil mechanics theory and seepage characteristics of sand drain in road base foundations, a 3D sand drain element in FEM format was generated, a matrix expression was formulated which was introduced into 3D Biot Consolidation of Abaqus finite element program. The 3D sand drain element generated in this study has been applied to Guangzhou-Zhujiang Highway as a case study. The Sand drain FEM been simulated and the conventional FEM, as well as the Hansbo solutions have been comparatively established. The results show that the simulated 3D sand drain element FEM method accurately represents the sand drain in the soft soil of road base when compared with the conventional methods. [Journal of American Science. 2010;6(10):65-72]. (ISSN: 1545-1003).

Keywords: Sand Drain Element; 3D Biot FEM; soft soil foundation; Guangzhou- Zhujiang Highway

1. Introduction

The first detailed studies of the coupling between the pore-fluid pressure and solid stress fields were described by Biot (1941). Vertical sand drain has been used to accelerate excess-pore water pressure dissipation and settlement caused by embankment fill loading (Van Helden et al. 2008; J. Chu et al. 2006; MartinDuque et al. 2004). Indraratna et al. (2005) reported that the efficiency of the vertical sand drain will depend on extent of the smear, the magnitude and distribution of vacuum pressure and the extent of air leak protection provided in the field and also concurred that a significantly reduction in height of sand surcharge could be applied if excess pore water is reduce by vacuum preloading. Experimental model of sand drains and sandwick reinforced soft soil mass to expedite in-situ settlement under preloading by radial drainage taking advantage of having more horizontal permeability than vertical (Shroff et al. 2007).

In the absence of appropriate ground improvement (Indraratna and Redana 2000; Indraratna and Chu 2005), excessive settlement and lateral movement adversely affect the stability of buildings, ports and transport infrastructure built on soft formations. Limited space, tight construction schedules, environmental and safety issues, maintenance costs and the longevity of earth structures have continued to demand unfailing innovation in the design and construction of essential infrastructures on soft clays. Zaman and Alvappillai (2000) used a nonlinear finite element (FE) to analyze the consolidation settlement of multilayered, saturated porous media under axisymmetry loading; the model was used to investigate the use of sand drains in accelerating the consolidation process at a bridge approach site in Clinton Oklahoma. Xie et al. (2005) used 1-D consolidation of non-homogeneous soft clay with specially varying coefficients of permeability and compressibility, the result obtained was in variance with Terzaghi's theory and that of non-linear consolidation. Xiangqiao (2006) compared numerical results with one-dimensional and two dimensional analytical solutions. The influences of vacuum degree above the ground water table on pore pressure was discussed by Chen et al. (2004) who observed that vacuum decreases with depth due to resistances.

A compaction-flow model for flows through porous medium is available in the commercial code ABAQUS for modeling consolidation of granular solids (Abaqus, 1995). Several applications of the use of the vacuum consolidation method to improve soft clayey deposits have been reported (e.g., Bergado et al. 1998; Chu et al. 2000; Tang and Shang 2000; Tran et al. 2004). However, the resulted sand drain transformations in their reports have some lapses.

The single well symmetrical analysis, however, only considers the role of a sand-drain for a single well, thus, incapable of determining the total horizontal deformation in the entire foundation and the general impact of the load on the foundation. Before applying the Plane strain finite element method, the sand drain would be transformed into the sand wall as shown in the Figure1.The first rule is that the consolidation in the sand drain is assumed to be equal to the consolidation in the sand wall. However, in this transformation from sand drain to the sand wall. Although there are negligible geometrical lapses but the accuracy of its geometrical positions could still be guaranteed. Consequently, this would be restricted to the simulation of the surface subsidence.

Mathematical and theoretical applications of 3D-methods of analysis are comparatively more accurate. In accordance to soil mechanics theory and seepage characteristics of sand drain and using mathematical methods, this paper generated a 3D sand drain element in FEM format and obtained a matrix expression which was imported into 3D Biot Consolidation of ABAQUS program. The Sand drain finite element method generated, and the conventional finite element methods, as well as the Hansbo analytical solutions have been compared. The results show that 3D sand drain element method can efficiently simulate sand drain in the soft soil when compared with other methods.

2. Mathematical model and numerical method

According to Biot (1941), the 3D equation governing the distribution of stress, water content, and settlement as a function of time in a soil under a specified load; can be illustrated as follows:

$$\begin{aligned}
&G\nabla^2 u + \frac{G}{1-2\nu}\cdot\frac{\partial \varepsilon_v}{\partial x} - \alpha\frac{\partial \sigma}{\partial x} = 0\\
&G\nabla^2 v + \frac{G}{1-2\nu}\cdot\frac{\partial \varepsilon_v}{\partial y} - \alpha\frac{\partial \sigma}{\partial y} = 0\\
&G\nabla^2 w + \frac{G}{1-2\nu}\cdot\frac{\partial \varepsilon_v}{\partial z} - \alpha\frac{\partial \sigma}{\partial z} = 0\\
&\frac{\partial \varepsilon_v}{\partial t} + \frac{\kappa}{\gamma_w}\nabla^2 u = 0
\end{aligned} \quad (1)$$

Where $u, v,$ and w are displacement components, $G = \mu = [\frac{E}{2(1+\nu)}]$ is the shear modulus, E is Young's modulus, μ is material property called Lame constant which is identical to modulus of elasticity, $\alpha = \frac{2(1+\nu)}{3(1-2\nu)}\frac{G}{H}$ is Biot's effective stress coefficient, $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$,

$\varepsilon_v = \frac{\partial u_\kappa}{\partial x_\kappa} = \frac{\partial u_x}{\partial x} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial x}$ is the volumetric strain, κ is a physical constant called the coefficient of soil permeability and $\gamma_w = \rho_w g$ is the unit weight of water , ν soil skeleton drained Poisson's ratio, $x, y,$ and z are coordinate axes and t is time.

2.2 Numerical methods

In this study, the load on the nodes are concentrated in one-dimension thus, we applied equation 2 to determine the loads which are only applicable in one dimensional as

$$\mathbf{P}^{e}_{bar} = \int_0^l \mathbf{N}^T f(x)dx = \int_{-1}^{1} \mathbf{N}^T f(\xi)\frac{l}{2}d\xi \qquad (2)$$

Considering the sand drain element as a one-dimensional line unit, we obtained a finite element matrix which will be extended into a three dimensional. In one-dimensional situation, the node value along the vertical direction of the sand drain could not be determined, as well as the pore pressure along the vertical direction of the sand drain. Therefore, using equation 2, we can determine the sand drain node displacement u_i , as

$$u(\xi) = \frac{1}{2}(1-\xi)u_1 + \frac{1}{2}(1+\xi)u_2 \qquad (3)$$

The measure of the resistance offered by an elastic soil to deformation is been expressed in matrix format as follows:

$$\mathbf{K}^{e}_{bar} = \frac{EA}{l}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} \qquad (4)$$

Where A is the original cross-sectional area through which the force is applied and l is original length before loading.

Extending the mechanical stiffness matrix into a space line unit is giving as:

$$\mathbf{K}^{e-3D}_{bar} = \frac{EA}{l}\begin{bmatrix} c_x^2 & & & & & \\ c_xc_y & c_y^2 & & symmetrical & & \\ c_xc_z & c_yc_z & c_z^2 & & & \\ -c_x^2 & -c_yc_x & -c_zc_x & c_x^2 & & \\ -c_xc_y & -c_y^2 & -c_zc_y & c_xc_y & c_y^2 & \\ -c_xc_z & -c_yc_z & -c_z^2 & c_xc_z & c_yc_z & c_z^2 \end{bmatrix} \qquad (5)$$

Where： $c_x = \cos\left(\hat{l,x}\right)$， $c_y = \cos\left(\hat{l,y}\right)$， $c_z = \cos\left(\hat{l,z}\right)$

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$$\bar{\mathbf{K}}^{3-D}_{bar} = \frac{A}{l}\begin{bmatrix} Ec_x^2 & & & & & & & \\ Ec_xc_y & Ec_y^2 & & & & \text{symmetrical} & & \\ Ec_xc_z & Ec_yc_z & Ec_z^2 & & & & & \\ 0 & 0 & 0 & -\theta\Delta tk & & & & \\ -Ec_x^2 & -Ec_yc_x & -Ec_zc_x & 0 & Ec_x^2 & & & \\ -Ec_xc_y & -Ec_y^2 & -Ec_zc_y & 0 & Ec_xc_y & Ec_y^2 & & \\ -Ec_xc_z & -Ec_yc_z & -Ec_z^2 & 0 & Ec_xc_z & Ec_yc_x & Ec_z^2 & \\ 0 & 0 & 0 & \theta\Delta tk & 0 & 0 & 0 & -\theta\Delta tk \end{bmatrix} \qquad (6)$$

In accordance with the finite element format, the above formulated sand drain element matrix would be introduced into the 3D Biot model program.

3 sand drain method

The major shortfall in the application of sand drain of 3D Biot consolidation method on soft ground is the presence numerous finite element nodes due to sand drain. Henceforth, several simulation units are required to be computed, thereby, making a 3D Biot method operation more cumbersome especially over a large area. This paper presents a new 3D sand drain unit approach which can effectively minimized the finite element node points, thus, reducing the number and time of calculation.

3.1 calculating parameters of sand wall

By comparing the Sand well diameter (usually 0.1m) with that of the surrounding soil size (usually 1.2 m ~ 3.0m) and the total length of the well (generally 10 m ~ 25m),it shows that the length will be too long compared to its diameter. Each element consists of eight nodes of uniform magnitude in three-dimensions. Therefore, considering the compatibility between these elements, the eight nodes line elements are coupled into 2-nodes elements as shown in figure 2b.

Our main target is to increase the penetration, while its Mechanical properties are of secondary importance. By these implications we would have suggested a new Sand Drain Element method to simulate the road foundation, where Sand drain would be considered in its original form as shown in Figure 2a and as a single line as shown in figure 2b respectively. Both the shear and twisting forces of sand drain are not considered in this study, but only considered the axial force impact and infiltration. This idea is analogous to the phenomenon of heat transfer within a steel unit.

The line element of the sand drain is shown in figure 2c as considered in this study, where i, η and ξ are space-functions with negligible self-weight of the unit elements.

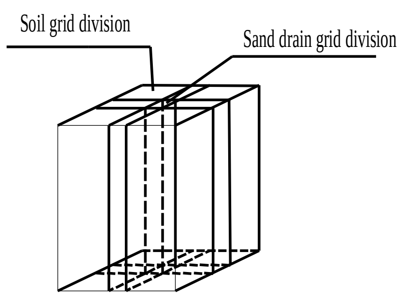

Figure 2a Conventional sand drain element partition

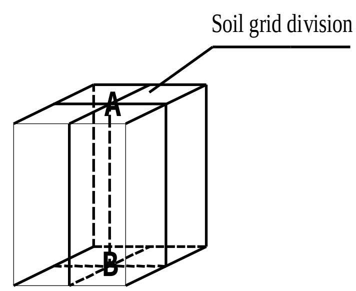

Figure 2b new sand drain element partition

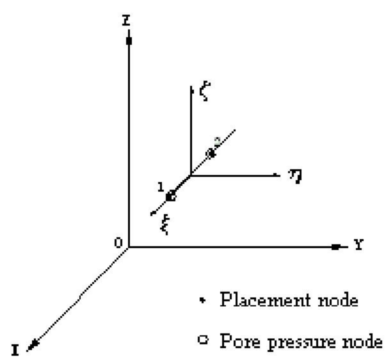

Figure 2c Sand drain element

4 Case studies

The study area is located on the pearl alluvial deposits plain, and the topography of the site is wide and flat. The sub-grade of the site consists of a layer with19.8m to 31.6m thick, of fully saturated, plastic flow soft soil, which is typical poor geological stratum for foundations. The soft soil, stratum has low shear strength, and remolded shear strength is even lower, indicating that the soil is fairly sensitive. Therefore, the soft soil has poor bearing capacity and low resistance to instability failure. The soft soil is highly compressible and has a low permeability value; hence it requires a long consolidation period (Dong et al., 2001).

After the transformation of the sand drain into sand wall, our model would be tested with a case study using specific data obtained from Guangzhou-Zhujiang highway with a little modification.

4.1 statement of problem

The Sand drain is a 2m squared layout, with total length between the top and bottom of 8m, and radius of 0.1m, a schematic illustration is as shown in Figure 4. To carry out a simulation of the sand drain, this layout is modified as follows, the sand drain squared layout is modified to have a wider impact, the radius is adjusted as effective radius r_e= 2m×0.564 = 1.128m. Hansbo's solution only considered the level of drainage. With Sand drain effective radius; r_e=1.128m, and the permeability coefficient of soil in the horizontal direction is k_h= 10^{-8} m/s, the elastic modulus E = 10^4kPa, Poisson's ratio υ=0.0. Sand drain actual radius r_w= 0.1m, infiltration coefficient k_w=10^{-2} m/s, the foundation thickness L=8m. Load P_0=20kPa (instantaneously imposed).

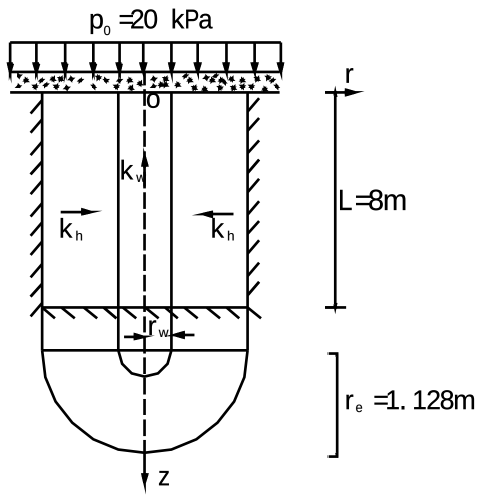

Figure 4 the sketch of single sand drain

4.2 Analytical solution

In order to test the accuracy of the sand drain element model designed in our study, the conventional analytical method and the 3D finite element analysis method are compared for verification. Sand drain consolidation of the soft ground is a classical problem in soil mechanics of which several solutions have been proffered to address this problem. In our own case, (Hansbo 1986; 1994; 2001) solution has been selected for comparative analysis.

The equation of an average degree of consolidation in depth z according to (Barron, 1947; Hansbo, 1994) is given as

$$U_z = 1 - \exp\left(-\frac{2c_h}{\mu' r_e^2} t \right) \tag{7}$$

Where:

The coefficient of consolidation: $c_h = \frac{E k_h}{\gamma_w}$, $\mu' = \mu + \frac{k_h}{k_w} \cdot \frac{n^2-1}{n^2} \cdot \frac{2Lz - z^2}{r_w^2}$,

$\mu = \frac{n^2}{n^2-1} \ln n - \frac{3n^2-1}{4n^2}$, $n = r_e / r_w$ 。

The average consolidation of the foundation is given as:

$$U = 1 - \frac{1}{L}\int_0^L \exp\left(-\frac{2c_h}{\mu' r_e^2}t\right)dz \tag{8}$$

$T_h = c_h t/(2r_e)^2$; Where T_h is the time factor.

4.3 Numerical Simulation

A sand drain element obtained using finite element method and conventional method of computing the 3D models are shown in Figure 8a and Figure 8b respectively. The following conditions are strictly adhered to in order to determine the sand drain consolidation at each point in time. (1)The bottom of the sand drain is fixed, i.e. there is neither a displacement nor, inflow of water to the bottom and around the sand drain well (2) around the sand drain well, there is only vertical displacement and also no-flow condition (3) in contrary, at the top of the sand drain, there are displacements, and inflow/outflow of water also takes place.

In order to verify sand drain in a vacuum preloading pressure, conventional finite element method and sand drain method have been analyzed and compared using the given coefficients in table 1 which were obtained through our model conceptualization and history of study area (Case study). We obtained the two types of load as shown in Figure 6

Table 1. Soil coefficient

λ	κ	e_{cs}	M	k_h (cm/s)	k_v (cm/s)
0.32	0.06	2.00	1.00	4.0E-8	2.0E-8

4.4 Results and Discussions

From our analytical solution a numerical solution has been obtained as shown in the history matching of figure 5. The results of the Hansbo solution, the sand drain solution and the conventional 3D solution are compared. The result shows a good match of the three conditions which implied that sand drain solution can accurately simulate the soft soil foundation.

Agreeing with linear elasticity model conditions in our sand drain, a mathematical model is formulated, and numerical solution are obtained accordingly as shown in Figure 6 (loading), Figure 7 (surface subsidence), Figure 8a and 8b are stratified settlements and Figure 9a and 9b depicted the pore pressure .

The above examples, by comparison, the sand drain element model in this paper has only 68% of cells compared with other conventional finite element model and only 69% of nodes as compared to the numbers of node in the conventional methods. By implication, the sand drain element model has limited numbers of nodes and cells, thus, making the sand drain application a less cumbersome and more efficient method.

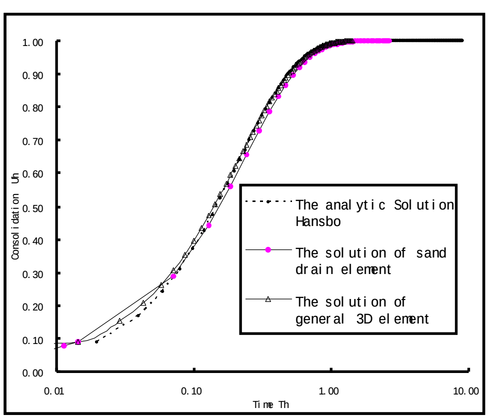

Figure 5. History matching

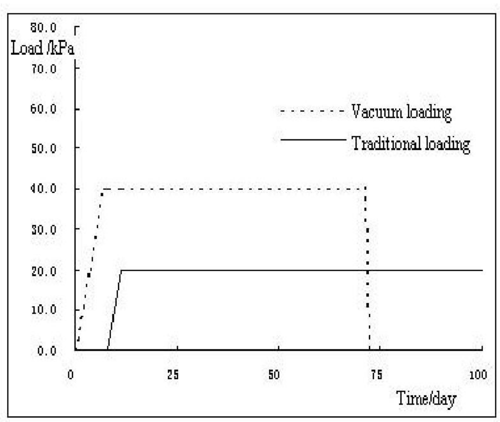

Figure 6 Loading

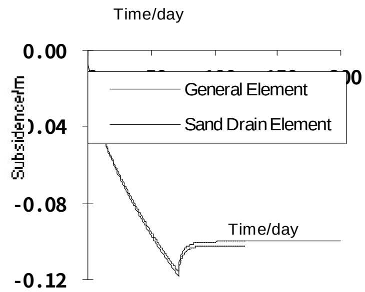

Figure 7. Surface subsidence

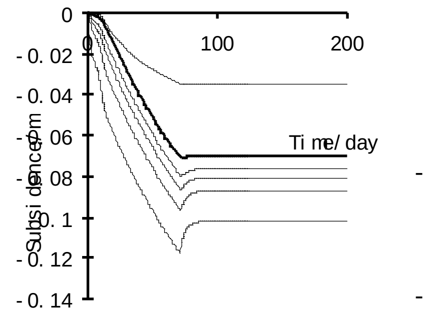

Figure 8a. General Element stratified settlement

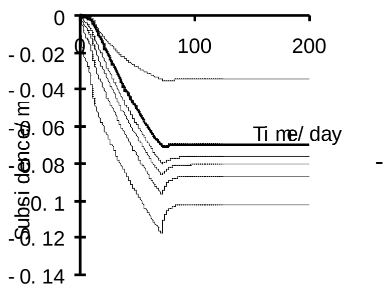

Figure 8b. Sand Drain Element stratified settlement

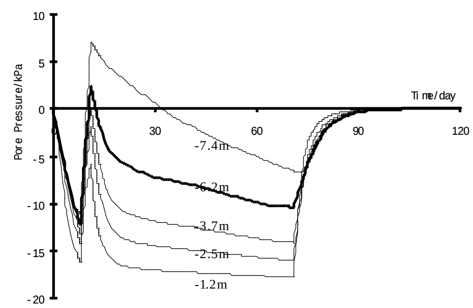

Figure 9a General Element pore water pressure

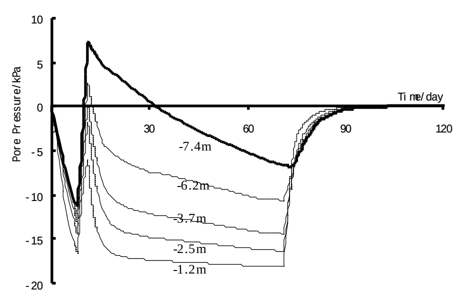

Figure 9b Sand Drain Element pore water pressure

5. Conclusions

Sand drains have been transformed into sand wall thereby minimizing the cells and nodes often generated by reducing the cells to 68% and the nodes to 69% when compared with the conventional method, thus, efficiently reducing the time taking for consolidation. 3D sand drain elements in FEM format are generated, and matrix formation is equally obtained in 3D. The matrix is introduced into a 3D biot consolidation of Abaqus finite element program. The simulated sand drain FEM and the conventional FEM, and analytical solution of Hansbo compared had shown a good match for our case history of Guangzhou- Zhujiang highway base course.

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