Numerical modelling techniques of soft soil improvement via stone columns: A brief review

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Abstract. There are a number of numerical studies on stone column systems in the literature. Most of the studies found were involved with two-dimensional analysis of the stone column behaviour, while only a few studies used three-dimensional analysis. The most popular software utilised in those studies was Plaxis 2D and 3D. Other types of software that used for numerical analysis are DIANA, EXAMINE, ZSoil, ABAQUS, ANSYS, NISA, GEOSTUDIO, CRISP, TOCHNOG, CESAR, GEOFEM (2D & 3D), FLAC, and FLAC 3. This paper will review the methodological approaches to model stone column numerically, both in two-dimensional and three-dimensional analyses. The numerical techniques and suitable constitutive model used in the studies will also be discussed. In addition, the validation methods conducted were to verify the numerical analysis conducted will be presented. This review paper also serves as a guide for junior engineers through the applicable procedures and considerations when constructing and running a two or three-dimensional numerical analysis while also citing numerous relevant references.

1. Introduction
There are a number of methods to analyze the geotechnical problems starting from closed-form analytical methods to the finite element (FE) based numerical methods. Each method has its own advantages and disadvantages. The solution will be accurate only if all the following conditions were satisfied [1].

i. Equilibrium of forces: external forces that should be exactly equal to the internal forces,
ii. Compatibility: the relation between displacements at different locations within a continuum also called as continuity equations,
iii. Constitutive behaviour: stress-strain equations of the material, and
iv. Boundary conditions: force or displacement conditions.

Finite Element (FE) analysis is the most widely used method to analyse the stone column-improved soil behaviour. The best way to represent the real conditions of soft soil behaviour is through a three-dimensional modelling; however, for practical purposes, either the axisymmetric or plane strain model is generally used. Many studies have utilised the axisymmetric model for the unit cell model of
uniformly loaded stone column groups or plane strain models (Barksdale & Bachus, 1983). The numerical analyses of stone columns generally need a complex modelling of the soil reinforcement system. As stated by Canizal et al. there are five main approaches for modelling stone columns numerically [2];

i. Unit cell approach: In the axisymmetric model, only one column and its surrounding soil consisting of a “unit cell” are modelled. (Balaam & Booker, 1981),

ii. Plane strain method: The numbers of columns are modelled as stone trenches that are usually used under continuous loads such as embankments. (Van Impe & De Beer, 1983),

iii. Axial symmetry technique: Stone rings are modelled instead of cylindrical columns to represent the columns under circular loads such as tanks and circular foundation. (Elshazly, 2008),

iv. Homogenization technique: The composite soil parameters are used to model the improved homogeneous soil with stone columns. (Schweiger, 1989), and

v. Full 3D Model: The most complex system to simulate the stone column-improved soil behaviour is three dimensional numerical models. (Weber et al., 2008).

The first four approaches are considered as the two-dimensional (2D) analyses.

Table 1 below summarize the suitability of some of these models to study on improvement of soft soil stabilized with non-encased stone column.

| Model            | Settlement       | Consolidation   | Stability     |
|------------------|------------------|-----------------|---------------|
| Unit cell        | Completely suitable | Completely suitable | Not suitable |
| Stone trenches   | Moderate suitable | Moderate suitable | Moderate suitable |
| Homogenization   | Moderate suitable | Slightly suitable | Slightly suitable |
| 3D model         | Completely suitable | Completely suitable | Completely suitable |

2. Finite element analysis (FE)

FE analysis can be applied in order to determine the complicated parameters that would be difficult to measure through experimental work. In addition, FE analysis is an effective way of alternative process for laboratory investigation studies, especially in the case of large physical models, which leads to saving the time and costs associated with the construction of physical models. However, the selection of suitable constitutive model to represent the actual soft soil behaviour is not simple since soils are complex material consisting of soil particles and void filled with water and/or air. It is very important to choose appropriate model when running the analysis so that the result produced will match the behaviour of soil since its behaviour is not always linear. Nowadays, the numerical modelling software was equipped with numerous constitutive models for modelling the stress-strain behaviour of soil starting from simple to more complex based on required analysis needs. In addition, several sets of laboratory tests should be done to collect all the important parameters regarding compression and shearing behaviour of soils, such as physical tests, triaxial and oedometer test. This parameters are essential for numerical analysis to be conducted. Despite the fact that, no soil constitutive model available that can describe the complex behaviour of real soils under all conditions completely. Other than that, the soil model should be calibrated through sensitivity analysis to define the most appropriate meshes, boundary condition, type of analysis; drained or undrained and soil interface interaction that will be utilised in the numerical analysis.
For example, the latest version of Plaxis 3D software is come up with 8 constitutive models for different conditions and type of soil analysis [4]. So that, the engineers should choose 'right' constitutive model which provides a reasonable fit to data obtained from laboratory tests. It is highly recommended to conduct various measurement comparisons along with additional experiment models and/or full-scale tests to ascertain the degree of reliability in the models in order to adjust and refine them to each type of different modelling application [5]. Poul V. Lade proposed three main categories for the evaluation and selection of suitable constitutive model to be used in numerical analysis [6];

i. Category 1: Model fulfil all the conditions 1 to 5 as tabulated in the Table 2 below.

ii. Category 2: Model lacks one or more conditions.

iii. Category 3: Model is deficient of several conditions as shows in the table below.

| Condition No | Description |
|--------------|-------------|
| 1            | Theoretically sound framework that is sufficiently transparent and accessible to anticipate and evaluate the model performance. |
| 2            | Model includes effects of confining pressure. |
| 3            | Model can handle 3D conditions. |
| 4            | Straight forward to find the parameters, which may be determined from conventional experiment. |
| 5            | Models exhibit the overall high quality of fit with the observed behavior. |

Even correct models were chosen, it should be emphasized that there are approximations within level of accuracy such as, approximation in the finite element method, assumptions made about the constitutive soil response and the detailed explanation of the numerical model and its boundary conditions.

2.1. Previous study on two-dimensional analysis

A comparison between two-dimensional numerical modelling (Plaxis V8 Software) and analytical and laboratory model has been done by Pivarc to estimate the settlement improvement factor of soft soil improved by stone columns [7]. All the models in this study were prepared by the vibro-replacement method, which means that the soil is removed from a hole and not compacted to the sides such as in the vibro-displacement method. For the numerical modelling, the Mohr-Coulomb (MC) elastic-perfectly plastic criteria was chosen to model a soft soil with fifteen node elements applied. The boundary conditions along the vertical boundaries of the axially symmetrical model were fixed for the lateral deformations to allow vertical deformation. The study found that the results of the improvement factor calculated by the Priebe`s method, numerical method, and results obtained from the laboratory experiments were in good agreement, show that MC model selected in this analysis was appropriated.

Joel Gnieł and Abdelmalek Bouazza predicted the site behavior of geogrid encased stone through small scale testing and two-dimensional numerical modelling using the PLAXIS software [8]. A numerical study was used to replicate the results of a small-scale testing in order to establish a method of modelling column installation and column behavior based on basic laboratory tests. Following this, the modelling process was scaled up to predict the behavior of columns installed on site including the impact of varying different parameters. For clay, the Soft Soil (SS) constitutive model in PLAXIS most closely matched the compressibility observed in the oedometer tests while for sand, the Hardening Soil (HS) model most closely matched the test behavior. The fiberglass mesh was modelled using an elastic tensile element with the tensile strength and stiffness derived from the uniaxial tensile testing of the mesh. Results from the small-scale testing and a detailed numerical study have indicated that fully encased stone columns with geogrid could extend the ground improvement technique to extremely soft soils.
A. Zahmatkesh and A. J. Choobbasti evaluated the settlement of soft clay reinforced by stone columns considering the effect of soil compaction [9]. The study was conducted using the two-dimensional numerical analysis then the results were verified with those available in the literature. A drained analysis was carried out using the Mohr-Coulomb’s criterion for soft clay, stones, and sand. The interface elements were used between the stone column and soft clay to evaluate the installation effect due to soil compaction activity. The column installation was simulated to calculate the stresses due to the compaction of soil. From the analysis, the variation of stress in the soft soil due to installation of the column with distance from the column is significantly reduced. Likewise, the research conducted by J. Castro et al. on the installation effects of stone columns in natural soft clay using numerical modelling found that the stresses near the column were related to the initial undrained shear strength of the soil. For normal column spacing, the soil is in a plastic state, which may be negative for a subsequent loading process due to over consolidation or positive if the yield surface has been notably expanded (strain hardening) [10]. Other studies on numerical analysis on the behavior of soft clay improved by stone columns with considering the installation effects also have been performed by Ellouze S et. al. [11], Sexton and McCabe [12], Guettif Z et. al. [13] and Castro J et. al. [14].

Meanwhile, the analysis of settlement and bearing capacity of stone columns and geogrid encased stone columns with various diameters was conducted using data obtained from an experimental investigation using FE software Plaxis 2D. An axisymmetric model of the stone column was configured while the load-settlement response of the stone column was defined using SS and MC model. Detailed parametric analyses were performed by varying the diameter of the stone column and stiffness of the geogrid used for encasement. The results were found to be in reasonable agreement between the experimental investigation and the FE method [15].

Munthohar et al. presented a numerical analysis of the pulverised fuel ash (PFA) column-treated peat and validated with the field static-loading test results [16]. Back analysis was performed to determine the material parameters and soil stiffness surrounding soil and soil-column. The peat and column-treated peat were modelled as Mohr-Coulomb model while the elastic behaviour was chosen for the loading plate. According to the basic design, the peat and column treated peat were assigned as undrained behaviour. The loading plate wall was modelled as the beam element with 10 mm thickness. The simulation results in this study showed that the elasto-plastic Mohr-Coulomb model for the peat and PFA column-treated peat can be applied to model the load-settlement behaviour. The study found that both models were reliable to simulate the field static-loading test for column-treated peat.

The stress concentration factor in stone columns was determined through a numerical modelling where two-dimensional plane strain models were utilized to specify the concentration of stress in the stone columns and reduction in settlement by improving the soil with stone columns [17]. In the scope of this study, drained case was defined for all materials including the soft silty clay, clayey sand, stones, and the sand drainage-stress for the generation of the FE model. Mohr-Coulomb failure criterion considering the elasto-plastic behaviour was utilised for all materials. The study concluded that the behaviour of change of the ratio with a modulus of elasticity of soil in floating and end bearing columns was similar to the rigid foundations while the stress concentration factors were almost constant at different flexible foundation pressures. However, no validation process conducted in the study. In order to verify the findings accuracy, experimental model or analytical calculation can be performed.

The behaviour of piled raft foundation considering pile-soil, raft-soil, pile-soil-raft, and raft-soil-raft interactions have been analyzed using 2D numerical method [18]. The settlements of the system were estimated to satisfy the compatibility of two separate models which were the flexible raft model supported by springs representing soils and piles and the group-pile model embedded in the layers of soil having different properties. The adequacy of the analysis was compared with the analysis result of
Plaxis 3D. The constitutive models used in Plaxis 3D analysis were the hardening-soil model for soil and linear-elastic model for the raft and piles. The interface between piles and soil in Plaxis 3D was simulated with elements of fictitious thickness showing elasto-plastic behaviour based on the Coulomb failure criteria. The elastic modulus of soil was assumed to increase with depth and estimated using the similar method proposed by Schmertmann and Hartmann (1978). Meanwhile, the effect of the stiffness of the outer and inner piles was verified through a series of experimental load tests. The numerical analysis was well adopted to identify the piled raft interaction using the FE package Plaxis 2D [19].

Other researchers, analysed a piled raft foundation on soft soil using Plaxis 2D by considering the various numbers of piles. The raft and piles were modelled as plate elements, while the entire soil material models were Mohr-Coulomb. The design process for piled rafts in this study involved three stages namely, to assess the required raft thickness, to assess the required pile length in the piled raft system and to obtain the optimum number of piles. From the analysis, it was found that the addition of piles could reduce the settlement but after reaching a certain number of piles, the increasing number of piles showed that the settlement tended to be constant. The researchers concluded that for an economic design, it is necessary to consider the optimum number of piles in piled raft foundation system based on the allowable settlements [20]. The effects of pile length and number of piles on the settlement of the piled raft foundation were investigated using two-dimensional analysis and found that the settlement was reduced with the increase in length and number of piles. In this study, the plane strain analysis was taken for analyzing the load-settlement behaviour where the raft was modelled as a plate element, while the piles were modelled as a series of beam elements. The Mohr-coulomb model was adopted for the soil medium while the linear elastic model was adopted for the raft and pile. This numerical analysis was validated by experimental results [21].

An analysis was carried out using the Mohr-Coulomb criterion model for stone columns and embankment fills (drained condition) and soft soil clay (undrained condition) to evaluate the bearing capacity of the square foundation on the ground improved with small groups of stone columns. All the analyses were performed using the axisymmetric idealization of a cylindrical unit cell consisting of the stone column and soft soil under the embankment fills. Meanwhile, the boundaries for unit cell model was used where the vertical and horizontal displacements in the bottom boundaries were restricted while only the horizontal displacement in the lateral boundaries was restricted [22].

The study on floating stone columns were conducted using the 2D FE analyses with the influence of different key parameters such as column length, area replacement ratio, loading intensity, and post installation lateral earth pressure on the settlement ratio, then the design chart developed from this study was validated by a case study where a reasonable agreement was obtained. The undrained analysis was implemented in this study and was verified using analytical method [23][24]. Other than that, the optimum length of stone column (floating column) also can be predicted using numerical method. The finite element study by Tan et al. [25] and Wood [26] showed the existence of the optimum length, Lo, for stone columns which is the column length where lengthening it will not significantly contribute to the reduction of settlement. Two dimensional numerical method was utilized to analysis the load-settlement behavior. The researcher established the method to predict the stone column optimum length which can be used for both homogenous and non-homogenous ground condition. The settlement predictions made by the proposed method are validated with the 3 dimensional finite elements results and field measurement [27].

A series of numerical analysis was performed to investigate the reliability of the axisymmetrical concentric ring model to be used in problems where the stone column was adopted as the ground improvement method to support a small foundation. This study adopted the model by Elshazly et al. (2008) where the thickness and radius of the ring are adjusted to give the correct equivalent area of the
stone columns. The 2D analysis was executed using the FE programme PLAXIS where the HS model was used for both the soft clay and column material. The 3D analysis was done as a validation process to the 2D analysis results. Generally, the 2D and 3D analyses display the same deformation mode of failure despite some discrepancies in detail [23]. Similar modelling simulation was used by others (Ambily and Gandhi [28]; Elshazly, Hafez, & Mossaad [29]; Nazari Afshar [30]; Mitchell and Huber [31]. The accuracy of the developed models were verified by experimental models conducted in a laboratory.

Other studies on the utilization of two-dimensional numerical software were also conducted by Lan et al. [32]; P. Mohanty and M. Samanta [33]; and Ornek et al. [34]. Table 3 represents summary of the numerous previous two dimensional numerical studies conducted. It is shows that most of the study used MC model with drained analysis, which are more suitable in term of short time consumed for running the analysis and limited soil parameters.

Table 3. Summary of 2D Numerical Study, Constitutive Model, Analysis and Validation Method Used.

| Bil | Author Name, Year | Software Name | Constitutive model* | Type of Analysis for Soil | Validation method | Focused study |
|-----|-------------------|---------------|---------------------|--------------------------|------------------|--------------|
| 1 | J. Pivarc, 2011 | Plaxis 2D | MC | MC | Drained | Experimental model & Analytical (Priebe’s Method) | Settlement |
| 2 | Gniel & Bouazza, 2009 | Plaxis 2D | SS | HS | Drained | Small Scale model | Settlement |
| 3 | A. Zahmatkesh & A. J. Choobbasti, 2010 | Plaxis 2D | MC | MC | Drained | Previous study/literature | Settlement |
| 4 | J. Castro et al., 2013 | Plaxis 2D | S-CLAY1 & S-CLAY1S | Drained | Modified Cam Clay model | Settlement, consolidation properties |
| 5 | A. Marto et al., 2013 | Plaxis 2D | SS | MC | Drained | Experimental model | Load-settlement |
| 6 | Muntohar et al., 2013 | Plaxis 2D | MC | MC | Undrained | Field static-loading test | Load-settlement |
| 7 | Yildiz M., 2013 | Plaxis 2D | MC | MC | Drained | Not mentioned | Stress concentration |
| 8 | Joon-Shik Moon & W. P., 2015 | Plaxis 2D | HS | LE | Drained | 3D numerical | Settlement |
| 9 | Elwakil A. Z. & Azzam W. R., 2016 | Plaxis 2D | MC | MC | Drained | Experimental load tests | Settlement, bearing capacity |
| 10 | R. Radhika, 2015 | Plaxis 2D | MC | LE | Drained | Experimental result | Settlement |
| 11 | Mohammadreza Jaberi Nasab A A, 2015 | Plaxis 2D | MC | MC | Undrained | Experimental result | Bearing capacity |
| 12 | K.S. Ng & S.A. Tan, 2014 | Plaxis 2D | MC | MC | Undrained | Analytical (Priebe’s Method & α-β Method) | Consolidation settlement |
| 13 | K.S. Ng, 2013 | Plaxis 2D | HS | HS | Undrained | 3D numerical | Settlement |
| 14 | Nima Rostami Alkhorshid, 2010 | Plaxis 2D | MC | MC | Undrained | 3D numerical | Settlement |
2.2. Previous study on three-dimensional analysis

A computer programme incorporating the proposed analytical method was developed and the adequacy of analysis was compared with the analysis result of Plaxis 3D (Brinkgreve & Broere, 2006). Plaxis 3D programme is based on three-dimensional FE method and its versatility and adequacy for both foundation design and research were verified by many engineers. This numerical modelling is a simple and effective alternative to approach the real behaviour of soils reinforced by stone columns as it allows settlement analysis, lateral deformation, and vertical and horizontal stresses in order to understand the behaviour of columns and soil. It also has the advantage of integrating the settlements of the underlying layers, especially those of least resistance.

The study conducted by Nima Rostami Alkhorshid investigated the performance of stone columns and encased sand columns in soft compressible clay using FE analyses. A drained analysis for stones and sand columns was carried out using the Mohr-Coulomb criterion whereas, for the soft clay, the undrained analysis was performed. In a full-scale three-dimensional FE analysis, the bulging and punching failure and vertical settlement of stone columns were analysed [37]. Three dimensional analysis was used to verify the two dimensional analysis in this study.

A numerical analysis was carried out by using the geotechnical FE software, Plaxis 3D Foundation to investigate the influence of raft thickness, pile length and spacing, and a number of piles on piled raft foundation behaviour. In this analysis, only one-quarter of the raft was modelled due to symmetry. The numerical analysis was conducted to verify the in-situ measured values [38]. Similar study on the piled raft foundation behaviour using the three-dimensional analysis was established by several researchers; Hussein H. Karim et al. [39]; E.Y. N Oh et. al. [40], Sreechithra P. & Niranjana K. [41]; K. Watcharasawe [42]; Comodromos [43].

Noura Nehab et al. established the relationship between the column spacing, properties, and length and the settlement improvement of column group using FE modelling (Plaxis 3D Foundation) and took a “Bouregreg Valley” project as a case study. The study concluded that the comparison of Plaxis 3DF and analytical methods in the case of isolated column gave early confidence in the ability of Plaxis 3DF to capture stone column behaviour [44].

Meanwhile, a three-dimensional FE analysis was conducted by Micheal M. Killeena and Bryan A. Mc Cabeb to identify the effect of variables of column arrangement, spacing, length, and Young’s modulus of the column material in the design process and the interactions between them [45]. A simplified method was proposed to relate the settlement of small groups to a reference unit cell settlement predicted by the current analytical approaches. 15-node wedge isoperimetric elements and lateral boundaries of the computational domain allowed vertical movement that was a restricted radial movement. Both the stone columns and host soft clay were modelled using the elasto-plastic HS model. Three analytical design methods by Balaam and Booker [46], Priebe [47], and Pulko et. al. [48] were used to validate the numerical analysis.
A series of three-dimensional numerical analysis was carried out to evaluate the settlement of mat foundation rested on soft peat reinforced by a group of cement columns [49]. The analysis was carried out using soft soil creep (SSC) constitutive model considering the elasto-plastic behaviour of peat, while the cement columns were simulated as the embedded pile. This model is appropriate for near-normally consolidated clay, clayey silt, and peat. A drained analysis was assumed for soft soil. It was found that the results from the analytical methods were comparable to those by using the FE analysis.

The research by Yogendra K. et. al. addressed a parametric study on the behaviour of embankment resting on the Geosynthetic Reinforced Stone Column (GRSC). The effects of stone column spacing to diameter ratio, deformation of stone column material and embankment fill, geosynthetic stiffness, the height of embankment, and soft clay thickness on the settlement of embankment were investigated by employing the three-dimensional FE modelling [50]. For the hydraulic boundary condition, the phreatic level was set at the top surface of the soft clay layer to generate a hydrostatic pore water pressure profile in the domain while the zero pore pressure boundary condition was applied at the top. The left and right boundary were assumed impervious to consider the fact that no flow entered or left the symmetry plane, while right boundary was too far from the embankment to have a significant influence on the results. The FE mesh was developed using 10-node tetrahedral elements to represent soft clay, stone column, and embankment fill, while the geosynthetic reinforcement was modelled as the geogrid element.

Recent research conducted by Akhila Shaji et. al. focused on comparative study of how an embankment of soft clay behaves in the absence of any reinforced technique and with the installation of the stone column using commercial software PLAXIS 3D. Mohr-Coulomb criterion was used for the analysis while drainage conditions suitable for developing effective pore pressure and stiffness parameters were used. The variation of deformation, stress, and strain with ultimate load acting on soil was obtained. From this study, the stone column was proven to be a better reinforced technique in slope stabilisation [51]. However, the researcher did not performed any validation method to proof the outcomes of this study. Validation can be made either using selected analytical method or others numerical software, which is easier compared to experimental model or full scale test.

The study focused on the numerical modelling of a small group of laboratory-modelled reinforced stone columns considering parameters like area replacement ratio, the stiffness of reinforcement material, and reinforcement length. The bottom face of the clay bed was considered as fixed. Mohr–Coulomb failure criterion was adopted for the stone column and clay, which has the linearly elastic-perfectly plastic behaviour. The geosynthetics were modelled as geogrid element available in PLAXIS 3D having axial stiffness only. The numerical analysis was conducted to verify the physical modelling established in the laboratory [52].

Other studies were conducted to utilise the three-dimensional numerical software and later validated through experimental works, analytical analysis or compared to actual case studies or contrariwise by Hasan et al.[53], Hasan M and Samadihya N.K [54], Weber, T M Springman, S M [55], Sreechithra P. and Niranjana K [56], S Muzammil et.al. [57], Y Tandel et. al. [58] and L Keykhosropur et. al. [59]. Table 4 tabulates summary of the numerous previous three dimensional numerical studies conducted.

| Bil | Author Name, Year | Software Name | Constitutive model* Type of analysis | Validation method | Focused study |
|-----|-------------------|---------------|------------------------------------|------------------|--------------|
|     |                    |               | Soft Soil Stone filler              |                  |              |
|     |                    |               |                                    |                  |              |
| No. | Author(s) | Software | Model | Condition | Analysis | Phenomena |
|-----|-----------|----------|-------|-----------|----------|-----------|
| 1   | Morteza Esmaeili & Seyed Mehrab Hakimpour, 2015 [60] | FLAC3D | MC    | MC        | Undrained | Centrifuge test results |
| 2   | Shaymaa Kadhim, 2007 [61] | FLAC3D | MC    | MC        | Drained   | Experimental load tests |
| 3   | K. Watcharasawe & P. Jongpradist, 2014 | Plaxis 3D | HS    | MC        | Undrained | Literature |
| 4   | Alireza Roshan & Issa Shooshpasha, 2014 | Plaxis 3D | MC    | -         | Drained   | Not mentioned |
| 5   | Noura Nehab et. al., 2016 | Plaxis 3D | MC    | LE        | Drained   | Analytical method |
| 6   | Kongpop Watcharasawe et. al., 2017 | Plaxis 3D | HS    | LE        | Undrained | Field static-loading test |
| 7   | Micheál M. Killeena & Bryan A. McCabe, 2014 | Plaxis 3D | HS    | HS        | Drained   | Three different analytical method |
| 8   | Ali Dehghan Banadaki, 2012 | Plaxis 3D | SSC   | -         | Drained   | Analytical method |
| 9   | Akhila Shaji et. al., 2016 | Plaxis 3D | MC    | MC        | Drained   | Not mentioned |
| 10  | Hasan et. al. (2016) | Plaxis 3D | MC    | MC        | Drained   | Experimental result |
| 11  | Basim Jabbar Abbas, 2016 [62] | Plaxis 3D | MC    | MC        | Drained   | Analytical Brom’s Method |
| 12  | Sexton & McCabe, 2016 [63] | Plaxis 3D | SSC   | HS        | Drained   | Field Study |
| 13  | Martin Gab & Helmut F. Schweiger, 2009 [64] | Plaxis 3D | HS, MCC | HS        | Drained   | Field Test |

* LE: Linear-elastic Model, MC: Mohr-Coulomb Model, SS: Soft Soil Model, HS: Hardening Soil Model, MCC: Modified Cam Clay model, SSC: Soft Soil Creep

3. Conclusion
From the review paper, it can be concluded that the numerical modelling software is the most popular and a good method to be utilised for the stimulation and difficult analysis of geotechnical behaviours. The software was equipped with different types of constitutive model to be selected during analysis based on the different conditions of the structure, soil type, and construction method and liquefaction phenomena. In term of analysis, 3D provide more precise results at all desired angle, compared to 2D.
which only presents the result based on plain strain model. However, the 3D analyses require longer execution times than the 2D analyses and relatively expensive. A major problem is to know how accurate the results from the numerical modelling correspond to what is happening in the field and actual geotechnical behaviour. Therefore, the analysis needs a further step for the verification and validation purposes. Verification is to certify that the computer model has been developed correctly, while validation is to ensure that the model fulfils its use. From the review, the numerical modelling can be validated using other numerical methods, analytical solution using established methods, experimental work or physical modelling, an actual case study and full-scale or field tests. The first two validation methods are simpler, faster and more economical than physical modelling and full-scale tests. However, physical modelling and full-scale testing can provide even more accurate verification though not economical and require more time to perform testing.

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