BAUET JOURNAL
Published by
Bangladesh Army University of Engineering & Technology
Journal Homepage: http://journal.bauet.ac.bd

Numerically Predicting Settlements and Stability of Slopes in Sand under Gravity Loading by Using Plaxis 3D

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Abstract: Slope stability and soil settlement are the vital issues in geotechnical problems. 3D numerical analysis expresses behaviors of failure mechanism of slopes under external gravity loadings of buildings with mat foundations. In this study, failure mechanism of slope and total settlement in sand under uniform gravity loading are observed by finite element code PLAXIS 3D. Gravity loads and number of stories are influenced on the settlement of soil and stability of slope. Total settlements and factor of safety of slopes against failure are predicted for various number of stories (0, 5, 10, 15, 20, 25 and 30). Each storey of super structure carries a constant uniform load. Maximum factor of safety and minimum settlement of sandy soil are 2.08 and 5.3mm. Failure mode of soil occurs when factor of safety is less than or equal to one. Non-liquefiable Mohr-Coulomb failure model of sandy soil and linear elastic model of mat foundation with retaining wall expresses stable condition of slope against failure upto twenty (20) stories.

Keywords: *Finite Element Method; Gravity Loadings; Plaxis 3D; Settlements; Slope Stability.*

Introduction: Normally, in hilly area, buildings, towers, bridges etc. stand on the slope, so the stability of slope is important factor for protection of slope against failure. Slope stability depends on several factors such as sloping angle, soil properties, sloping height, super structure loads on the slope etc. Numerical analysis performs better results than analytical analysis and failure of slope causes damage of superstructure. Cracking phenomena of building walls due to failure of slope has been expressed by finite element based PLAXIS 3D numerical code [1]. Stable condition of slope has been influenced by several analytical methods [2]. Various patterns of failure of slopes have been observed by finite element strength reduction and limit equilibrium method [3]. Dilatancy angle and land sliding hamper stability of slope [4, 5]. In numerical analysis, slope stability analysis performs two different aspects such as drained and undrained conditions. Sometimes, undrained condition of slope occurs gravity loading. For isolated column foundation on the slope of soft soil, undrained stability is critical than drained stability [6]. Factor of safety represents stable condition of slope. Slope has considered to be stable when factor of safety greater than one. Sequential reduction of strength impacts on the factor of safety in finite element method [7, 8]. Angle of inclination and height of sloping ground effect on the slope stability [9, 10]. Slope losses its stability if inclination angle is 90^0. Strength reduction method and others numerical methods have not achieved convergence during iteration process if the sloping angle is 90^0. [11, 12]. Plain strain numerical analysis cannot expresses proper failure mechanism in longitudinal direction of slope but 3D numerical analysis expresses failure surface of slope in three orthogonal directions. In addition, 3D analysis shows soil particle settlement along the length.

Generally, sand shows anisotropic and non-linear behavior and it is very complex to evaluate numerically the anisotropic behavior of sand. To avoid complexity, sandy soil considers linear elastic and perfectly plastic material (Mohr-Coulomb). Constitutive model influences settlement and stability of slope. In this study, two variable parameters, sloping angles and loads of superstructures are considered to evaluate the influence the stability of slope and overall settlement. Minimum settlement and maximum factor of safety are considered for the stable condition of slope.

Numerical Model and Material Parameters: Numerical model represents sloping ground of sandy soil. Two different types of sand layers are considered for analysis. Various number of stories such as 0, 5, 10, 15, 20, 25 and 30 nos. stand on the sloping ground. Slopes vary at an angles of 20^0, 25^0 and 30^0. Fig. 1 represents numerical model of this research. Sloping width (B) varies with the sloping angles. Foundation depth of mat foundation is 1m. External

Article history:
Received 01 June, 2021
Received in revised form 2 October, 2021
Accepted 15 November, 2021
Available online 15 November, 2021

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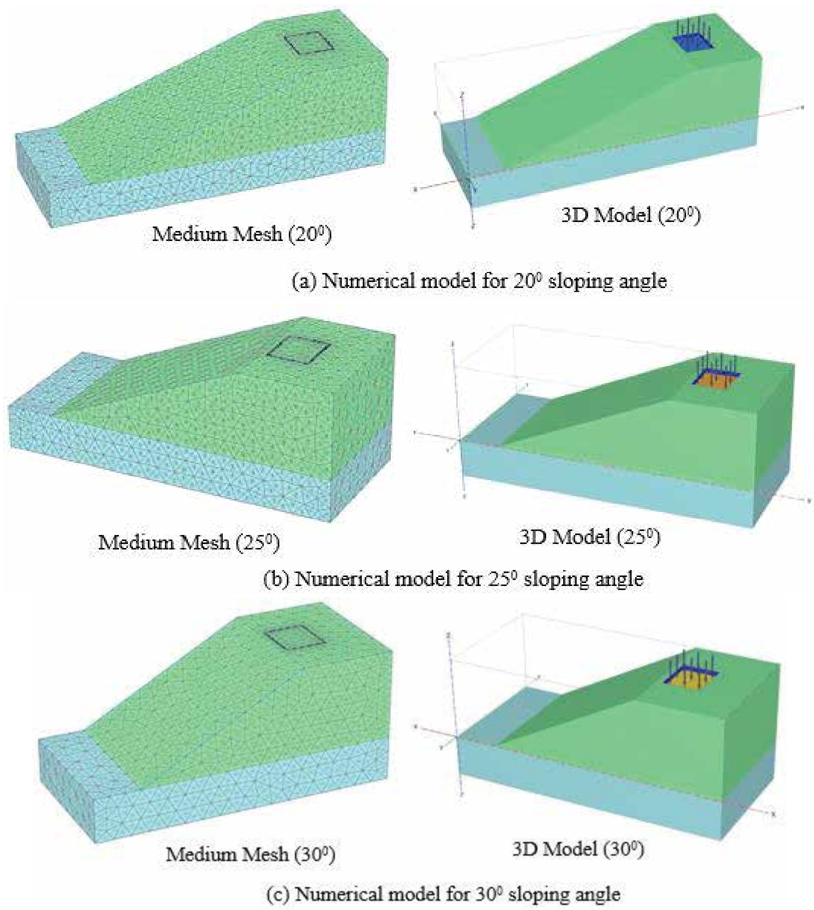

Fig. 2: 3D numerical mesh model for various sloping angle.

Table 1: Mesh sensitivity study of 20^0 sloping angle with number of storey of 5 nos.

Mesh Categories	Maximum vertical settlement (mm)	Optimum mesh size (mm)	Maximum mesh size (mm)	Average mesh size (mm)
Coarse	139.7	995.2	14560	6479
Medium	139.2	895.6	10240	5173
Fine	138.8	731.1	7386	3881

Table 2: Loadings of various stories.

Number of stories	Loadings (kN/m^2)
0	0
5	72
10	144
15	216
20	288
25	360
30	432

During numerical analysis, Mohr-Coulomb material model were considered for sandy soil and linear elastic model were considered for mat foundation with reinforced concrete retaining wall. For both the cases drained condition were considered for analysis. Material parameters of soil have been taken from laboratory triaxial test. Drained tri-axial test was performed in the laboratory for three different samples. Vertical and horizontal pressures were applied until failure occurs. Necessary parameters for numerical analysis were recorded from that test which are summarized in Table 3. Material properties of retaining wall and mat foundation were evaluated from general consideration. Normally, 300 mm thickness retaining wall is used for the construction of reinforced concrete wall. For multi-storied structure, thickness of mat foundation is around 900 mm. However, typical but reasonable, material properties were taken for numerical analysis. Material properties of mat foundation and reinforced concrete retaining wall are represented by Table 4.

Table 3: Laboratory test data of sands for numerical analysis.

Parameter	Name	Lower sand	Sloping sand	Units
Bulk unit weight	γ_{unsat}	16.6	18	kN/m^3
Saturated unit weight	γ_{sat}	18.8	19.5	kN/m^3
Young's Modulus	E'	29000	30000	kN/m^2
Poission's Ratio	ν'	0.25	0.25	-
Cohesion	C'_{ref}	1.0	1.0	kN/m^2
Friction Angle	φ'	33	35	degree (^{0})
Dilatancy Angle	ψ	3	5	degree (^{0})

Table 4: Material properties of mat foundation and RCC retaining wall.

Parameters	Name	Mat	Wall	Unit
Isotropic	-	Yes	Yes	-
Thickness	d	0.9	0.3	m
Weight	γ	23	23	kN/m^3
Young's modulus	E_1	24855576	24855576	kN/m^2
Poisson's ratio	ν_{12}	0.20	0.20	-

Results and Discussion: Total settlement and factor of safety are the function of number stories of superstructures. Factor of safety for slope stability analysis means the ratio between available true shear strength and minimum shear strength which are required for equilibrium. Unit factor of safety represents most critical or unstable condition of slope. Present study numerical results are validated with the Bishop and Janbu formulae. This validation is performed for the calculation of factor of safety. This validation results are very close to each other.

Factor of safety slightly varies due to the increment of number of stories for 30^0 and 25^0 sloping angles. Mainly, factor of safety varies with the increment of sloping angles. Fig. 3 represents variations of factor safety with the increment of number of stories. Maximum factor of safety is 2.08 for 20^0 sloping angle. Slopes are unstable for 20^0 sloping angle at 25 to 30 stories and 30^0 sloping angle at 30 stories. In these cases, available shear strengths are lower or equal to shear strength at equilibrium. Slope is stable for all stories at 25^0 sloping angle. Minimum factor of safety has been found to be 1.11 at slopping angle of 20^0.

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Maximum vertical settlement (MVS) effects on the stability of slopes. Maximum allowable settlement of sandy soil is 300 mm by considering larger damage of slope [11]. For that reason, any of settlement value crosses 300 mm to be treated as unstable condition of slope. MVS increases gradually with the increment of number of stories. Variations of MVS with number of stories are represented by Fig. 4. MVS crosses its limiting value for 20^0 sloping angle at 25 to 30 stories and 30^0 sloping angle at 30 storey. Settlement stands within limit for 25^0 sloping angle. Shear strength crosses its limiting value when slope fails. Minimum vertical settlement is 5.3 mm for 20^0 sloping angle at none of storey. Maximum vertical settlement is 271.6 mm for 20^0 sloping angle. Settlement values are fluctuated for 20^0 and 25^0 sloping angles.

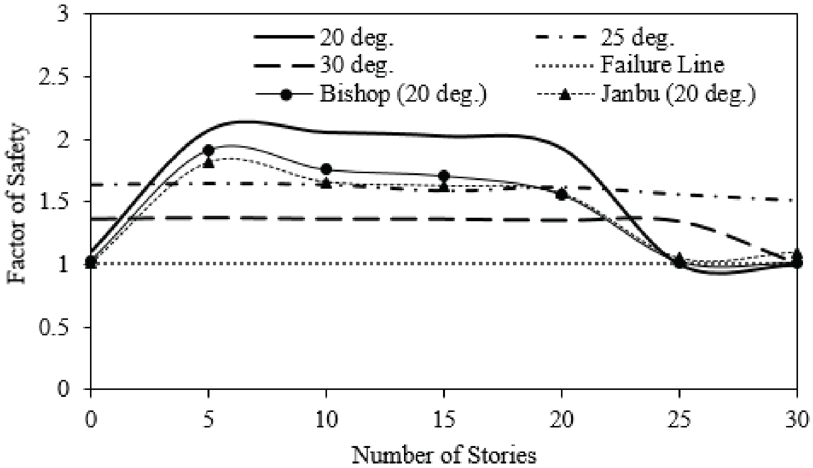


Fig. 3: Variations of factor of safety for various number of stories and sloping angles.

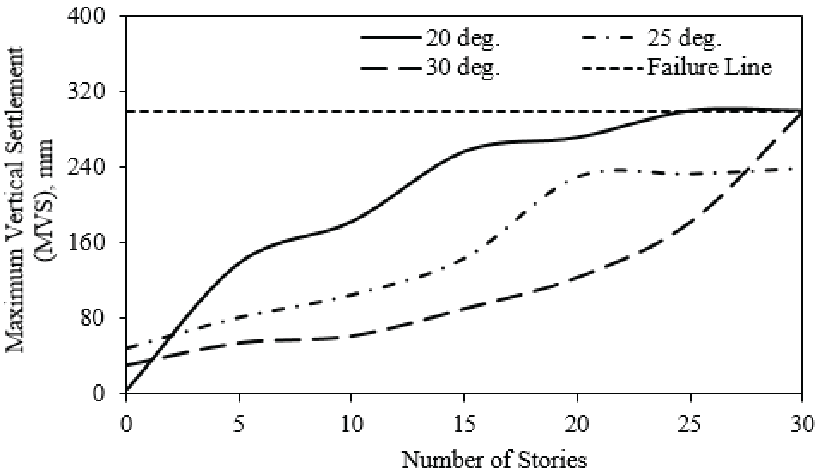
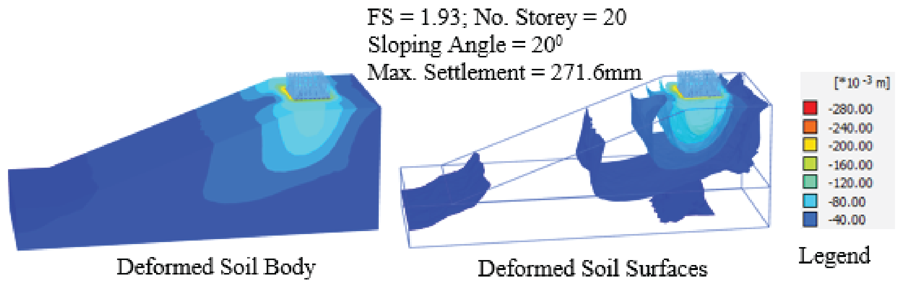


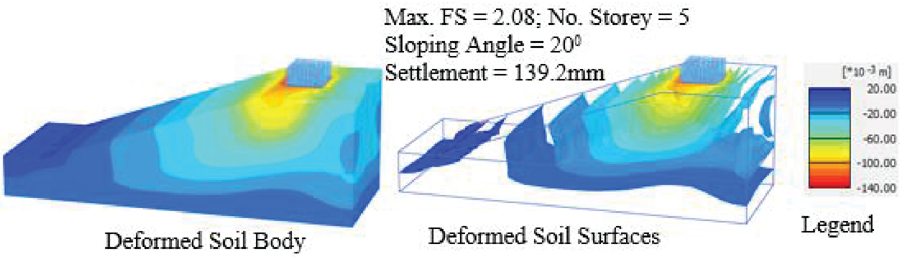
Fig. 4: Variations of settlements for various number of stories and sloping angles.

Deformed shapes of soil body and 3D deformed surface of sandy soil for various sloping angles and number of stories are represented by Fig. 5. Red color of legend represents maximum value of settlement. 3D deformed surface of sandy soil expresses deformation mechanism under external loadings. Deformed shapes and surfaces show for maximum and minimum settlement and factor of safety.

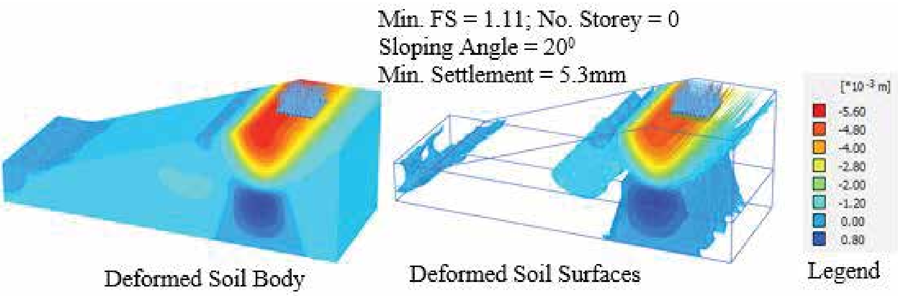
Distance of mat foundation with retaining walls from sloping face is 1.5 m. Therefore, based on above results, factor of safety and maximum vertical settlement are not reached to failure line within a storey range of 20.



(a) Maximum settlement and factor of safety



(b) Maximum factor of safety and settlement



(c) Minimum factor of safety and minimum settlement

Fig. 5: Deformed shapes of soil bodies and surfaces for various number of stories and sloping angles.

Conclusions: Stability of slopes are influenced by geometric parameters, material model, external loads, natural disasters etc. In this study, stable condition of slope has been predicted by considering static uniform loadings. Seismic effects, land sliding, extreme non-linearity, anisotropy etc. are not addressed in this paper. However, failure line of slope has been predicted by considering several damage state of slope under incremental static loadings.

Factor of safety and settlements reach at failure line after crossing 22 stories for 20^0 and 30^0 sloping angles. Minimum settlement and factor of safety observe at sloping angle of 20^0 with no storey effect. Maximum settlement and maximum factor of safety occur different locations with same sloping angle. Maximum and minimum values of settlements have been found to be 271.6 mm and 5.3 mm. Maximum factor of safety has been found to be 2.08. Variations of factor of safety are nearly constant with the variations of external vertical static loads but it increases gradually with the increment of sloping angles.

Present study of slope is not hampered against any type's failure due to external gravity loadings upto five stories at sloping angle of 20^0. All values of factor of safety and settlements for 25^0 sloping angle are lied below the failure line. Therefore, 25^0 sloping angle is more suitable than sloping angles of 20^0 and 30^0.

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