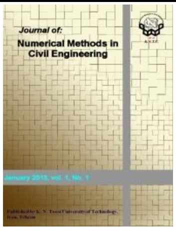

Numerical Methods in Civil Engineering

Comparing Advanced Constitutive Models in Stability Analysis of Slopes on Liquefiable Layers under Seismic Loading Conditions

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Abstract:

One of the most challenging issues in the field of geotechnical engineering is liquefaction that causes great damage to the earth slopes during earthquakes. Since seismic analysis and modeling of liquefaction phenomenon in loose saturated sandy soils requires the use of advanced constitutive models, two different approaches are used for analyzing the response of slopes on liquefiable layers, including (1) UBCSAND (UBC) and (2) Mohr Coulomb (MC) and Finn constitutive models. In the current paper, to assess the liquefaction potential, firstly a comparison will be done among different constitutive models, then seismic stability analysis of slopes on liquefiable layers are studied by finite difference method using FLAC^{2D}. The results of dynamic analysis indicated that, estimated seismic displacements using advanced constitutive models are more accurate than the ones using common models. Subsequently, the effects of different parameters such as the thickness of liquefiable layer and the frequency content have been investigated .Finally, the relationship among mentioned parameters and horizontal displacement of the slopes is investigated using the MC, Finn and UBC constitutive models. It should be mentioned that, the reduction in frequency and increase in the thickness of liquefiable layer have an increasing effect on the horizontal displacement of slopes.

1. Introduction

Dynamic excitations such as earthquakes are the main causes of the pore pressure build-up in the liquefiable soils. Excess pore pressure may pose danger to the soil bearing capacity. If pore pressure is unable to dissipate on time, the effective stress will decrease and the soil skeleton will lose its shear strength. This phenomenon is known as liquefaction. The primary objective of this paper is to compare the well-known Mohr Coulomb (MC) and Finn constitutive models with the relatively new and innovative UBC criterion, both implemented in the computational system called FLAC^{2D} [1]. FLAC^{2D} is capable of introducing new constitutive models that are defined by the users; therefore, the advanced constitutive models which can model seismic loading conditions, cumulative cyclic strains and liquefaction mode are more likely to be utilized.

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The UBC simulates the stress-strain behaviour of soil under static or cyclic loading for drained, undrained, or partially drained conditions by using an elasto-plastic formulation at all stages of loading rather than just at the failure state. In this way plastic strains, both shear and volumetric, are predicted at all stages of loading. The obtained plastic parameters in the model are compared with the results of several simple shear element tests considered to most closely replicate conditions in the field during earthquake loading. UBC criterion consists of a relatively simple but powerful approach in order to model the onset of the liquefaction phenomenon which will be described later on. It should be mentioned that, to study the seismic behaviour of non-liquefiable soils, in this research, another advanced constitutive model, UBCHYST (UBCH), has been assigned to medium and dense materials [2, 3].

The seismic behaviours of an earth dam on lagging layers using nonlinear and plastic constitutive models have been studied by Beaty and Perlea (2011). The obtained results indicated that the seismic responses of advanced and simple constitutive models are completely different from each other [4]. According to researches performed by Seid-Karbasi and Atukorala (2011) on seismic responses of a tailing dam using FLAC^{2D}; tailing slurry suffers liquefaction phenomenon in huge areas, and causes large deformation in the dam structure [5]. Shahzad Khalid (2013) studied the stability of tailing dams under dynamic loading conditions. For this purpose, advanced constitutive models were used to evaluate build-up pore pressure and liquefaction phenomena [6].

In general, stability analysis of slopes on liquefiable layers under seismic loading condition is of great importance. In the current paper, unlike previous studies, the effect of all parameters affecting seismic response of slopes, such as geometry, thickness of the liquefiable layer, constitutive models and frequency content of earthquakes, are investigated. Finally, the relationship between the horizontal displacement of the slope crest and above mentioned parameters was extracted under different seismic loading conditions.

2. Dynamic analysis and geotechnical parameters

In this section, the two-dimensional (2D) plane–strain models that were developed in FLAC^{2D} to calculate static and seismic response of the slope as well as the liquefaction potential of the liquefiable layer are redundant. By considering various thicknesses of liquefiable layers, distinct constitutive models, and different earthquakes the seismic behaviour of slopes under different conditions will be compared. Then, by evaluating these parameters, the relevancy between the horizontal displacement of the slopes crest and the mentioned parameters will be investigated by the MC & Finn and UBC models.

2.1. Constitutive Models

2.1.1 UBC and UBCH models

The UBC is an elastic-plastic (incremental) model that is controlled by variations in the effective stress ratio. This model predicts the stress-strain behaviour of the soil through the hyperbolic relationship and evaluates the volumetric response to the soil skeleton using the current law, which is a function of the current stress ratio [2, 7]. UBCH advanced constitutive model is used for undrained resistance parameters in low permeability clays and in silty soils or in granular soils in which the water pore pressure generated is easily eliminated. Also, this model is used to simulate the seismic response of dense granular soils and sticky soils [3].

2.1.2. Finn model

Dynamic build-up pore pressure can be modelled by accounting for the irreversible volumetric strain in the constitutive model. This is done with the modified form of MC plasticity model called “Finn” Model, which can perform coupled dynamic-groundwater flow calculations and can simulate the effects such as liquefaction [8]. Byrne (1991) proposed equation (1) that relates the increment of volume decrease, to the cyclic shear strain amplitude [9].

$$\Delta\varepsilon_{vd} = C_1\left(\gamma - C_2\varepsilon_{vd}\right) + \left(C_3\varepsilon_{vd}^2 \;/ + C_4\varepsilon_{vd}\right) \qquad (1)$$

Where, C_1 to C_4 are constants parameters. γ, ε_{vd}, $\Delta\varepsilon_{vd}$ are shear strain, volumetric strain and the increment of volumetric strain respectively.

2.2. Model description

In order to model and simulate the stability of slopes, various layers with different properties are used for foundation, liquefiable layer and the embankment. Then, a parametric study will be conducted for three thicknesses of foundation, 25, 50, 75m, liquefiable layer 1.5, 3, 4.5m and for embankment 5, 10, 15m, respectively. The length of the embankment equals to the value of 75+ $h_0/\tan(\theta)$, where h0 and θ are the thickness of embankment and slope angle, respectively. Therefore, around 60 models have been built to compare the static and seismic behaviour of slopes and for each of them three angles of 10, 20 and 30 have been considered. The details of the slope are shown in Fig.1.

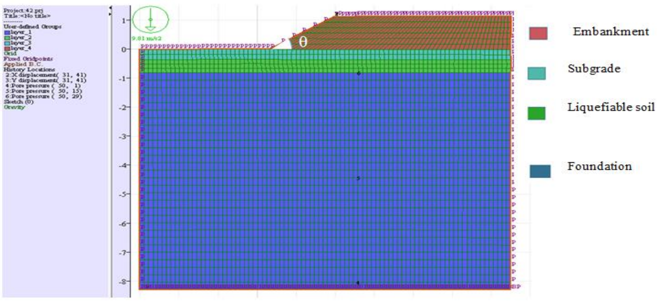


Fig. 1: Geometric model of the slope on liquefiable layer

2.3. Geotechnical parameters

As shown in Fig. 1, distinct layers have different properties. The material properties of the embankment, subgrade, liquefiable soil and foundation listed in Table .1, have been extracted from previous studies.

Table 1: Material properties [1, 2,10]

Soil type	V_s (m/s)	$(N_1)_{60}$	ν	C (Pa)	φ	γ (kN/m^3)
Embankment	630	50>	.26	300	35	24.5
Subgrade	73.5	7	0.4	5	30	14.7
Liquefiable soil	117.4	10	.32	5	40	18.4
Foundation	117.4	10	.32	5	40	18.4

For static analysis, MC constitutive model is used for all layers. It should be noted that the values of dilation angle (ψ), tensile strength, shear and bulk modulus of material sets can be calculated according to the following equations [1].

$$\psi = \varphi - 30 \quad (2)$$

$$\text{Tension} = \sqrt{3}\, c / \tan\varphi \quad (3)$$

$$G = \rho v_s^2 \quad (4)$$

$$K = 2G(1+\upsilon)/3(1-2\upsilon) \quad (5)$$

As we know, the main focus of dynamic analysis is to assess the stability and deformations of the slopes under liquefaction conditions. Therefore, a suitable constitutive model should be assigned to model this phenomenon. For this reason, the Finn and UBC models have been used to evaluate the liquefaction. The UBC model is only assigned to the second layer because this material is more sensitive to liquefaction as compared to other material sets. The MC and UBCH models are also assigned to the materials with non-liquefiable soil. The values of the used parameters in UBC and UBCH models (liquefiable and non-liquefiable layers) are listed in Tables (3, 10, 11).

Table 2: Input parameters of UBC used in $FLAC^{2D}$ [10, 11]

Parameter	**Meaning**	**loose to medium dense sand**
D_r(%)	Relative density	30-35
Density	Dry density	1.47
n	Porosity	0.4
$(N_1)_{60}$	Normalized Corrected SPT	7
K_G^e	Elastic shear modulus	$21.7*15*((N_1)_{60})^{0.33}$
m_e	Elastic shear exponent	0.5
α	Bulk modulus coefficient	$2(1+\upsilon)/3(1-2\upsilon)$
K_B	Elastic bulk modulus multiplier	$\alpha * K_G^e$
n_e	Elastic bulk component	0.5
K_G^p	plastic bulk modulus multiplier	$100 + ((N_1)_{60})^2*0.003*K_G^e$
n_p	Plastic bulk component	0.4
φ_{sc}	Critical state friction angle	33
φ_{peak}	Peak friction angle	$\varphi_{sc} + (N_1)_{60}/5$
R_f	Failure ratio	$1 - (N_1)_{60}/100$
m_hfac1	Model parameter	1
m_hfac2	Model parameter	1
m_hfac3	Model parameter	1
m_hfac4	Model parameter	1.5
anisofac	Model parameter	1

Table 3: Initial parameters of UBCH used in $FLAC^{2D}$ [3]

Parameter	$(\sigma_0^{'})$ 25.33kPa	$(\sigma_0^{'})$ 101kPa	$(\sigma_0^{'})$ 404kPa	$(\sigma_0^{'})$ 1616kPa
hGmax (kPa)	2.7×10^4	5.35×10^4	1.07×10^5	2.14×10^5
hbulk (kPa)	2.7×10^4	5.35×10^4	1.07×10^5	2.14×10^5
hcoh (kPa)	0	0	0	0
hfric (deg.)	35	35	35	35
hdil (deg.)	0	0	0	0
hten (kPa)	0	0	0	0
hn	3	3.3	4	4
hrf	0.98	0.98	0.98	0.98
hdfac	0	0	0	0
hrm	0.5	0.5	0.5	0.5
hpa (kPa)	100	100	100	100
hn 1	1	1	1	1

2.4. Modeling process

2.4.1. Construction of zones

In dynamic analyses, the boundaries may cause the applied propagating waves to reflect back into the model. Using a larger model may minimize this problem; However, the large computational time becomes a problem. An alternative is to use a silent boundary to overcome the problem. Silent boundary was suggested by Lysmer and Kuhlemeyer [12]. It operates in the time domain and was based on the use of independent dashpots in the normal and shear directions applied at the model boundaries. $FLAC^{2D}$ states that a silent boundary is effective in absorbing the propagating waves for waves arriving at angles of incidence larger than 30°. For this purpose, it is necessary to meet the recommended requirements according to the following equation [1].

$$\Delta L \le \frac{C}{10 \times f_{max}} \quad (6)$$

In the above equation, ΔL is the largest element, f_{max} is the maximum input wave frequency and C is the compressive or shear wave velocity in the environment. In order to obtain the optimum dimension of the zones for the transmission of waves, preliminary calculations have been implemented according to the equation (6); totally, 85 zones in the horizontal direction (j=1 to j=41), 40 zones in the vertical direction (i=1 to i=86) and the rectangular zones with appropriate and smaller dimensions were obtained and chosen with regard to the numerical accuracy of the wave transfer conditions for the slope modelling.

2.4.2. Damping

Beaty and Bayern compared MRC[1] predicted by UBC model with common graphs for sands and concluded that UBC model predicts lower damping values for the range of strains less than 0.01% and higher values for large strain range as compared to its actual values. Thus, in order to compensate this defect, 2% Rayleigh damping was considered to the model [13].

2.5. Methods of dynamic analysis

In this section, according to Fig.1, static and seismic response of different slopes as well as the liquefaction potential of liquefiable layer is evaluated. For dynamic analysis, two different combinations of constitutive models have been considered as follows:

1. MC & Finn constitutive models
2. UBC & UBCH Constitutive Models

2.5.1. Method 1: Application of MC & Finn models

As we know, MC constitutive model is a monotonic and elastic-perfect plastic model which is not capable of dynamic analysis. For this purpose, in addition to MC for non-liquefiable materials, Finn constitutive model has also been assigned to liquefiable layer to study the seismic behaviour of saturated loose sand [14]. Dynamic analysis of the slopes is performed using the MC & Finn constitutive models at the whole effective time of applied earthquake (t_d). By this method, a relatively small deformation can be observed during t_d. After this analysis, the slope reached the equilibrium and the maximum unbalanced forces of the slope became asymptotic to zero for a situation in which the slope angle is 30 degrees and the thickness of foundation, liquefiable and subgrade are given as 75, 4.5 and 15 meters respectively, under the acceleration time history of Bam earthquake, according to Fig. 2.

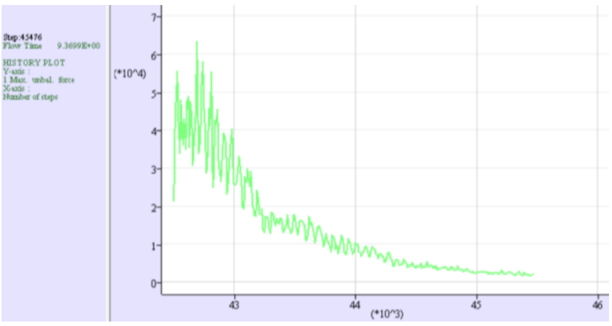


Fig. 2: Maximum unbalanced force for static analysis

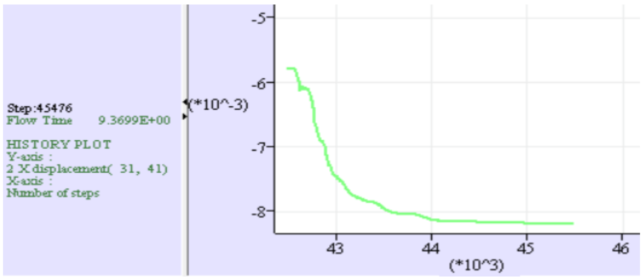


Fig. 3: Horizontal displacement at the points of i = 31, j = 41

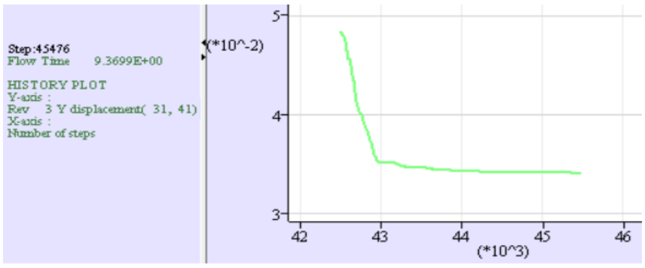


Fig. 4: Vertical displacement at the points of i = 31, j = 41

Considering the horizontal and vertical displacements for slope crest at the points of i = 31 and j = 41, which is the most critical point in the desired slope (Figs. 3 and 4) and the maximum unbalanced force which has reached a certain and acceptable limit amount which has been true for other models, it can be said that the model is stable. In order to reach the final static stability for all models, the safety factor should be greater than 1.5 (i.e. FS > 1.5), according to tables (4 -6).

Table 4: Static FS for liquefiable layer thickness of 4.5m

Foundation's thickness (m)	Slope angle	Liquefiable layer thickness (m)	Static safety factor (FS)
75	30	4.5	1.58789
75	20	4.5	2.20264
75	10	4.5	2.99072

Table 5: Static FS for liquefiable layer thickness of 3m

Foundation's thickness (m)	Slope angle	Liquefiable layer thickness (m)	static safety factor (FS)
50	30	3	1.7832
50	20	3	2.13525
50	10	3	2.93506

Table 6: Static FS for liquefiable layer thickness of 1.5m

Foundation's thickness (m)	Slope angle	Liquefiable layer thickness (m)	static safety factor (FS)
25	30	1.5	1.81836
25	20	1.5	2.08838
25	10	1.5	2.9292

It should be noted that, in this analysis, seismic loadings in the format of Bam, Chi-Chi, Kobe, Northridge and Tabas earthquakes have been applied as the bottom of models. In order to evaluate the liquefaction potential, specific parameter, r_u, defined as the ratio of excess pore water pressure over the variation of vertical effective stress, is as follows:

[1] Modulus Reduction Curve

$$r_u = \frac{\Delta u}{\sigma'_{v0}} \tag{7}$$

Previous researches [13] indicate that if the value of r_u is greater than 0.7, then the soil has a high tendency to show liquefaction potential. However, with respect to the Contour of the excess pore water pressure ratio in Fig. 5, the r_u parameter value in all areas of liquefiable layer is less than 0.7, which means the liquefaction for this slope with the mentioned state under Northridge earthquake does not occur with the use of MC & Finn constitutive models.

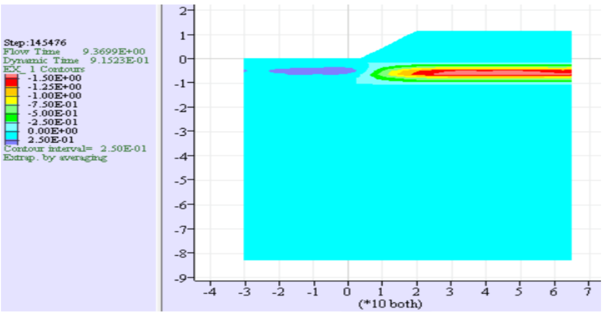


Fig. 5: Contour of the excess pore water pressure ratio r_u at the end of the dynamic analysis steps using MC and Finn models

2.5.2. Method 2: Application of UBC & UBCH models

In this method, to study the liquefaction potential, UBC model which is a user-defined model in $FLAC^{2D}$ is applied to the liquefiable layer, and UBCH model is assigned for the other layers [3]. For static analysis, MC model is required, but for dynamic analysis UBC and UBCH models will be applied to the model. In Fig. 6, the history of the excess pore water pressure ratio, r_u, is plotted for the liquefiable layer. According to Fig. 6, in liquefiable layer, r_u at the end of the dynamic analysis steps reaches to 0.7, that indicates the region where liquefaction phenomenon occurs in a large zone. It can be concluded that in this case, UBC model can predict the liquefaction phenomenon, while the liquefaction does not occur using Finn model.

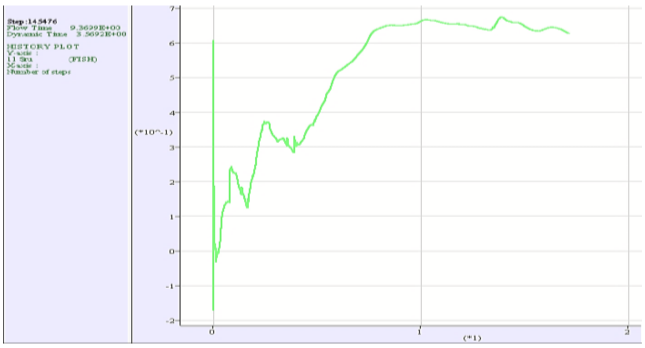


Fig. 6: History of the excess pore water pressure ratio r_u at the end of the dynamic analysis step using the UBC and UBCH models

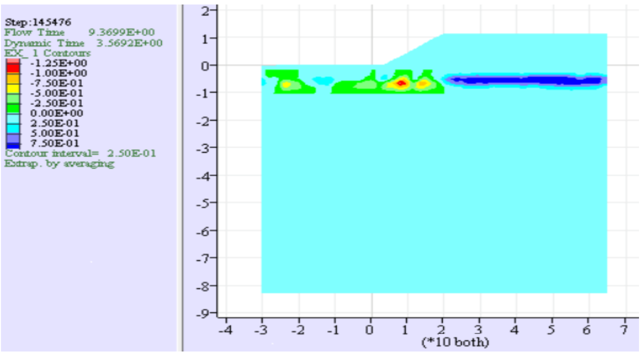


Fig. 7: Contour of the excess pore water pressure ratio r_u, using UBC and UBCH models

To ensure the results, by introducing the r_u parameter written by FISH functions to all zones of the liquefiable layer according to the equation (7) in Fig. 6, and also using the r_u contour in Fig. 7, the liquefaction behavior of the mentioned layer is evaluated. Dynamic analysis of the slope has been conducted in another model with geometric features including the slope angle of 10 degrees, foundation, liquefiable layer and the subgrade thicknesses of 25, 3 and 5 m, respectively using MC and Finn models at the total effective time, t_d. With respect to contour of the excess pore water pressure ratio shown in Fig. 8, the r_u parameter in large area of the liquefiable layer is greater than 0.7. This means that the liquefaction is predicted in recent case and not as in comparison to the previous case with the same material properties, using Finn & MC model.

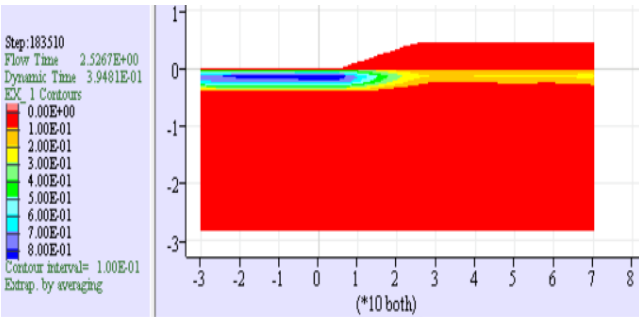


Fig. 8: Contour of the excess pore water pressure ratio r_u at the end of dynamic analysis using the (MC) and Finn models

According to Figs. (6-8), it can be concluded that the results of UBC and Finn constitutive models are completely different from each other.

3. Effect of liquefiable layer thickness on horizontal displacement

3.1. Application of Finn model

Horizontal displacement of the slope crest under different acceleration time series such as Bam, Chi-Chi, and Northridge earthquake with corresponding frequencies of 8.276, 0.299, and 1.196 Hz, have been calculated using Finn model for distinct slope geometries, as shown in tables (7) to (9). The effective time of the applied earthquakes is almost the same. Totally, three kinds of embankments are considered with the foundation thickness of 75, 50 and 25 m, slope angles of 30, 20 and 10 degrees, and three different thicknesses of liquefiable layer. Since the key variables are the thickness of liquefiable layer and the imposed frequency, the relationship between them for each condition can be computed using regression method in order to consider how these parameters can affect the displacement of the slopes crest.

Table 7: Horizontal displacement using Finn model for different thickness of liquefiable layer, FT=75 m

Foundation's thickness (m)	Slope angle	Liquefiable layer thickness (m)			Embankment thickness (m)
75	30	1.5	3	4.5	15
75	30	1.5	3	4.5	15
75	30	1.5	3	4.5	15

FT denotes, Foundation's thickness

Table 7: Continued

PGA and Earthquake's name		Frequency	Effective time (s)	Horizontal displacement of crest (m)		
1	Bam	8.276	7.475	0.006	0.007	0.008
1	Chi-Chi	0.299	7.17	0.013	0.014	0.014
1	Northridge	1.196	7.195	0.017	0.017	0.017

$$x_{disp} = -0.00105H + 0.00053 f_{max} + 0.01444 \quad (8)$$

Table 8: Horizontal displacement using Finn model for different thickness of liquefiable layer, FT=50 m

Foundation's thickness (m)	Slope angle	Liquefiable layer thickness (m)			Embankment thickness
50	20	1.5	3	4.5	10
50	20	1.5	3	4.5	10
50	20	1.5	3	4.5	10

FT denotes, Foundation's thickness

Table 8: Continued

PGA and Earthquake's name		Frequency	Effective time (s)	Horizontal displacement of crest (m)		
1	Bam	8.276	7.475	0.003	0.004	0.006
1	Chi-Chi	0.299	7.17	0.008	0.009	0.01
1	Northridge	1.196	7.195	0.011	0.011	0.012

$$x_{disp} = -0.00076H + 0.00063 f_{max} + 0.00902 \quad (9)$$

Table 9: Horizontal displacement using Finn model for different thickness of liquefiable layer, FT=25 m

Foundation's thickness (m)	Slope angle	Liquefiable layer thickness (m)			Embankment thickness
25	10	1.5	3	4.5	5
25	10	1.5	3	4.5	5
25	10	1.5	3	4.5	5

FT denotes, Foundation's thickness

Table 9: Continued

PGA and Earthquake's name		Frequency	Effective time (s)	Horizontal displacement of crest (m)		
1	Bam	8.276	7.475	0.002	0.002	0.003
1	Chi-Chi	0.299	7.17	0.004	0.004	0.005
1	Northridge	1.196	7.195	0.0044	0.005	0.006

$$x_{disp} = -0.0003H + 0.00053 f_{max} + 0.00337 \quad (10)$$

Where, x_{disp}, H and f_{max}, are the horizontal displacement, thickness of liquefiable layer and maximum frequency of applied earthquakes, respectively. According to the results, it is clear that the thickness of liquefiable layer (H) has a great impact on crest displacement. It should be mentioned that the effect of f_{max} is in its maximum value in models with lowest thickness and slope's angle.

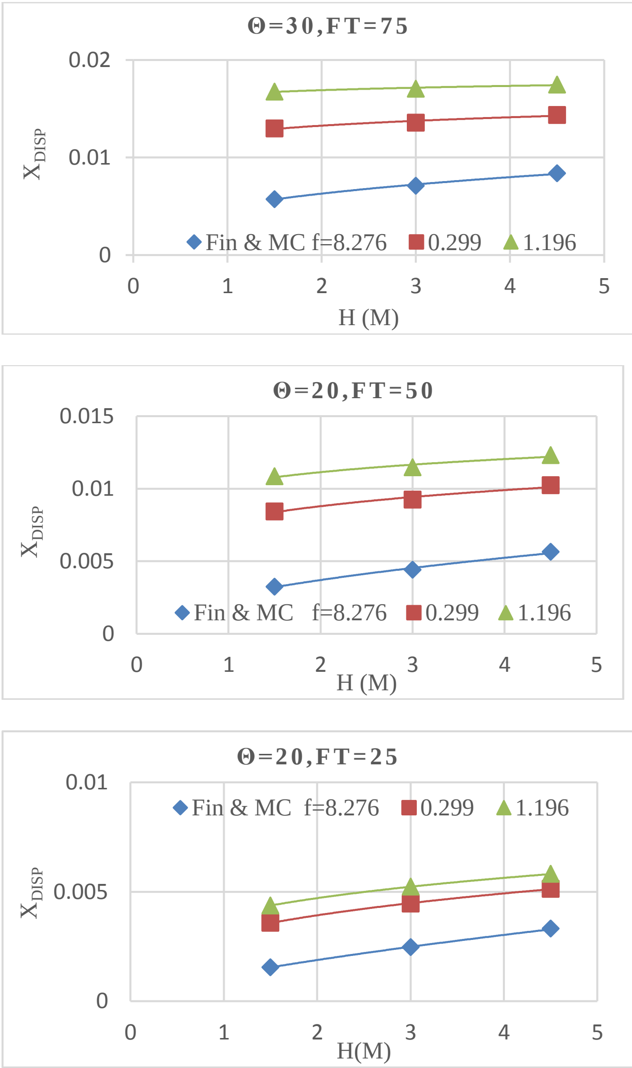


Fig. 9: Horizontal displacement for various thicknesses of liquefiable layer for dynamic analysis using Finn models

According to Fig. 9, as the thickness of the layer increases, the horizontal displacement increases under different geometrical circumstances.

3.2. Application of UBC model

The results of horizontal displacements of the crest has been shown for the slope with a foundation and embankment thickness of 75, 15 m, slope angle of 30 degree and various thicknesses of the liquefiable layer under the acceleration time history of Bam earthquake in Figs. 10 to 12.

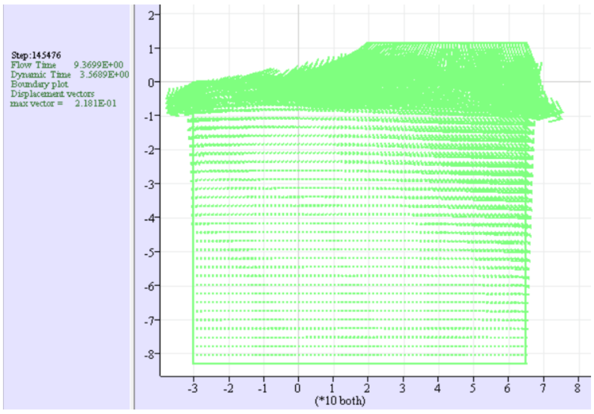


Fig. 10: Contours of slope displacement vectors for liquefiable layer of 4.5 m using UBC & UBCH models

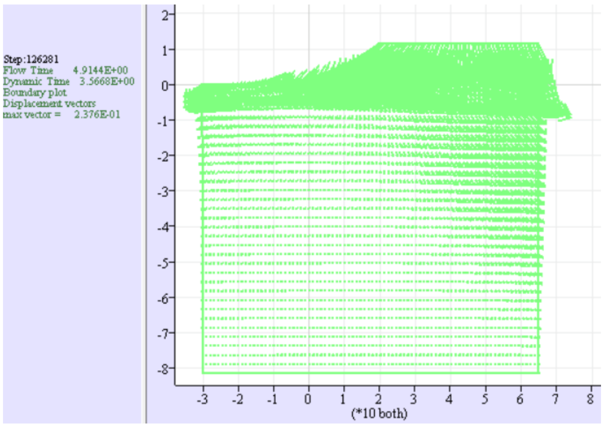


Fig. 11: Contours of slope displacement vectors for liquefiable layer of 3 m using UBC & UBCH models

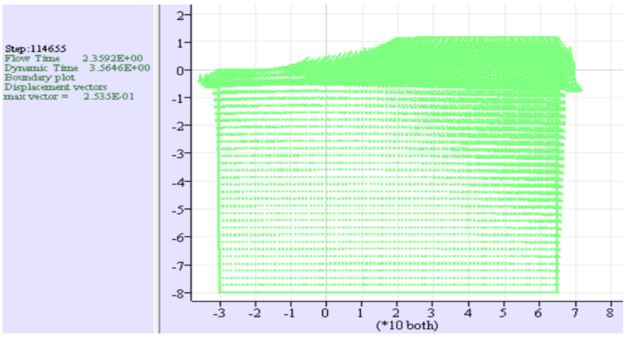


Fig. 12: Contours of slope displacement vectors for liquefiable layer of 1.5 m using UBC & UBCH models

Based on Figs. 10 to 12, it can be observed that by decreasing the thickness of liquefiable layer, the displacement and the deformation of the slope decreases. In Tables (10) to (12), the results of horizontal displacement using UBC and UBCH, under different acceleration time history of Bam, Chi-Chi and Northridge earthquakes with frequencies of 8.276, 0.299 and 1.196 Hz have been presented. It should be mentioned that the effective time for all of them are the same.

Table 10: Horizontal displacement using UBC & UBCH models for different thickness of liquefiable layer, FT=75 m

Foundation's thickness (m)	Slope angle	Liquefiable layer thickness (m)			Embankment thickness (m)
75	30	1.5	3	4.5	15
75	30	1.5	3	4.5	15
75	30	1.5	3	4.5	15

FT denotes, Foundation's thickness

Table 10: Continue

PGA and Earthquake's name		Frequency	Effective time (s)	Horizontal displacement of crest (m)		
1	Bam	8.276	7.475	0.171	0.136	0.145
1	Chi-Chi	0.299	7.17	0.151	0.117	0.14
1	Northridge	1.196	7.195	0.127	0.097	0.136

$$x_{disp} = 0.00275H - 0.00323f_{max} + 0.13644 \quad (11)$$

Table 11: Horizontal displacement using UBC & UBCH models for different thickness of liquefiable layer, FT=50 m

Foundation's thickness (m)	Slope angle	Liquefiable layer thickness (m)			Embankment thickness (m)
50	20	1.5	3	4.5	10
50	20	1.5	3	4.5	10
50	20	1.5	3	4.5	10

FT denotes, Foundation's thickness

Table 11: Continued

PGA and Earthquake's name		Frequency	Effective time (s)	Horizontal displacement of crest (m)		
1	Bam	8.276	7.475	0.046	0.058	0.136
1	Chi-Chi	0.299	7.17	0.007	0.027	0.116
1	Northridge	1.196	7.195	0.017	0.009	0.111

$$x_{disp} = 0.00418H + 0.03265f_{max} - 0.05301 \quad (12)$$

Table 12: Horizontal displacement using UBC & UBCH models for different thickness of liquefiable layer, FT=25 m

Foundation's thickness (m)	Slope angle	Liquefiable layer thickness (m)			Embankment thickness
25	10	1.5	3	4.5	5
25	10	1.5	3	4.5	5
25	10	1.5	3	4.5	5

FT denotes Foundation's thickness

Table 12: Continued

PGA and Earthquake's name		Frequency	Effective time (s)	Horizontal displacement of crest (m)		
1	Bam	8.276	7.475	0.002	0.002	0.003
1	Chi-Chi	0.299	7.17	0.004	0.004	0.005
1	Northridge	1.196	7.195	0.0044	0.005	0.006

$$x_{disp} = 0.00299H + 0.01309f_{max} - 0.01211 \quad (13)$$

According to the equations (8) to (13), which have been derived from tables (7) to (12), it can be concluded that by decreasing the slope angle and the thickness of layers including the liquefiable layer and the Embankment height, the effect of f_{max} on the displacement value increases; therefore, similar results have been obtained for both Finn and UBC constitutive models. Also, it should be noted that equations (8) to (13) have good correlations and the standard error in these relationships can be ignored for the predicted displacement.

3.3.Frequency effect on MC and Finn models

Fig. 13 shows the horizontal displacement of the slope crest against the frequency of applied earthquakes for the MC & Finn constitutive models.

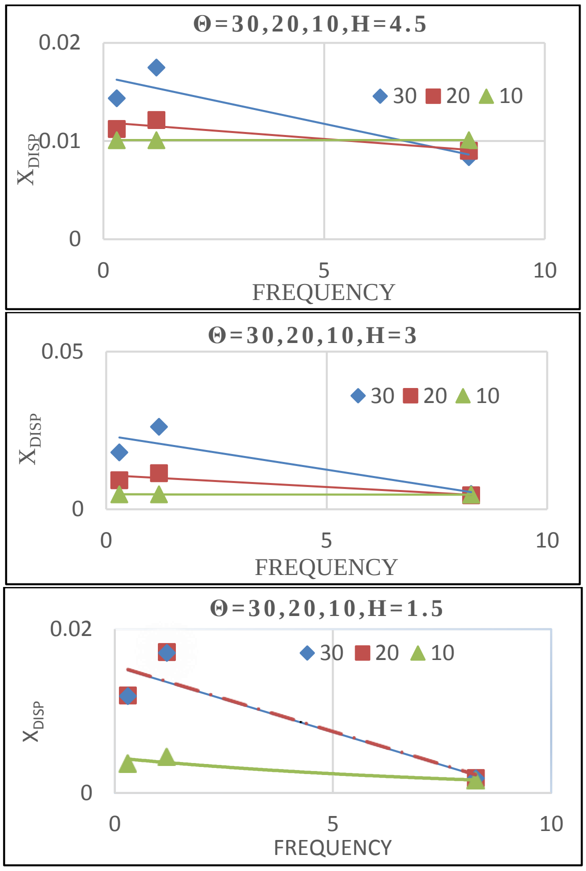
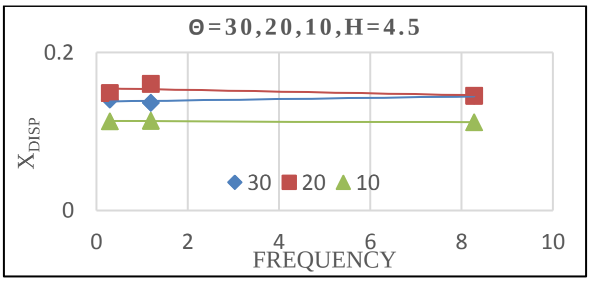


Fig. 13: Effect of different frequency on horizontal displacement of crest using MC& Finn models

3.4. Frequency effect on UBC and UBCH models

Fig. 14 shows the trend of horizontal displacement of the slope crest against the frequency of applied earthquakes for UBC & UBCH constitutive models.



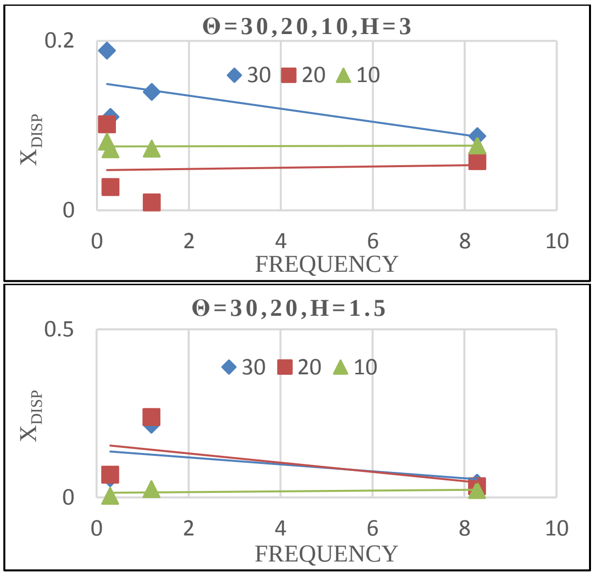


Fig. 14: Effect of different frequency on horizontal displacement of crest using UBC & UBCH models

As shown in Figs. 13 and 14, by increasing the applied frequencies, the displacement of the slope crest decreases or is almost remains constant. Therefore, the results should be the same for both methods, according to the similarity of both curve trends."

4. Summary and Conclusions

As shown in the current paper, Finn and UBC models could model the liquefaction phenomenon with different trends so that the process of increasing in pore water pressure resulting in liquefaction in the UBC is more accurate than the Finn model. In simulated models, by $FLAC^{2D}$ based on UBC & UBCH advanced constitutive models, the second layer has been liquefied in wide regions which lead to larger deformations as compared to MC and Finn, and slopes go towards active mode and failure, whereas in the first method, they may not reach liquefaction and remain stable. Furthermore, the results of this study showed that, for evaluating the seismic response of the slope, in addition to PGA, the frequency content and the thickness liquefiable layer should also be considered as essential parameters.

Regarding the results of dynamic analysis, it can be concluded that in UBC constitutive model similar to Finn's model, by reducing the slope angle and layers' thickness, the frequency effect on the horizontal displacement of slopes will be increased. Therefore, both models exhibit similar results. The results also show that by decreasing the liquefiable layer thickness and increasing the frequency content, the displacement and the slope deformation are also reduced.

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