EVALUATION OF UNSATURATED SOIL RESPONSE UNDER SEISMIC LOADING

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ABSTRACT

The influence of matric suction as a stress state variable of unsaturated soil on shear modulus and also nonlinearity of soil has been recognized in several researches. Therefore, it is clear that presentation of seismic response of unsaturated soil profile with consideration of the suction effect provides a more realistic response of the soil profile. The aim of this study was to evaluate and validate the impact of suction on ground response analysis by available two unsaturated dynamic models in the literature that can predict shear modulus at very small strain and generate G/G_0-γ, D-γ curves with considering of suction. The paper presents a parametric study of linear, equivalent linear and nonlinear site response analysis of the imaginary soil profiles in terms of the amplification function and pseudo acceleration-displacement response spectra and obviously show major effects of suction on the mentioned parameters.

INTRODUCTION

The basis of one-dimensional ground response analysis is a presentation of the procedure by using simplifications avoids of wave scattering. In this method, SH is the input wave that radiated from rock to soil, because when the wave traveling from one medium to another, produces itself exclusively. Moreover, the soil layers that overlaying the bedrock must be parallel with both themselves and bedrock direction. Eventually the response of a point on the bedrock will be transferred to the surface of the soil profile and it is assumed that the response is similar to all of the site points.

Assumptions that soil is either dry or saturated, often is not consisting with reality and in many engineering problems, however, a soil is partially saturated (degree of saturation is between 0 to 100 percent).

The Influence of matric suction as a stress state variable of unsaturated soil on shear modulus and also nonlinearity of soil has been recognized in several researches. So it is clear that presentation of seismic response of unsaturated soil profile with consideration of the suction effect provides a more realistic response of the soil profile.

A research of d'Onza et al. (2008) is the pioneer investigation in this field. The investigation is the basis of linear ground response analysis by considering the soil suction on the shear wave velocity or damping ratio of the unsaturated soil deposits. They have discussed the amplification function in terms of the amplification ratio of surface motion and concluded that the natural frequency of soil deposit significantly increases with suction increase and the maximum amplification ratio is substantially reduced. More recently, Biglari & Ashayeri (2013) and also Biglari et al. (2014) investigated linear, equivalent linear and nonlinear seismic ground response analysis of unsaturated soil deposits with considering suction effects on G/G_0 and D curves that demonstrated increasing of suction level led to increasing natural frequency. Also, it was found that the responses of the structures on the unsaturated soil profiles are more severe than saturated ones, particularly at higher frequencies.

In this study, three different soil specimens that earlier have been studied on unsaturated dynamic models is used to produce various profiles with a variety of suction for analysis of their seismic response in both frequency domain (linear and equivalent linear) and time domain (nonlinear) analysis. A computer program of DEEPSOIL.V5 is used based on the latest achievements and various techniques in both solution domains. The results are discussed in terms of the maximum amplification ratio, first natural frequency, pseudo acceleration-displacement response spectra and acceleration spectrum intensity of the transferred ground motion by changing the amount of suction.

INPUT INFORMATION

To obtain the dynamic response of soil deposit, depth, shear modulus, damping ratio, unit weight of soil profile layers and also input earthquake motion is required. Moreover, to evaluating response of the soil deposit with considering the nonlinear behavior of the soil, G/G_0-γ and D-γ curves is required too.

Wong et al. (2014) extracting model parameter values for Biglari et al. (2011) model for three different low plasticity fine grained soils, namely ZK, CDT and PO reported by Biglari et al. (2011), Ng and Yung (2008) and Vassallo et al. (2007) respectively and predicts shear modulus at very small strain in variable matric suction and mean net stress. Furthermore, Biglari & Ashayeri (2012) modified the empirical equation proposed by Ishibashi & Zhang (1993) to take into account the influence of the suction level as well as stress state and index properties for unsaturated soils. In this paper, according to the available information about the physical properties (Table 1 and figs 1-2) of mentioned soil samples (i.e. ZK, Po and CDT), G/G_0-γ, D-γ curves and also shear modulus of the unsaturated soils standing on the unsaturated models of Biglari et al. in small and wide range strain (2011 and 2012) is obtained.

Table 1. Index properties of soils used in the evaluation of models

Parameters	Zenoz kaolin	CDT	Po silt
Specific gravity	2.65	2.73	2.74
Liquid limit(%)	29	43	51
Plastic limit(%)	17	29	33
Plasticity index (%)	12	14	18
Classification (USCS)	CL	ML	ML/MH

Variations of degree of saturation with mean net stresses and suctions for ZK and PO are presented in figs. 1–2. It should be noted that variation of degree of saturation with mean net stresses for CDT is not available. The degree of saturation is inferred from water retention curve and does not vary with mean net stress. The degree of saturations are respectively 1.0, 0.92, 0.77 and 0.65 for suctions of 0, 50, 100 and 200 kPa (Wong et al. 2014).

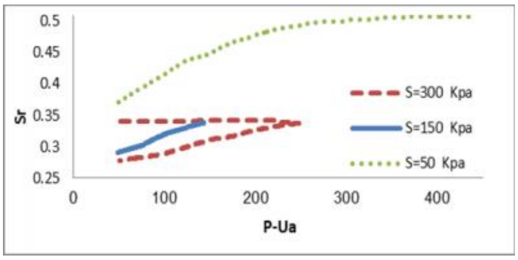

Figure 1. Variations of degree of saturation with mean net stress for Zenoz kaolin

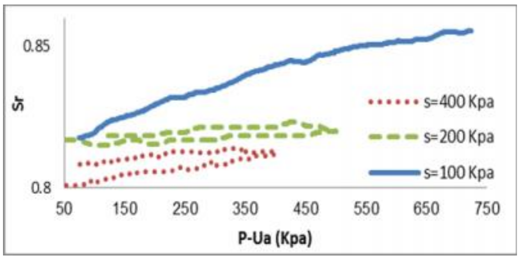

Figure 2. Variations of degree of saturation with mean net stress for Po silt

Fig of 4 and fig 5 shows soil profiles, including mean net stress, shear wave elocity and total unit weight of different layers in various suction levels. These Fig shows four soil profiles of ZK in suction levels of 0, 50, 150 and 300 kpa, four soil profiles of CDT in suction levels of 0, 50, 100 and 200 kpa and three soil profiles of PO in suction levels of 100, 200 and 400 kpa (suction of zero is referred to saturate condition).

All of the unsaturated soil profiles were divided into four 6 meter layers overlying the elastic bedrock in constant suction and variation of mean net stress layers (Figure 3).

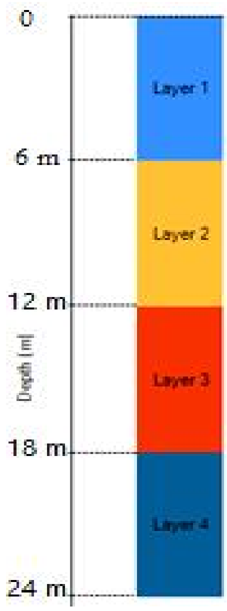

Figure 3. Typical soil profile

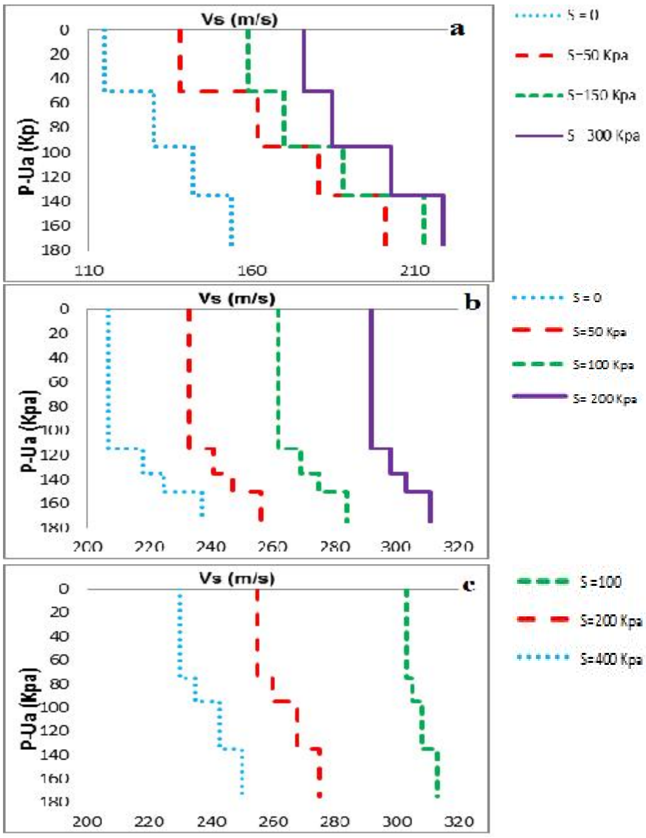

Figure 4. Variation of unit weight with mean net stress and matric suction
a) ZK, b) CDT, c) PO

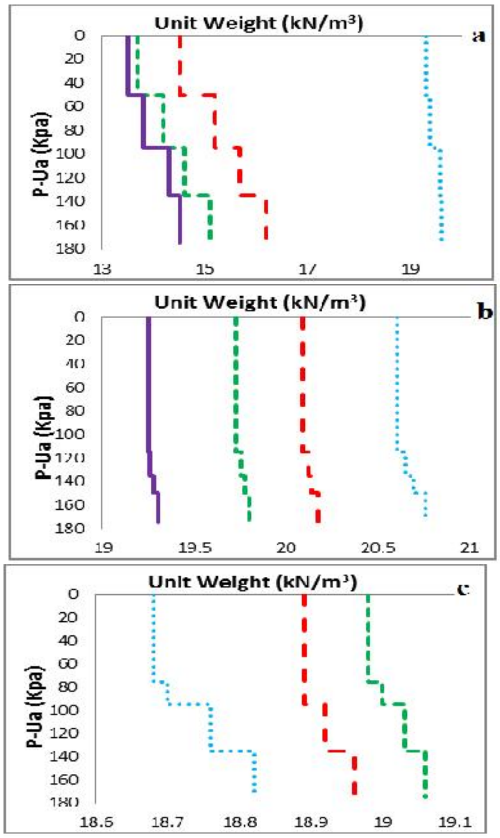

Figure 5. Variation of unit weight with mean net stress and matric suction
a) ZK, b) CDT, c) PO

EVALUATING OF THE OUTPUT RESULTS OF GROUND RESPONSE ANALYSIS

In the many situations, soil deposits depending on climatic conditions and water table level of a region are unsaturated and soil suction is the one of the parameters that affects nonlinearity and also dynamic parameters of the unsaturated soil. Therefore, the purpose of the current study was to determine the suction effect of unsaturated soil in ground response analysis. The analysis results of this study compares the acceleration-displacement response spectra and amplification function in variable matric suction with the both solution methods (time domain and frequency domain).

- **AMPLIFICATION FUNCTION**

surveys such as that conducted by Kramer (1996) have shown that, for undamped soils in linear analysis, the only thing that decreasing maximum amplification is increasing of the impedance (ρv_s). As shown in fig 6 in the linear analysis, the amplification function is independent of characteristics of input motions and it should be noted that in a linear visco-elastic medium, the maximum amplification decreased when soil suction increasing because the suction level affected impedance of soil by changing of the shear wave velocity. Of course it should be mentioned, in conditions that void ratio is reduced extremely (i.e. ZK) due to expansion in moving from saturated situation to unsaturated situation, the maximum amplification could be amplified (refer to table, 2 the impedance of profiles with variation of suction level). Also obviously it is observed from the fig of 6, corresponding frequency of the first maximum amplification (first natural frequency) increased with suction increasing.

In order to obtain the average impedance of the soil profiles average shear wave velocity, should be determined based on Iranian code (Standard 2800), in accordance with the thickness and shear wave velocity of various soil layers by the following formula:

$$\bar{V_s} = \frac{\sum d_i}{\sum \left(d_i / v_{si} \right)} \qquad (1)$$

Where d_i and v_{si} are the thickness and shear wave velocity in each layer respectively

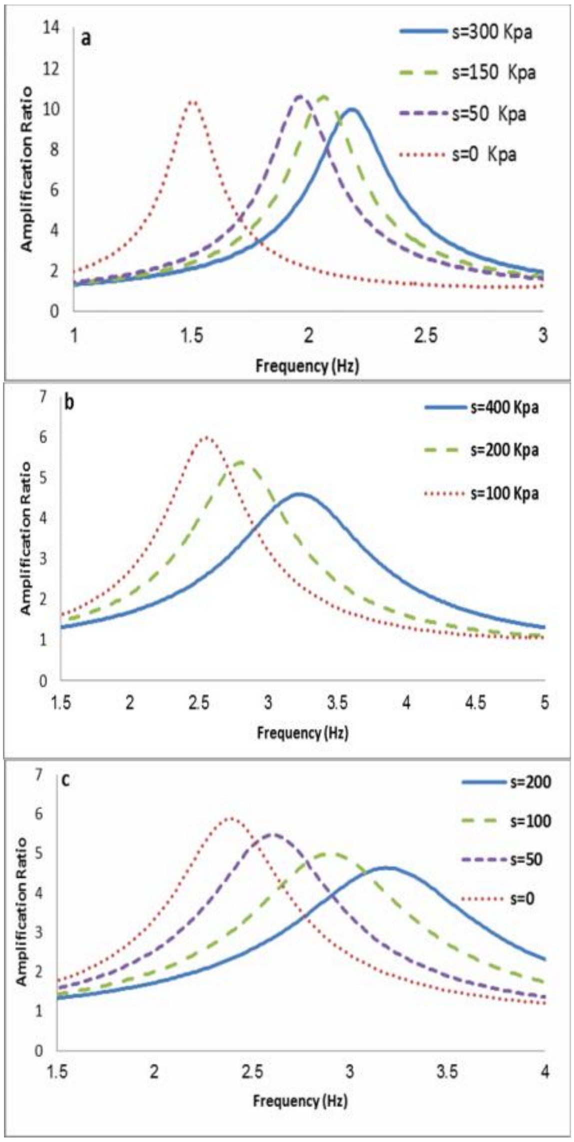

Figure 6. Linear amplification function in variation of suction a) ZK, b) PO, c) CDT

Table 2. Average impedance (IM) versus suction for soil specimens in linear analysis

Zenoz kaolin		CDT		Po silt	
Suction (Kpa)	**IM**	**Suction (Kpa)**	**IM**	**Suction (Kpa)**	**IM**
0	264.7	0	556.4	100	457.0
50	262.6	50	568.4	200	510.1
150	265.0	100	614.8	400	596.0
300	277.9	200	648.0		

Equivalent linear (EQL) method is a frequency domain solution that approximation real nonlinear behavior of soil by using of an iterative approach. This part of the section presents the results of EQL analysis of the unsaturated soil profiles of ZK, PO and CDT in terms of the first natural frequency and first maximum amplification. As it's expectable, the output results on mentioned parameters for ZK have completely agreement with the results obtain by Biglari and Ashayeri (2013). Table 4 shows the parameters, versus changing of suction level for ZK in various earthquake motions (Table 3 shows the details of the input motions). By refer to the table; it should be observed that the maximum amplification and first natural frequency would increase sharply when the soil suction increased. The same results about the first natural frequency of ZK is obtained for profiles of CDT and PO (Table 4). Unlike the results of ZK profiles about the maximum amplification, the other soil profiles show the inverse relation between soil suction and maximum amplification . These soil samples (PO and CDT) have a higher plasticity index (PI) and lower void ratio (e) rather than ZK soil sample. These physical properties due to the soil limited in smaller strain ranges than ZK (Fig 7 shows the EQL stress strain behavior of the soil samples in cape Mendocino earthquake).

Table 3. Details of the input motions

No.	Name of earthquake	Date of earthquake	Station	Magnitude (Mb)
1	Cape Mendocino	25/04/1992	89005 Cape Mendocino	7.1
2	Chi-Chi	20/09/1999	ALS	7.6
3	Kobe	16/01/1995	KJMA	6.9
4	Loma Prieta	18/10/1989	47379 Gilroy Array #1	6.9
5	Northridge	17/01/1994	24207 Pacoima Dam (upper left)	6.7
6	Tabas	16/09/1978	9101 Tabas	7.4

Fully nonlinear ground response analysis in comparison with the frequency solution methods would render in more acceptable results when the all of nonlinearity soil parameters have been considered. For nonlinear analysis (NL) in time domain, the dynamic equation of motion is solved in time steps with the aid of numerical methods and at each step, hysteretic behavior of the soil is modeled with the system updating stiffness and damping matrix (Hashash et al., 2011).

In nonlinear analysis, MRDF model was used for determining the best fit curves of shear modulus and damping ratio. This model proposed a formulation that modifies the loading-unloading criteria that result from using the Masing rules (1926). The new formulation provides better agreement with the damping curves for larger shear strains (Phillips and Hashash, 2009).

The results of nonlinear time domain solution method about of the first maximum amplification and first natural frequency shows a direct relation between the parameters and matric suction (In this study, the value of number of moving average was considered equal to100, it means that 100 times the amplification function is to be smoothened by applying a three-point moving average). Regardless of the smoothing effects, when the analysis would more accurate (i.e. NL method) output results in comparison with the EQL analysis in term of first maximum amplification show the same trend in the all of soil samples (i.e. ZK, PO and CDT). Figure 8 shows the NL stress-strain behaviour of the soil samples in Cape Mendocino earthquake.

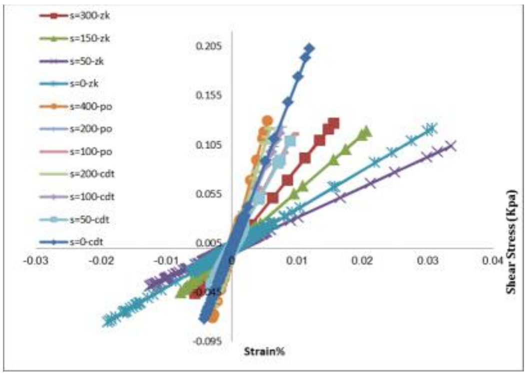

Figure 7. EQL stress-strain behaviour in Cape Mendocino earthquake

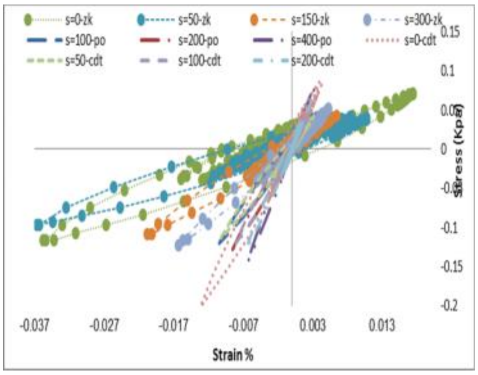

Figure 8. NL stress-strain behaviour in Cape Mendocino earthquake

Table 4. First maximum amplification and first natural frequency versus suction in NL and EQL analysis for ZK, CDT and PO

First maximum amplification and first natural frequency (HZ) for ZK in NL analysis.												
Suction	***Cape Mendocino***		***Chi-Chi***		***Kobe***		***Loma Prieta***		***Northridge***		***Tabas***	
300 Kpa	2.49	0.72	2.85	1.08	2.69	0.99	2.23	0.43	2.50	0.80	2.52	0.95
150 Kpa	2.44	0.72	2.65	1.07	2.70	0.85	2.19	0.43	2.38	0.77	2.44	0.67
50 Kpa	2.38	0.44	2.49	0.60	2.64	0.73	2.06	0.26	2.34	0.48	2.42	0.39
0	1.78	0.16	1.91	0.33	1.84	0.33	1.84	0.09	2.09	0.14	1.97	0.29
First maximum amplification and first natural frequency (HZ) for ZK in EQL analysis.												
300 Kpa	2.98	1.77	2.69	1.59	2.69	1.58	2.74	1.62	2.97	1.77	2.82	1.68
150 Kpa	2.88	1.57	2.62	1.39	2.59	1.35	2.64	1.40	2.86	1.57	2.73	1.48
50 Kpa	2.76	1.38	2.56	1.20	2.54	1.15	2.58	1.21	2.75	1.39	2.65	1.28
0	2.57	0.96	2.40	0.76	2.48	0.84	2.50	0.85	2.67	1.04	2.50	0.89
First maximum amplification and first natural frequency (HZ) for CDT in NL analysis.												
200 Kpa	2.47	1.48	2.70	1.78	2.80	1.74	2.65	1.48	2.41	1.63	2.65	1.64
100 Kpa	2.44	1.16	2.61	1.61	2.76	1.75	2.47	1.41	2.38	1.38	2.48	1.46
50 Kpa	2.31	0.86	2.52	1.30	2.42	1.41	2.16	1.36	2.25	1.09	2.32	0.98
0	2.23	0.74	2.47	1.07	2.37	0.99	2.13	0.60	2.19	0.80	2.20	0.74
First maximum amplification and first natural frequency (HZ) for CDT in EQL analysis.												
200 Kpa	2.27	2.38	2.20	2.25	2.20	2.23	2.21	2.26	2.28	2.42	2.23	2.31
100 Kpa	2.32	2.14	2.22	1.96	2.22	1.95	2.24	1.99	2.32	2.16	2.27	2.06
50 Kpa	2.37	1.89	2.25	1.69	2.26	1.69	2.28	1.75	2.37	1.90	2.32	1.81
0	2.42	1.71	2.28	1.49	2.27	1.48	2.30	1.53	2.41	1.71	2.34	1.60
First maximum amplification and first natural frequency (HZ) for PO in NL analysis.												
400Kpa	2.54	1.65	2.80	1.99	2.90	2.28	2.74	1.61	2.50	1.65	2.71	1.77
200 Kpa	2.52	1.16	2.75	1.61	2.92	1.75	2.60	1.42	2.48	1.37	2.59	1.45
100 Kpa	2.39	0.97	2.64	1.30	2.61	1.40	2.31	1.36	2.35	1.09	2.44	1.09
First maximum amplification and first natural frequency (HZ) for PO in EQL analysis.												
400Kpa	2.39	2.54	2.34	2.45	2.34	2.45	2.33	2.44	2.40	2.58	2.36	2.48
200 Kpa	2.52	2.16	2.42	2.02	2.41	2.00	2.43	2.04	2.52	2.17	2.47	2.10
100 Kpa	2.59	1.93	2.46	1.75	2.46	1.75	2.49	1.79	2.59	1.93	2.53	1.86

- **PSEUDO ACCELERATİON-DİSPLACEMENT RESPONSE SPECTRA**

Pseudo acceleration-displacement response spectra is a technique to display the spectral curves and has the special application in the earthquake engineering codes. The purpose of tracing this spectrum is displaying the information of pseudo acceleration-displacement into a curve in order to avoid of complexities of drawing a tri-spectrum.

Fig 9 shows pseudo acceleration-displacement response spectra of the EQL analysis in various suction levels for Chichi earthquake. As the mentioned fig shows, the results presented about pseudo acceleration- displacement response spectra revealed that with increasing of suction level, pseudo-acceleration spectra increases at shorter periods and displacement spectra decreases at longer periods. The importance of aforesaid result will be a summary of this statement that, design of structures in an imaginary site at the lower suction level in comparison with the higher suction level in short periods is underestimated and in long periods is overestimated.

In order to more clear the results in short periods ranges, a well-known intensity parameter has been used (Figs 10 and 11). ASI[1] is defined as the integral of the pseudo acceleration spectral (Sa) over the period range of 0.1 – 0.5 Sec (Bradley, 2010).

$$ASI = \int_{0.1}^{0.5} Sa(T, 5\%)\,dT \qquad (2)$$

1- Acceleration Spectrum Intensity

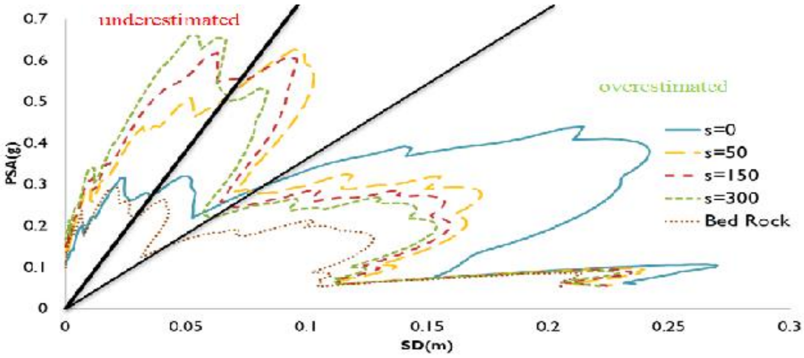

Figure 9. pseudo acceleration-displacement response spectra of ZK profiles in EQL analysis for Chichi eartquake

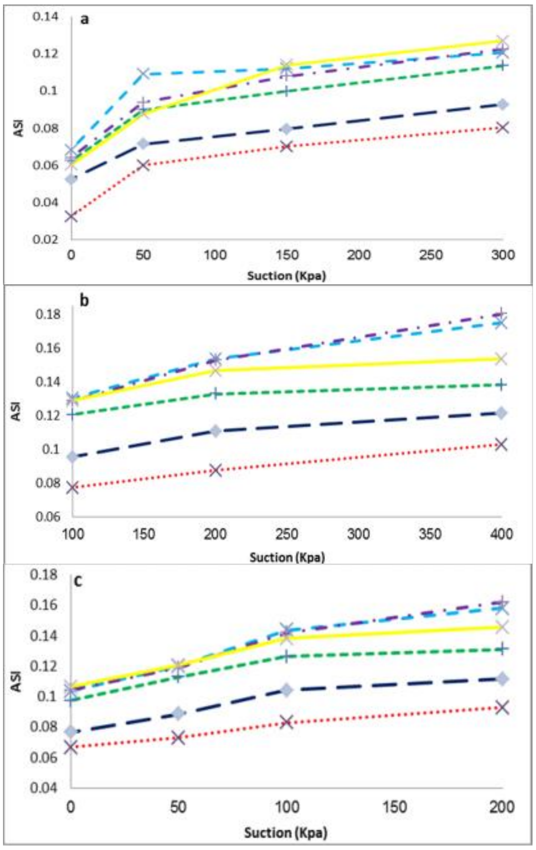

Figure 10. Variation of ASI with suction in NL analysis for the all of earthquakes
a) ZK, b) PO, c) CDT

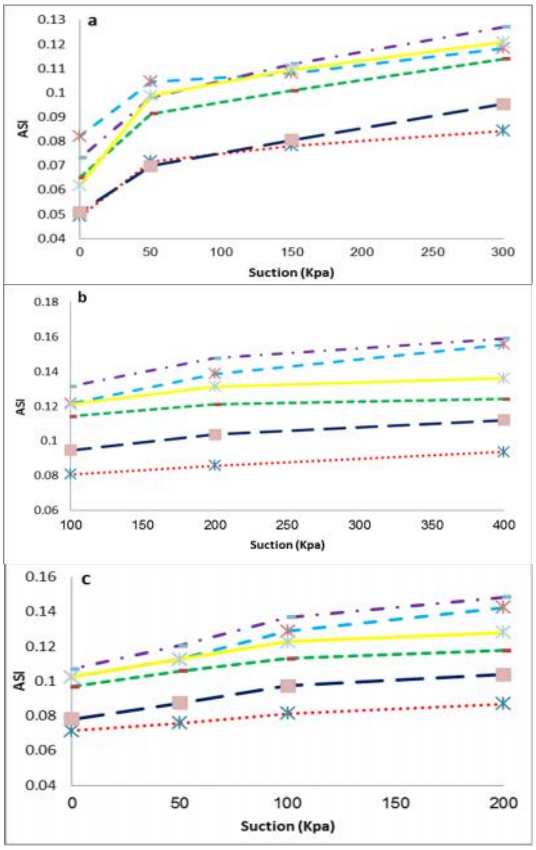

Figure 11. Variation of ASI with suction in EQL analysis for the all of earthquakes
a) ZK, b) PO, c) CDT

CONCLUSIONS

In this study, seismic response of saturated and unsaturated soil profiles in variation of suction and degree of saturation by using of "DEEPSOIL" which is capable to calculate the dynamic response of soil in frequency domain methods (linear and equivalent linear) and time domain method (nonlinear) has been conducted.

Analyzes, were performed on various soil profiles by using of 6 acceleration records in different solution methods and the influence of matric suction as a stress state variable of unsaturated soil have been evaluated on strong ground motion parameters. Stress-strain behavior of different soil samples (i.e. ZK, PO and CDT) shows that dynamic response of soils in addition of matric suction, is affected by plastic index, void ratio and mean net stress extremely, as the important parameters in determining of nonlinearity of soils. So, the changes in suction level of a soil sample that have more nonlinearity, has always direct relation with maximum amplification ratio. The results of both linear, equivalent linear and nonlinear solution indicated that the first natural frequency in the all of soil profiles increases with suction increasing. Additionally, the results presented about pseudo acceleration-displacement response spectra revealed that, with increasing of suction level, pseudo-acceleration spectra increases at the short periods and displacement spectra decreases at the long periods.

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