Prediction of Liquefaction triggering in crude oil contaminated sand using UBC3D-PLM model in PLAXIS 2D

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Abstract. Earthquake induced soil liquefaction has been a major issue of concern because of its devastating impacts and the complexity attenuates when the soil is contaminated. The paper assess the liquefaction propensity of crude oil contaminated silty sand using UBC3D-PLM constitutive model in PLAXIS 2D which is believed to be one of the most capable model in simulating seismic liquefaction in sands. The applicability of the model has been verified beforehand for its use in oil contaminated sands. The model parameters have been evaluated by conducting monotonic consolidated drained triaxial test on silty sand contaminated with varying crude oil content (0, 6, 8 and 12% W/V). Numerical simulations have been performed for varying oil content and seismic excitations. The results revealed that oil contamination has a significant effect on liquefaction triggering and settlement response of the soil under seismic loading.

Keywords: Liquefaction; Soil contamination; UBC3D-PLM; PLAXIS.

1 Introduction

Among all the sources of energy worldwide, oil and natural gas are the most significant ones. Their importance is increasing owing to their upsurging global demand. Nevertheless, the major drawback associated with such an energy source is the serious damage they cause to the environment due to the massive oil spills and leakages during their production and transportation [1]. Crude oil contamination significantly impacts the engineering properties of the soil [2]. It is likely to affect the overall response of the structures founded on such soil. Remediation techniques like electrokinetic soil remediation, thermal desorption, soil washing and bio-remediation have been recommended for oil contaminated soil but their cost-effectiveness seems to be questionable [3]. A smarter choice would be to utilize oil contaminated soil in construction practices.

There have been several severe oil spills round the globe which have contaminated the land resources and posed a threat of unsafe construction practices. As per the data released by World Petroleum Council, the average number of spills due to pipeline bursts are increasing significantly. Apart from this, other sources like oil-based drilling muds, industrial effluents etc. also add on to this problem. During the past decade, several studies pertaining to the geotechnical properties and behavior of hydrocarbon contaminated soil have been carried out [2,4,5,6]. Gulf countries and Alps are the most severely affected areas with the well blowouts and oil spills. In India, north eastern regions have large number of oil fields. Moreover, they are also among the areas which lies in high risk seismic zones. Only a handful of research has been conducted on seismic response of oil contaminated soils. Therefore, due to the necessity of studies in this field, the main subject of this research is to investigate the effect of seismic loading on crude oil contaminated soil.

2 UBC3D-PLM Model

The UBC3D- PLM model has been developed by [7] and implemented as a user-defined model introduced by [8,9]. The original UBCSAND is a 2-D model developed for the prediction of liquefaction in sandy soil.

Table 1. Material parameters required for UBC3D-PLM model

Name	**Symbol**	**Method used for determination**	**Remark**
Constant volume friction angle	φ_{cv}	Consolidated Drained Triaxial Test	
Peak friction angle	φ_p	Consolidated Drained Triaxial Test	
Cohesion	c	Consolidated Drained Triaxial Test	
Elastic Shear Modulus	[illegible]	Curve Fit	
Plastic Shear Modulus	[illegible]	Curve Fit	
Elastic Bulk Modulus	[illegible]	Curve Fit	
Elastic Shear Modulus Index	ne	0.5	Default
Elastic Bulk Modulus Index	me	0.5	Default
Plastic Shear Modulus Index	np	0.5	Default
Failure Ratio	R_f	Curve Fit	
Atmospheric pressure	P_A	Standard Value (100kPa)	
Tension Cut-off	σ_t	0	Default
Densification Factor	f_{achard}	Curve fit	
SPT value	$(N1)_{60}$	In-situ testing	
Post Liquefaction Factor	F_{acpost}	0.2	Default

UBC3D-PLM is an effective stress based elastic-plastic model which is capable of simulating the liquefaction behaviour of sands and silty sands under seismic loading [10]. Earlier, this model was used for dynamic analysis of dam tailings in Japan. The results predicted by the model were in good agreement with the actual failure pattern of the dam induced due to seismic liquefaction [8,11,12]. The UBC3D-PLM model is utilized in this study which has been incorporated as one of the soil material model in the finite element based software PLAXIS2D.

The soil input parameters required for the UBC3D-PLM model are listed in table 1. The method employed in determining each parameter are clearly indicated against them.

3 Experimental Program

3.1 Basic Properties of soil samples and crude oil

Guwahati sand classified as silty sand (SM) as per the Unified Soil Classification System, has been used for all the investigations presented in this research. The specific gravity of soil sample based on pycnometer test was 2.62. The grain size distribution curve of the soil is shown in Fig. 1 according to which the percent of sand, silt and clay in the soil was 67%, 30% and 3% respectively. Standard compaction test was carried which gave optimum moisture content and maximum dry density as and 13.5% and 18.2 kN/m^3 respectively.

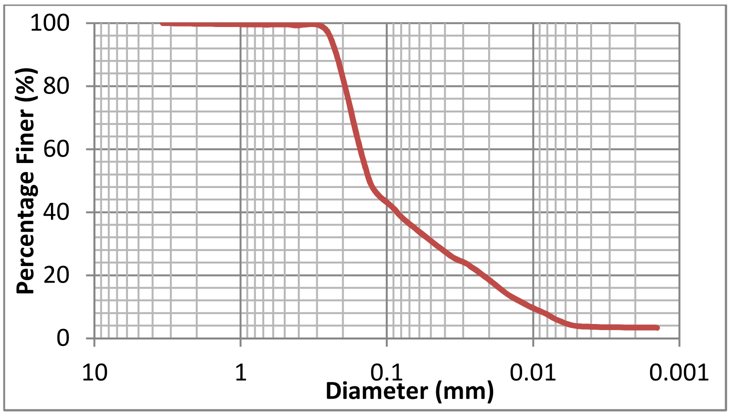


Fig. 1. Grain Size Distribution Curve of Guwahati Sand

Light crude oil, collected from IOCL Barauni refinery was used in the study. Light crude oil was chosen over medium or heavy crude oil as it is believed to be one of the most adverse soil contaminant because of its low viscosity which allows it to easily penetrate into the oil matrix. Crude oil properties used in this study are given in Table 2.

Table 2. Properties of Light Crude Oil

Property	Value
Kinematic Viscosity (10^-6x m^2/s)	15.8
Density (kN/m^3)	7.71
Specific Gravity	0.76
Pour Point (^{0}C)	-18

3.2 Sample Preparation

The current research does not exactly replicate the field scenarios since its main aim is to study the change in the liquefaction characteristics of the soil due to crude oil contamination. So, the specimens used in the experimental program was reconstituted. Firstly, air dried soil was sieved through 4.75mm sieve to separate any undesired matter. It was then oven dried and contaminated (hand-mixing) by light crude oil in varying percentages, i.e. 6%, 8% and 12% (W/V). The samples were kept in sealed bags for one-week interaction period to ensure uniform absorption of oil in the soil. The soil was then tested to evaluate its engineering properties.

3.3 Consolidated Drained Triaxial Test

In order to evaluate the input parameters for finite element analysis, consolidated drained triaxial tests were conducted on both uncontaminated soil and crude oil contaminated (at 6%, 8% and 12%) soil at 50% relative density. Fig 2. shows the effect of crude oil on both constant volume friction angle and peak friction angle. The results obtained showed that both constant volume friction angle and peak friction angle decreased continuously with increasing oil content while cohesion increased till 8% contamination after which it dropped at 12 %. Reduction in shear strength and a softer stress strain behavior was observed with increasing oil content.

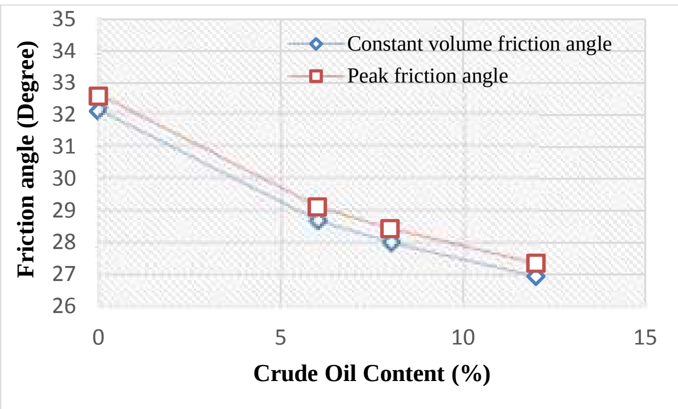


Fig. 2. Effect of crude oil content on constant volume and peak friction angle from consolidated drained triaxial test

4 Numerical Modelling

4.1 Modeling soil and earthquake motion

The boundaries of the soil are taken as x_{min}=0.0m, x_{max} = 12.0m, y_{min} = 0.0m and y_{max} =8.0m. Fifteen-noded triangular elements were used to model the soil layer. The soil is modeled to follow UBC3D-PLM model. The model input parameters determined in the laboratory have been listed in Table 3. The plane strain condition was assumed in all the simulations.

Table 3. Input parameters for UBC3D-PLM soil model

Parameters	Unit	Uncontaminated Sand	6% crude oil contaminated sand	8% crude oil contaminated Sand	12% crude oil contaminated sand
Depth	m	8.0	8.0	8.0	8.0
Unsaturated unit weight	**kN/m^3**	18.2	16.67	16.4	16
Saturated Unit weight	**kN/m^3**	20	18	17.7	17.9
Constant volume friction angle		32.11	28.68	28.01	26.94
Peak friction angle		32.59	29.11	28.43	27.35
Cohesion	**kPa**	6	10	12	16
Elastic Shear Modulus		735.25	709.74	704.30	695.98
Plastic Shear Modulus		152.31	140.84	138.705	135.61
Elastic Bulk Modulus		514.67	496.81	493.0	487.18
Elastic Shear Modulus Index		0.5	0.5	0.5	0.5
Elastic Bulk Modulus Index		0.5	0.5	0.5	0.5
Plastic Shear Modulus Index		0.5	0.5	0.5	0.5
Failure Ratio		0.867	0.881	0.884	0.889
Atmospheric pressure		100	100	100	100
Tension Cut-off		0	0	0	0
Densification Factor		0.487	0.438	0.428	0.413
Post Liquefaction Factor		0.2	0.2	0.2	0.2

The earthquake is modelled using prescribed displacement option by defining appropriate displacement multiplier. The record of earthquake accelerations with time is obtained from Strong Motion Database The analysis has been carried out utilizing two input ground motions of Nepal earthquake and Chi Chi earthquake and is shown in Fig. 3 and Fig. 4.

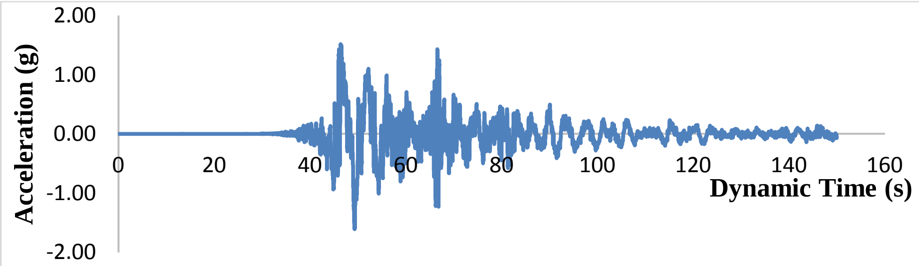


Fig. 3. Acceleration-time history for Nepal Earthquake in 2015

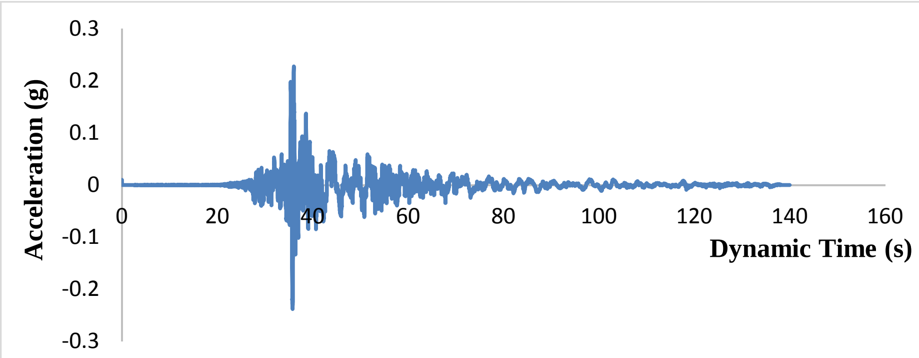
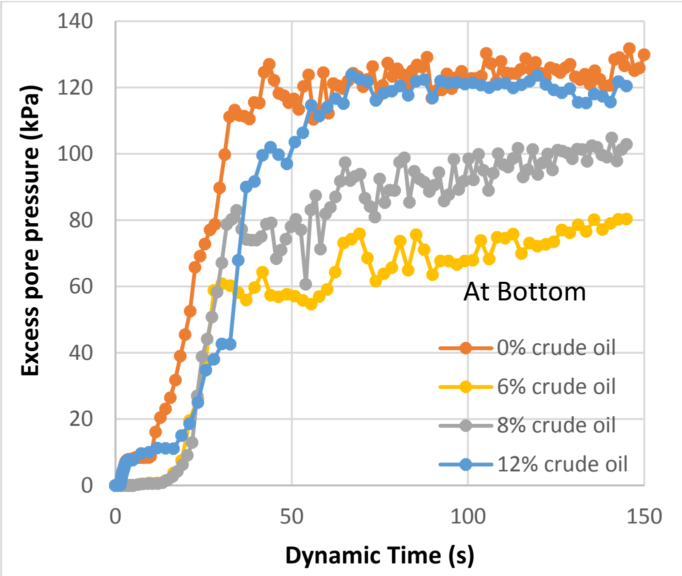


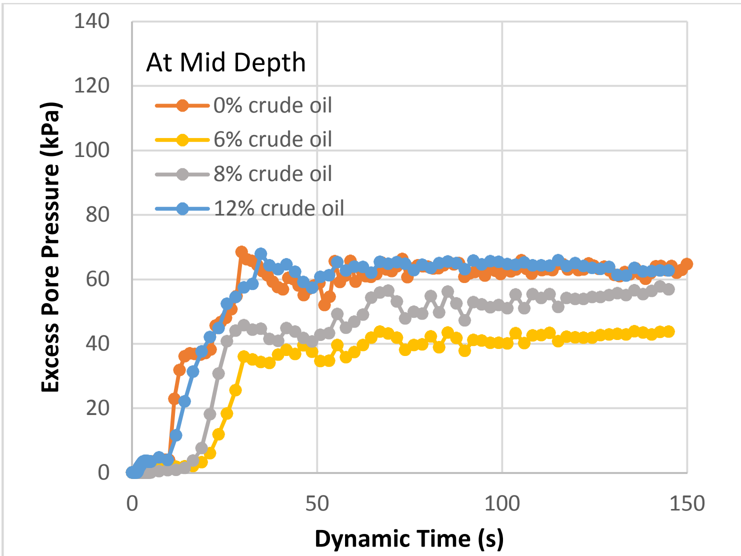
Fig. 4. Acceleration-time history for Chi Chi Earthquake in 1999

4.2 Results and Discussion

Effect of crude oil content on pore pressure development Results obtained from numerical simulations conducted on clean as well as contaminated sand specimens in PLAXIS revealed that oil contamination has a significant effect on the dynamic behavior of sands. Fig. 5 and Fig. 6 shows the development of excess pore pressure at bottom and mid depth of soil layer for Nepal and Chi Chi earthquakes respectively. It can be observed that the magnitude as well as the rate of development of excess pore pressure drops down sharply as the oil content increases from 0 to 6%. This can be attributed to the increased pore fluid viscosity which increase cohesion and in turn in liquefaction resistance. Any further increase in oil content (8% and 12% in this case) increases the magnitude of excess pore pressure. This behavior could be interpreted on the basis of reduced permeability and effective stress in the soil matrix due to presence of oil. At 12% oil content, the excess pore pressure almost attains the same value as in the case of uncontaminated sand. However, time to reach that value was more in case of contaminated sand. Similar trend is observed for both the input motions. Therefore, for this study, 8% can be considered as threshold oil content. It should be noted that the excess pressure developed in the voids is the total fluid pressure exerted by both oil and water.

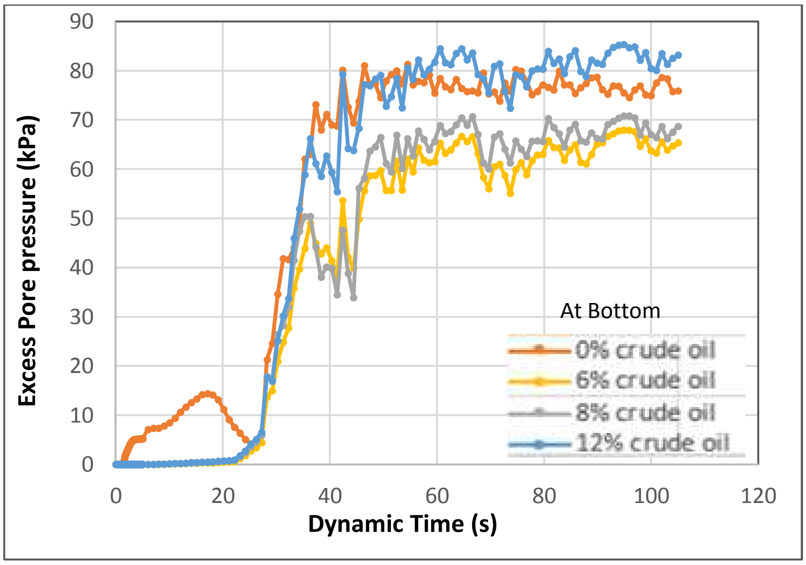


(a)

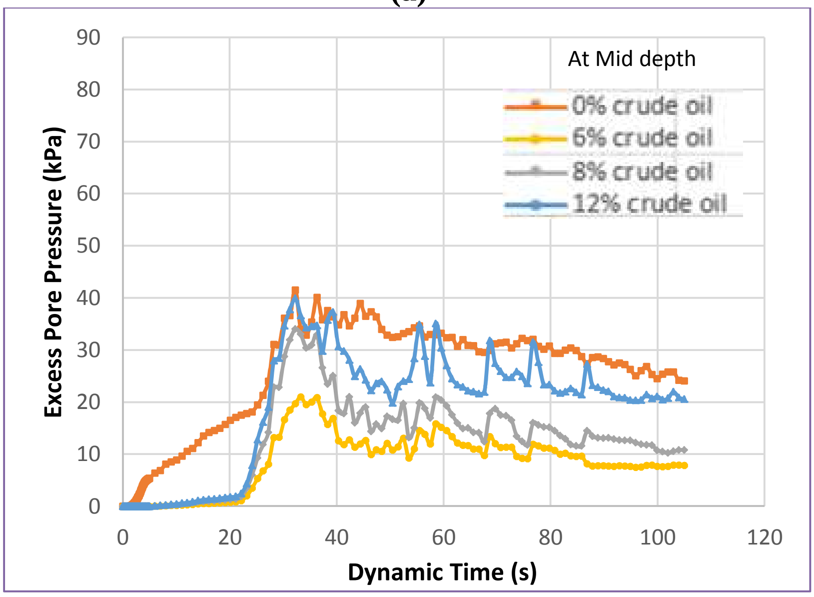


(b)

Fig. 5. Excess pore pressure development for Nepal earthquake at (a) bottom (b) mid depth of soil layer



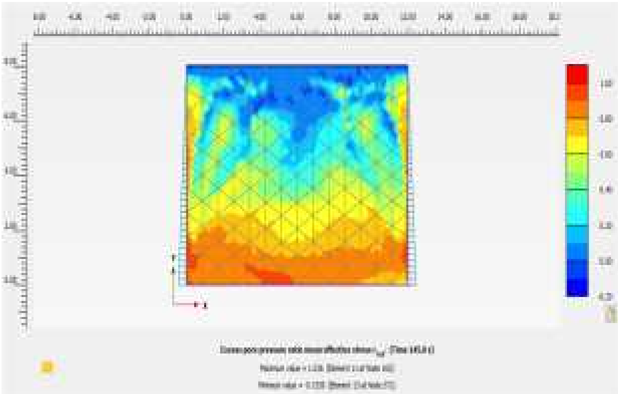
(a)



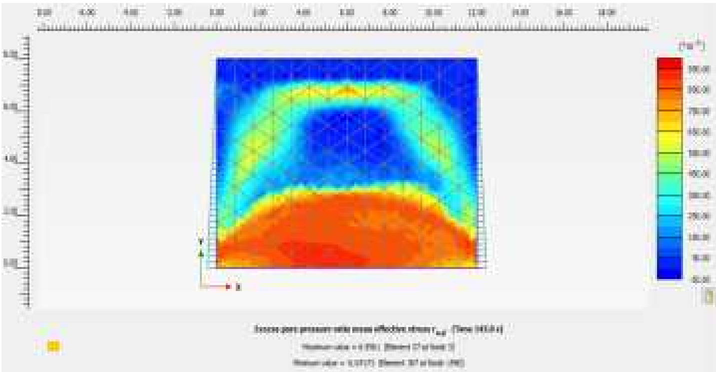
(b)

Fig. 6. Excess pore-pressure development for Chi Chi earthquake at (a) bottom (b) mid depth of soil layer

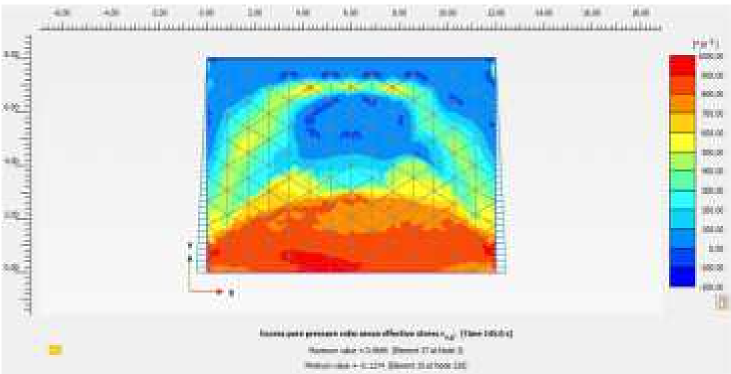
Fig. 7 shows the variation of excess pore pressure ratio with respect to vertical effective stress in the two dimensional soil domain for each crude oil percentage. The red and blue color indicates the liquefied and non-liquefied zones respectively. As can be observed clearly, for 12% crude oil contamination major portion of the soil layer is liquefied. On the other hand, for 6% and 8% crude oil content the liquefied zones are less intensified restricted only to the bottom layer.



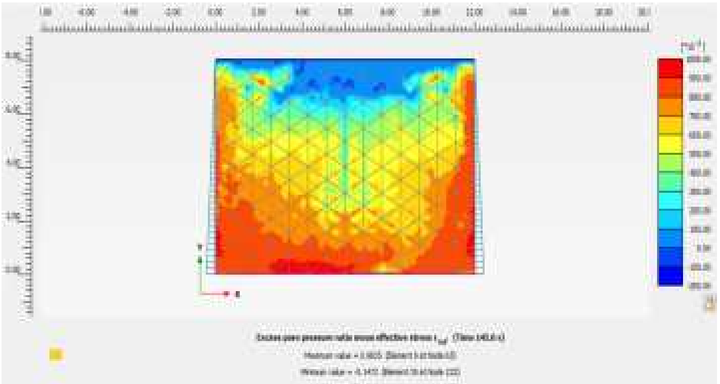
(a) 0% crude oil contamination



(b) 6% crude oil contamination



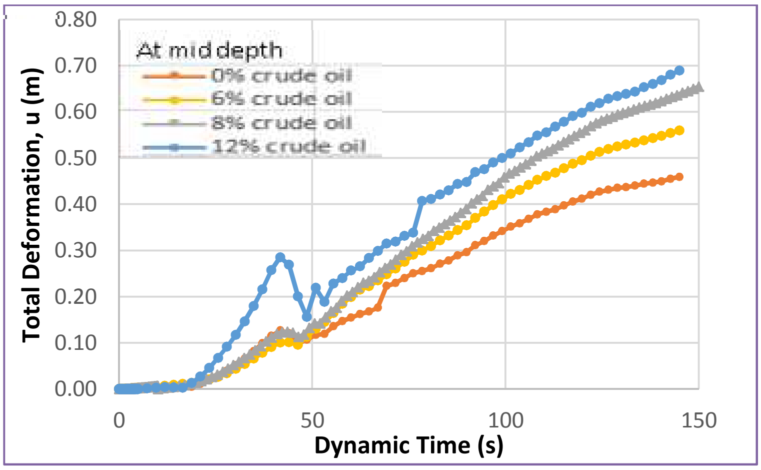
(c) 8% crude oil contamination



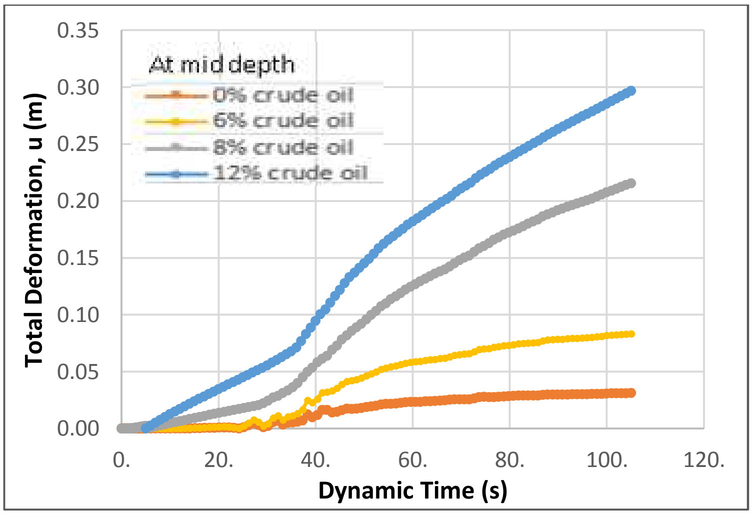
(d) 12% crude oil contamination

Fig. 7. Excess pore pressure ratio w.r.t to vertical effective stress for various crude oil percentages

Effect of crude oil content on the deformation behavior. The deformation behavior of crude oil contaminated soil under seismic loading also shows a similar trend for both the input motions (Fig. 8). With increase in oil content, the total deformation of the soil layer increases due to lubricating effect of oil which causes slipping of soil particles against each other. Also it is evident from Fig. 2 where frictional resistance of the soil is continuously decreasing with increasing oil content.



(a)



(b)

Fig. 8. Total Deformation at mid depth for (a) Nepal earthquake and (b) Chi Chi earthquake

5 Conclusion

The work simulates the effect of crude oil contamination on the liquefaction characteristics of the silty sand under seismic loading conditions. A series of CD triaxial tests followed by numerical simulations using UBC3D-PLM material model in PLAXIS has been performed for different crude oil percentages (0, 6,8 and 12%). The results from numerical simulations reveals that the presence of crude oil in soil initially increases its liquefaction resistance owing to the increased pore fluid viscosity which causes increase in cohesion. Adding crude oil above 8% cause sharp decrease in liquefaction resistance which may be due to significant reduction in effective stress and hydraulic conductivity. Hence there exists a threshold oil content at which the soil offers maximum liquefaction resistance. However, further experimental investigations are required in order to achieve more accurate interpretation.

References

1. Rahman, Z. A., Hamzah, U., Taha, M. R., Ithnain, N. S., & Ahmad, N. Influence of oil contamination on geotechnical properties of basaltic residual soil. American journal of applied sciences, 7(7), 954, (2010).
2. Khosravi, E., Ghasemzadeh, H., Sabour, M. R., & Yazdani, H. Geotechnical properties of gas oil-contaminated kaolinite. Engineering Geology, 166, 11-16, (2013).
3. Riser-Roberts, Eve. Remediation of petroleum contaminated soils: biological, physical, and chemical processes. CRC press, 1998.
4. Shin, E. C., & Das, B. M. Bearing capacity of unsaturated oil-contaminated sand. International Journal of offshore and polar Engineering, 11(03), (2001).

5. Mashalah K, Amir HC, Majid T. Effects of crude oil contamination on geotechnical properties of clayey and sandy soils. Eng Geol 89:220–229, (2007).
6. Khamehchiyan, M., Charkhabi, A. H., & Tajik, M. Effects of crude oil contamination on geotechnical properties of clayey and sandy soils. Engineering geology, 89(3-4), 220-229, (2007).
7. Tsegaye A. Plaxis liqueafaction model. report no. 1. PLAXIS knowledge base., 2010.
8. Puebla, H., Byrne, P. M., & Phillips, R. Analysis of CANLEX liquefaction embankments: prototype and centrifuge models. Canadian Geotechnical Journal, 34(5), 641-657, (1997).
9. Beaty, M., & Byrne, P. M. An Effective Stress Model for Pedicting Liquefaction Behaviour of Sand. In Geotechnical Earthquake Engineering and Soil Dynamics III (pp. 766-777). ASCE, (1998, August).
10. Beaty, M. H., & Byrne, P. M. UBCSAND constitutive model version 904aR. Itasca UDM Web Site, 69, (2011).
11. Seid-Karbasi, M., & Byrne, P. M. Seismic liquefaction, lateral spreading, and flow slides: a numerical investigation into void redistribution. Canadian Geotechnical Journal, 44(7), 873-890, (2007).
12. Byrne, P. M., & Seid-Karbasi, M. Seismic stability of impoundments. In 17th Annual Symposium, Vancouver Geotechnical Society, (2003).