THE EFFECT OF LIQUEFACTION ON COASTAL SHEET PILE WALLS

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ABSTRACT

Earthquake occurrence in the areas having saturated loose sandy soil causes an increase in the pore water pressure and decreasing resistance of the soil which is called liquefaction. So far there has been a great deal of damage to earthquake stricken areas of the world especially in coastal areas haring liquefying conditions. The importance and the sensitive role of the coastal sheet pile walls and also the weak performance of these structures at the time of liquefying soil need more researches to find out the behavior of the wall during the earthquake and the soil liquefaction.

In this research the behavior of the walls of the restricted sheet pile towards the dynamic loading has been studied by taking into account the impact of pore water pressure increase and liquefaction of the soil near the wall. Also for stimulating the module to take into account the sheer variation of soil with sheer strain during dynamic loading, a program by means of the criterion concepts Massing has been written in FISH environment which is a program writing environment which is programming FLAC software environment. The method for analysis in this project is based on dynamic analysis of the effective, non-linear stress and by means of numerical modeling using finite differences and FLAC software. To model the increase of pore water pressure in this software, the behavioral model of “Finn” has been used. The results gained out of the analyses demonstrated that soil improvement and the zone of improving are the most important effective factors enhancing the behavior of sheet pile. It has been shown that the increase of dynamic vibration duration causes an increase in sheet pile displacement. A study on results reveals the occurrence of the large displacement in the last seconds is due to liquefying of the soil in the back of sheet pile.

KEYWORDS: Sheet pile, Liquefaction, Effective stress, Dynamic loading, Earthquake, FLAC.

1-INTRODUCTION

So far there has been a great deal damage to the earthquake stricken areas of the world due to earthquake and the occurrence of its coincident liquefaction. Among the most important ones in aspect of the extent of destruction due to the occurrence of liquefaction are earthquake of Nigata (Japan) and Alaska 1964, California in 1925, 1971 and Akita (Japan) in 1989 and 1983, Hukido (Japan) 1993 and the last and the most important one was the earthquake of Kube (Japan) in 1995. To point some instances of due to these earthquakes, it may be pointed to the damages to the slopes, weaking of the structures in harbors and ports and damages to earth dams. Some instances of liquefaction and damages due to it have been seen in Manjil earthquake (Iran, 1989). Coastal walls are of sensitive structures to the earthquake and soil liquefaction. There are many instances of damage to sheet pile and caisson due to liquefaction during the earthquake. Taking into account the importance of coastal walls and especially the sensitive role of these structures in harbors and ports, a good deal of researches has been done to study the coastal wall’s behaviors subjected to earthquake causing soil liquefaction. In order to do so the method of non-linear effective stress analysis by means of FLAC software which uses the method of finite differences had been used. The behavioral model used in the analysis for modeling the increase of pore water pressure and soil liquefying is the behavioral model of Finn which is included in FLAC version 4.0 software. This behavioral model, as model of mohr-colomb makes use of a constant sheer module as an equivalent linear sheer module. As one know in practice the cyclic sheer stress of soil is not linear to sheer strain, the soil sheer module is based on the level of sheer strain. To get close to the real behavior of the soil, criterion concepts of Massing is used. The program Massing.fish has been written in the program writing environment of “FISH” which is of capabilities of FLAC software.

2-LIQUEFACTION ON SHEET PILE

Coastal walls are the major parts of harbors and posses a lot of weight in structural calculations. The important role of coastal walls is to provide a support for ships and protecting the soil behind it. Sheet piles are one of the kinds of coastal walls. These walls are often regarded as flexible walls. Design of these walls is more complicated than the design of gravity or cantilever walls. The major force affecting sheet pile results from the soil pressure whose magnitude depends on physical characteristics of the soil and the interaction between the soil and the structure. For great sheet pile on which a great force is acting on it, it is necessary to restrict the displacement of the top of the wall. Therefore, in this case one or more anchor bolts are used. Sheet piles are so sensitive to the earthquakes and especially to the liquefaction of the soil. So far there have been seen a lot of damages to this kind of walls due to the earthquake as well as soil liquefaction. As a result damages to the rear structures such as cranes, cargo transport units and buildings. It has been seen in several cases that the displacement on earth surface due to sheet pile destructions were extended around 75 meters a way to the wall. The sheet pile are sensitive to liquefaction in three cases: as shown in figure 1 which part a of figure 1 shows the liquefaction of the soil around the anchor bolt which causes lowering soil resistance and as a result poses deformation or distortion of the structure yielding of anchor bolt. Part b of the figure 1 reveals the occurrence of liquefaction around the sheet pile which causes increase of soil pressure and finally yielding of sheet pile. Part c of the figure 1 shows the liquefying of the soil at the base of sheet pile which causes reduction of resisting forces. Analysis of dynamic behavior of retaining walls is done in way such as static equivalent analysis and dynamic analysis.

Soil behavioral models at the time of liquefaction differ from normal models and for analysis and exploring the behaviors of the soil around the walls which is liquefying, modern behavioral soil models and specific software are required.

Verification of the models and software's, is accessible through model experiments such as centrifuge tests shaking table. Now there have been several computer software made, each of which make use of one of the numerical modeling methods for analysis engineering problems. In this research finite difference software is used. FLAC is an explicit finite difference program for solving engineering problems, it was written in 1986 by Pr. Peter Cun Dall.

The term "FLAC" derives from the phrase "fast lagrangian analysis of continua". This software has been constructed on the basis of lagrangian calculation process which is very appropriate for modeling large displacement. Materials are presented by elements and zones that would form networks which eventually get the problem environment structure. Each element reacts to the incoming force according to the linear or non-linear stress-strain law. Materials can yield and liquefy and the network can deform (in mode of large deformations) and move with relevant environment. The explicit and lagrangian calculation method and the mixed discretization technique which is used in FLAC Causes the modeling of flow and plastic failure. This software is used because of its capabilities.

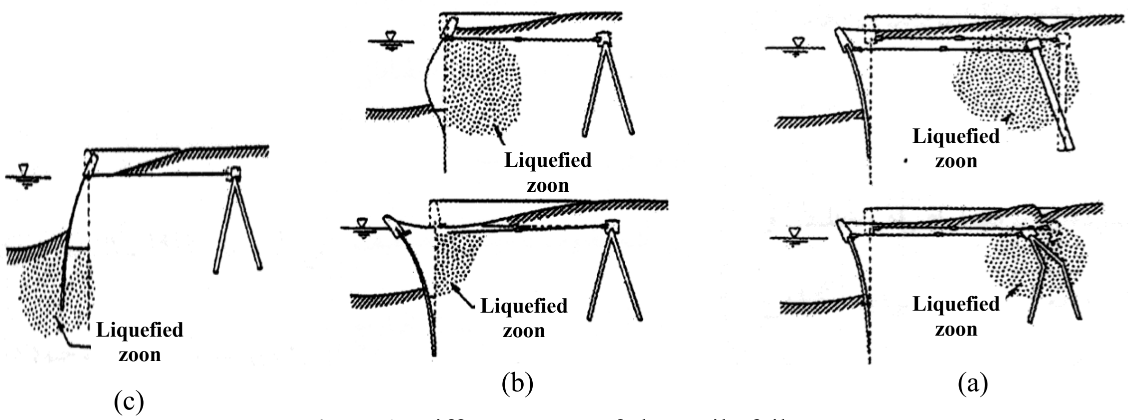

Figure1: Different cases of sheet pile failure

3- MODELING AND ANALYSIS

In this analysis, the dynamic behavior of the coastal restrained sheet piles has been investigated in two dimensional environments by FLAC software using of the non-linear dynamic effective stress and considering the effect of increased pore water pressure during the dynamic loading and liquefaction. By considering the geometrical conditions and loading of the problem, all analyses have been done in the plane strain mode. To model the increase of pore water pressure during dynamic loading the Finn model which is complimented in FLAC version 4.0 has been used. As well as, to model the variation of the shear modules the program of Massing.Fish which has been written in Fish environment is used. It is to be mentioned that all analysis has been done in untrained condition. The characteristics of the soil layers existing in the filed and the modified layers of the soil is presented in Table 1.

Table 1: Material properties used in the model

Materials	γdry (kg/m³)	e	ϕ (degrees)	C (kPa)	V (m/s)	υ
General Fill(+gwt)	1560	0.42	37	0	185	0.3
General Fill(-gwt), loose (unimproved)	1405	0.47	30	0	234-306	0.3
General Fill(-gwt), dense (improved)	1500	0.42	35	0	234-306	0.3
Structural Fill	1660	0.38	40	0	194-334	0.3
Dune Sand	1650	0.39	38	0	435	0.3
Upper Lagoonal Clay (untrained)	1315	0.39	0	70	158	0.49
Upper Lagoonal Clay (drained)	1315	0.39	22	0	158	0.3
Upper Kurkar	1650	0.39	37	0	419-441	0.2
Lower Lagoonal Clay untrained	1462	0.47	0	140	199	0.49
Lower Lagoonal Clay drained	1462	0.47	24	0	199	0.3
Lower Hamra untrained	1790	0.35	0	150	491	0.4
Lower Hamra drained	1790	0.35	30	0	491	0.3
Lower Kurkar	1650	0.39	37	0	454-512	0.2

The drained soil characteristics which are presented in table 1 are used in analysis at static phase, and the untrained soil characteristics are used in analysis at dynamic phase. To approximate the soil sheer module (G), the measured sheer wave speed (V_s) and the total soil density (ρ_{tot}) are used in the following equation:

$$G = \rho_{tot} \times v_s^2 \quad (3.1)$$

Also balk module has been obtained by the following equation:

$$\beta = \frac{2G\ (1+\upsilon)}{3\,(1-2\upsilon)} \quad (3.2)$$

Where, υ is the poison ratio. Earthquake acceleration history presented in figure 2 is applied to the base of the model. The earthquake history has been filtered by EERA program so that the frequency elements greater than 10 HZ containing very low energy and whose modeling causes interference in numerical model, would be ruled out from earthquake acceleration. Soil mortality has been considered mortality of Rail kind with the amount of 5 percent for the frequency of 5 HZ. For structural elements also structural mortality has been chosen according to mass (α=1, β=0) with the amount 10 percent at the frequency of 10 HZ.

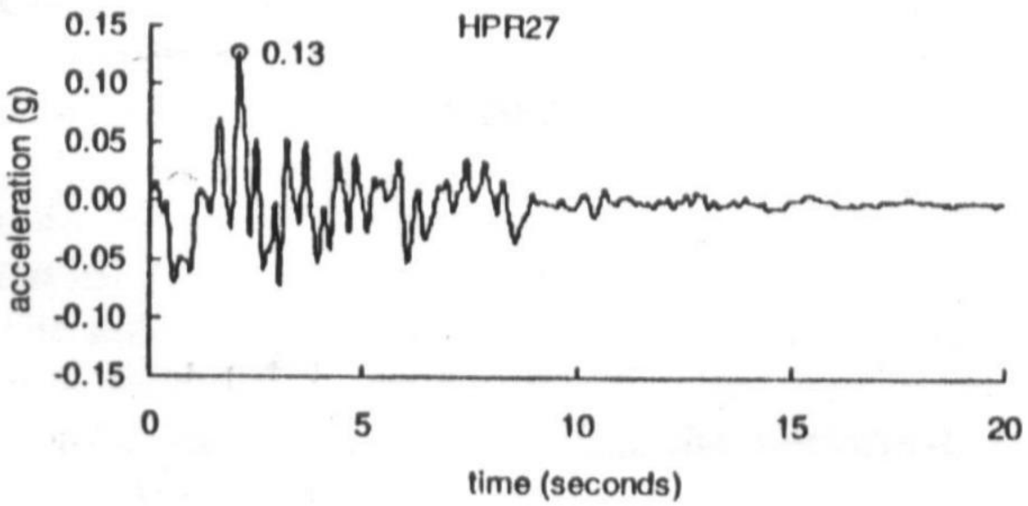

Figure 2: Earthquake acceleration history (McCullough and Dickenson 2001)

Dimensions of the model must be chosen in away so that the diffusion and disappearance of the wave energy would occur appropriately in the area and the produced stress and displacement do not influence the environment and especially coastal wall behavior. Doing some simple analyses the optimum dimensions for the model has been chosen which has 200 m in both side of sheet pile and 100 m in vertical directions. The soil layer underneath which is dense and non-liquefied soil layer has a thickness of 18 m and the upper soil layer with liquefying potential is 26 m thick. An example of the network formed at FLAC for analyzing the sheet pile is shown in figure 3.

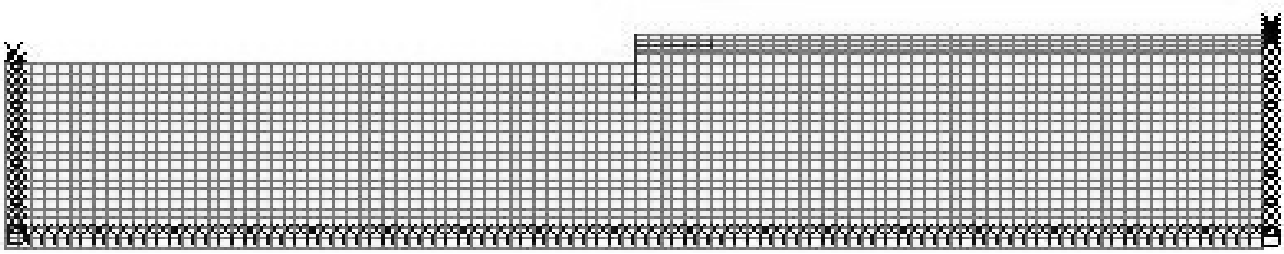

Figure 3: An example of the network created at FLAC for analyzing sheet pile.

A layer of 26 m thick sand soil with the liquefaction potential placed in over the 18 m thick dense and unliquefy layer is defined. To study the effect of soil improvement, the standard penetration number (N) of liquefying layer (layer 1) which was considered N=10 to 20, in improve condition it was increased to N=25 to 40. In the mean time, zone of improved soil is changed in order to find out the best effective zone.
Dynamic load variation (as a sheer stress wave) with time shown in figure 4, as well as pore water pressure variation with time shown in figure 5 set is set to the lower boundary of the model. Setting this load, initially the maximum acceleration of the earthquake at the ground level (a_{max}) is assumed and then the maximum sheer stress as function of depth for the lower boundary is calculated using the Seed and Idriss (1971) equation:

$$\tau_{cyc} = \frac{a_{max}}{g} \sigma_v r_d \quad (3.3)$$

Where σ_v is the total vertical stress, r_d is stress reduction factor which base on depth of maximum cyclic sheer stress is considered 0.5 and g is gravity acceleration 9.8 m/Sec^2.

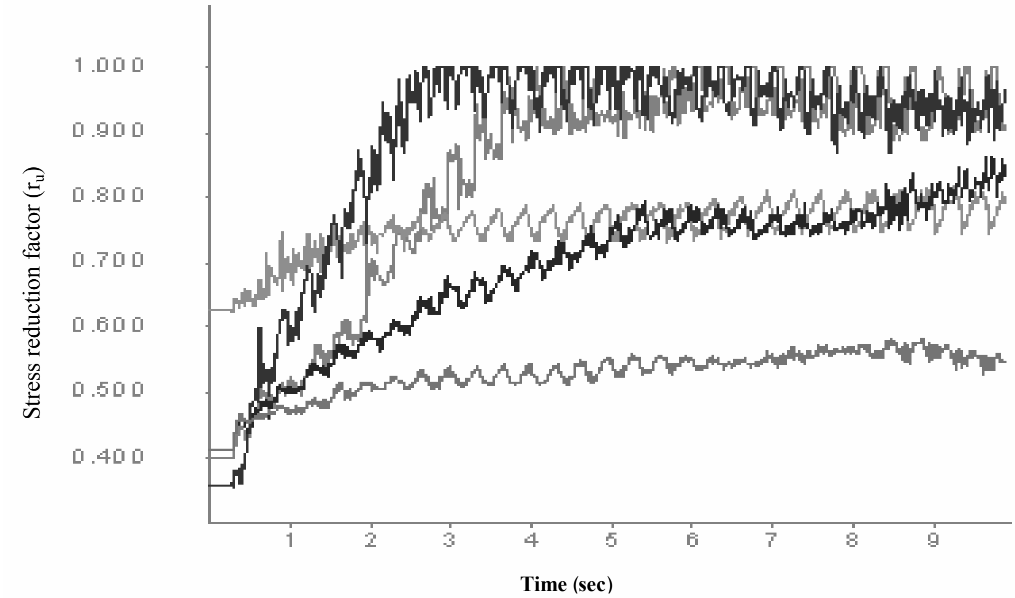

Figure 4: An example of dynamic loading set in model

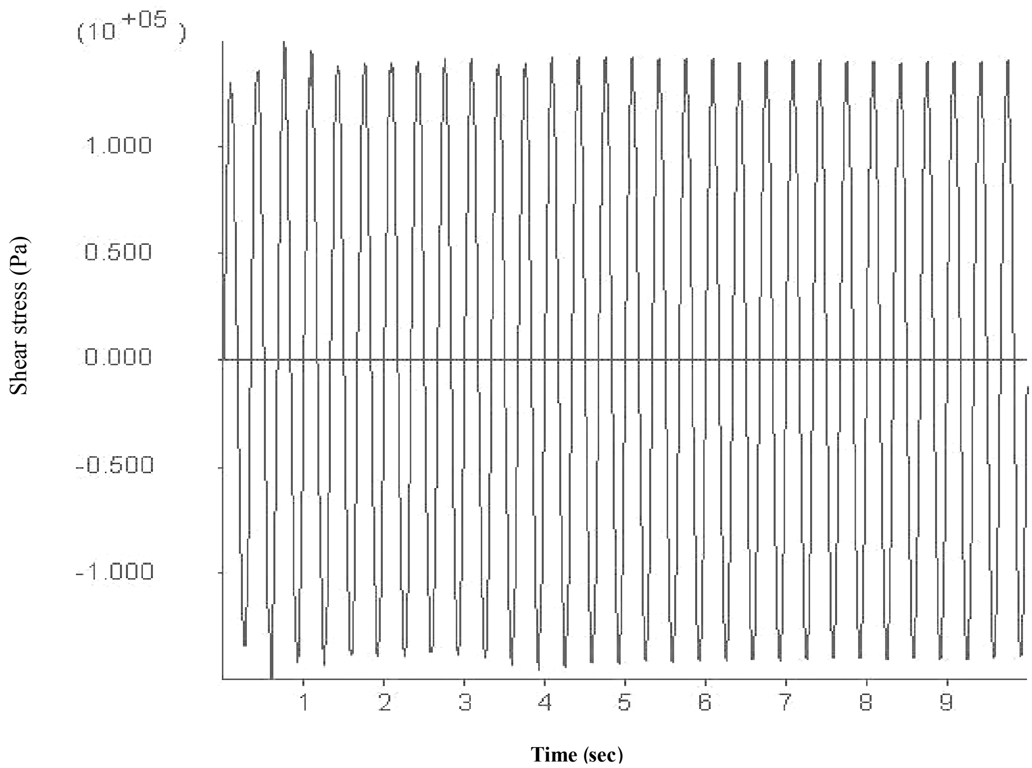

Figure 5: An example of pore water pressure increase r_n during dynamic loading set in model.

4- RESULTS AND DISCUSSION

4.1 The Effect of Maximum Earthquake Acceleration on Sheet Pile Behavior

Displacement of points A, B and C as shown in figure 6 were calculated as a function of maximum earthquake acceleration, a_{max}, and presented in table 2 as well as in figure 6. As one can see from figure 4, by increasing maximum earthquake acceleration, a_{max}, the difference of displacement at Points A, B and C are distinguishable. It also shows that up to seventh second of dynamic loading, the displacement variation with accelerations at al points are almost the same, however after the seventh second, displacement at point A and B increases rapidly which is due to occurrence of liquefaction around the sheet pile.

Table 2: Displacement of points A, B and C (cm) as a function of a_{max} for time loading 8 and 10 second.

T (sec)	Point	a_{max}											
		0.1g		0.12g		0.14g		0.16g		0.18g		0.2g	
		Δx	Δy	Δx	Δy	Δx	Δy	Δx	Δy	Δx	Δy	Δx	Δy
8	A	26	11	31	11	35	13	43	14	56	15	63	14
	B	23	11	27	11	32	13	40	14	47	15	54	14
	C	21	11	24	11	27	13	29	14	33	15	37	14
10	A	30	12	35	12	47	14	71	20	134	21	206	28
	B	26	12	31	12	41	14	68	20	82	19	118	21
	C	24	12	26	11	30	14	36	20	38	17	39	16

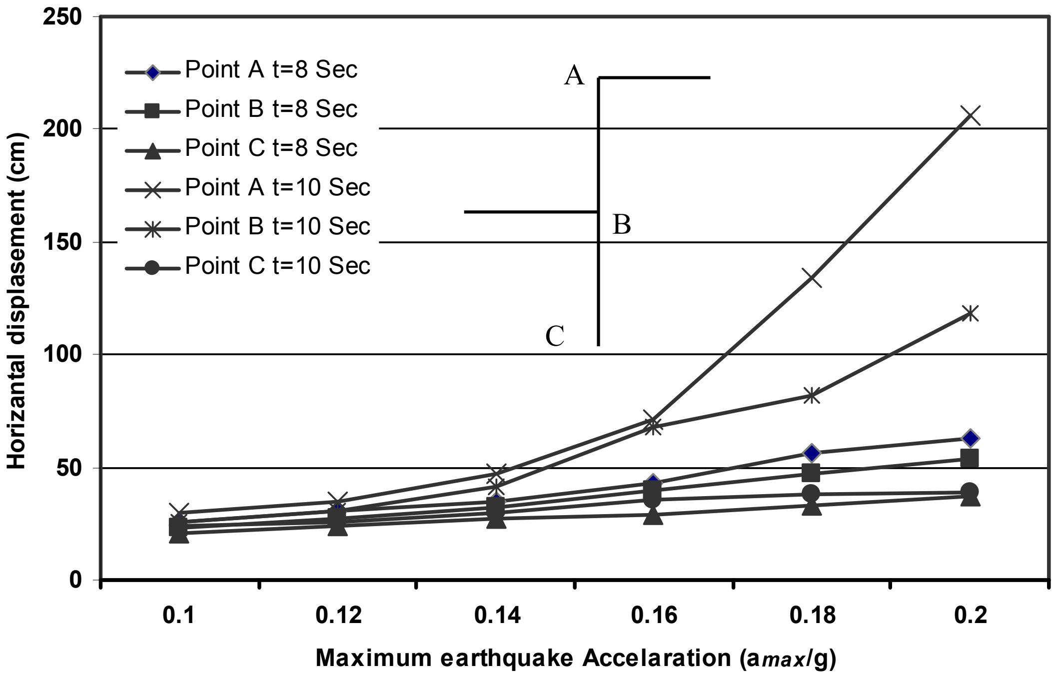

Figure 6: Horizontal displacement variation with maximum earthquake acceleration for points A, B and C.

4.2 TheAnchor bolt Length

The anchor bolt length sheet pile in dense layer is one of the effective parameters on the behavior of the sheet pile. The summary of investigations done in this regard is presented in Table 3 and figure 7. These results show that as the anchor bolt length increases, the displacement of sheet pile decreases, hence, it improves the sheet pile behavior against dynamic loading and liquefaction occurrence.

Table 3: Displacement of points A, B and C (cm) as a function of anchor bolt length for time loading 8 and 10 second.

T (sec)	Point	L (m)									
		8.0		10.0		12.0		14.0		16.0	
		Δx	Δy	Δx	Δy	Δx	Δy	Δx	Δy	Δx	Δy
8	A	268	66	208	55	83	17	50	15	51	15
	B	180	50	152	29	68	16	46	15	47	15
	C	28	14	29	14	37	16	38	15	35	15
10	A	--	--	--	--	258	38	56	18	54	17
	B	--	--	--	--	132	25	52	18	54	17
	C	--	--	--	--	40	18	43	17	40	17

The horizontal displacement of point A of sheet pile for different anchor bolt length presented in figure 8 shows that the amount and trend of displacement increasing at initial stage until about the third second of loading is almost the same for different anchor bolt length. However, soon after the third second the displacement for anchor bolt length with L=8 m increases suddenly which causes forward movement of sheet pile. This incident happens for L=10 m and L=12 m in order of fifth and seventh second after the initiation of dynamic loading and as its apparent the sudden displacement speed increase does not happen for L=14 m. This demonstrates that the resistant force which has been gathered in front of the wall to prevent movement of sheet pile forward. In spit of former situations in which soil resistance vanished due to increase of pore water pressure and soil liquefaction, in this case it is not completely vanished and has caused the restriction of wall displacement.

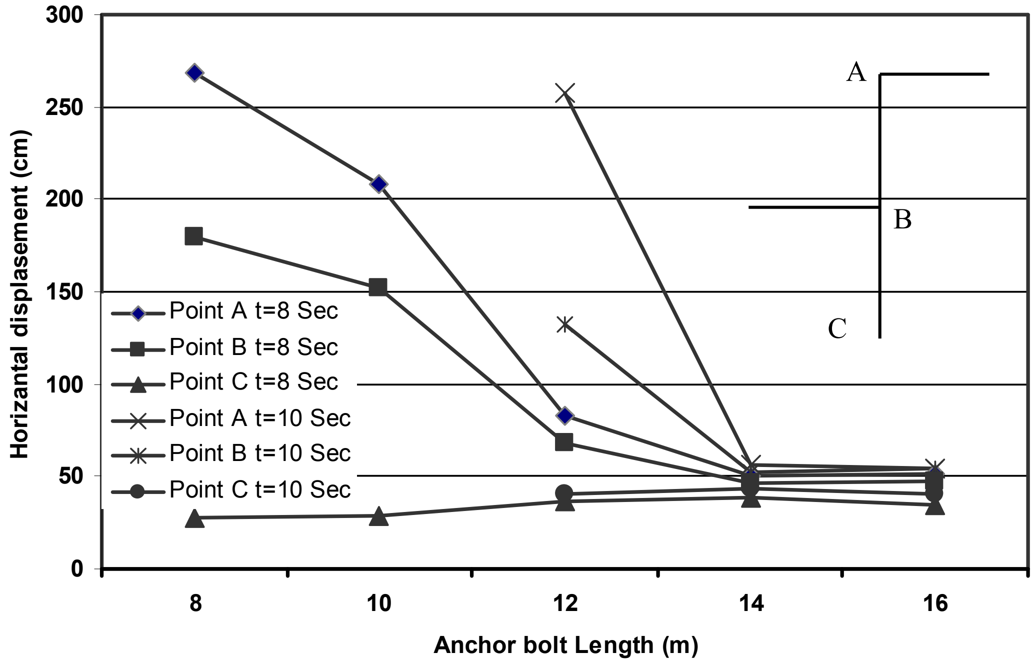

Figure 7: Displacement variation with time as a function of anchor bolt length

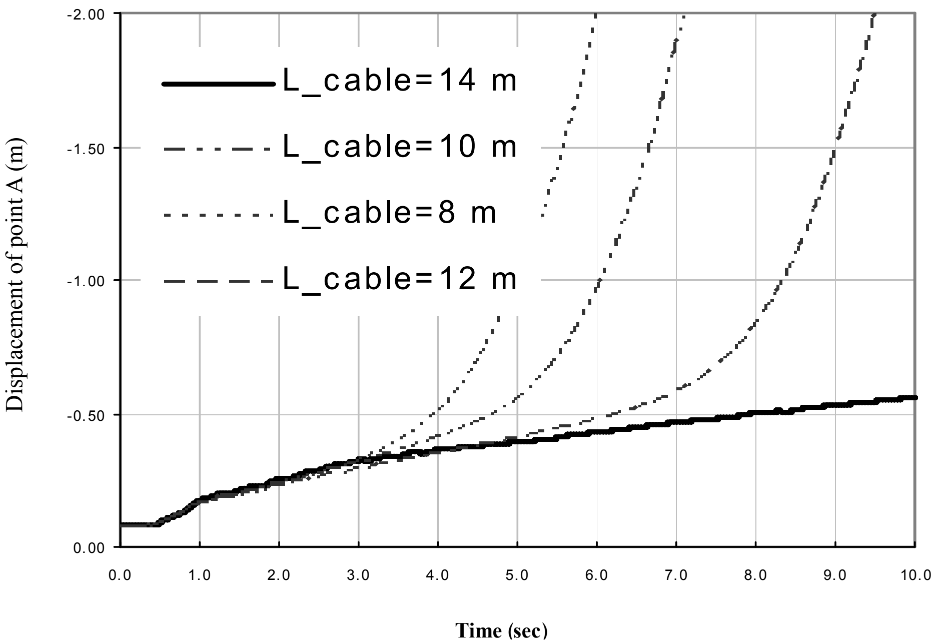

Figure 8- Displacement variation with time as a function of anchor bolt length for point A

4.3 The Effect of Penetrated Length of Sheet Pile in Dense Layer

In this part of study the sickness of the upper liquefied layer is considered to be 10 m and the penetration length of the sheet pile in lower dense non-liquefied layer has been considered to be variable as shown in figure 9. Results of this analysis have been presented in Table 4 and figure 9. Doing these analyses it has been observed that in all cases, the upper layer which is a loose sandy layer would be under the effect of liquefaction during the dynamic loading. However, with increase of sheet pile penetration in the lower dense layer, the fixed length of the sheet pile increases and hence, resulting reduction of sheet pile displacement.

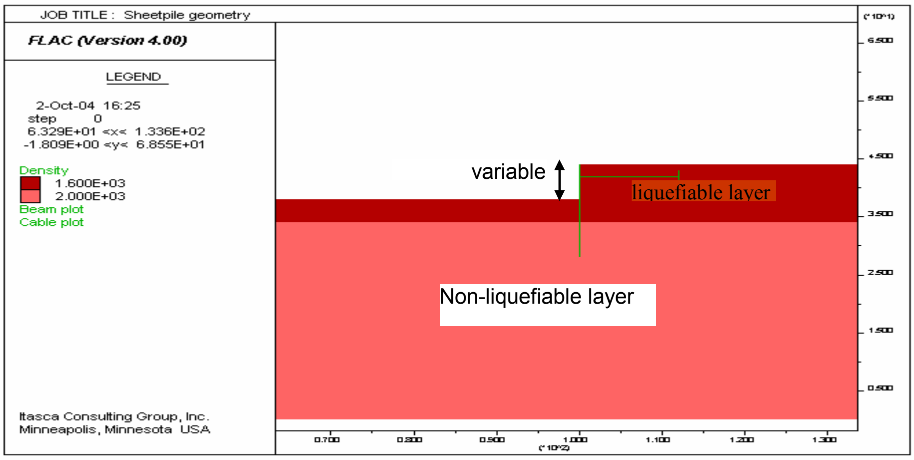

Figure 9: Soil layers and sheet pile geometry

Table 4: Displacement of points A, B and C (cm) as a function of penetrated length for time loading 8 and 10 second.

T (sec)	Point	Penetrated length (m)							
		2.0		4.0		6.0		8.0	
		Δx	Δy	Δx	Δy	Δx	Δy	Δx	Δy
8	A	225	19	104	4	91	5	95	6
	B	110	8	55	2	45	3	47	4
	C	5	2	6	1	8	2	9	3
10	A	286	31	132	6	116	6	114	7
	B	141	12	72	3	58	3	56	4
	C	3	4	5	0	9	2	9	3

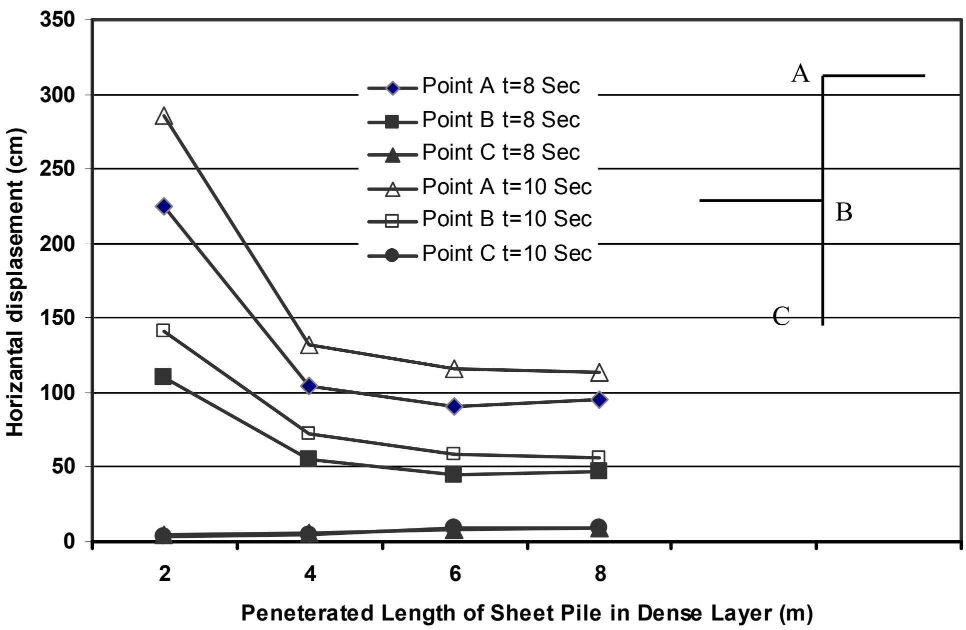

Figure 10: Horizontal displacement variation with the length of sheet pile penetration in dense layer for different point

5- Conclusion
According to the present study, the following points could be concluded:
- one of the effective factors in restricting the sheet pile displacement subjected to dynamic loading with liquefaction occurrence in the top layer is the length of penetrated sheet pile in dense nonlequify layer.
The results out of these analyses show that increase of the length of sheet pile in lower dense layer decreases the displacement of it with the presence of liquefying layer at the top. It observed too that as the fixed length of the sheet pile increases more than a certain critical length in dense layer it will not have much effect on restricting sheet pile displacement.
- One of the determining factors in sheet pile displacement during liquefaction is the anchor bolt length. Presented displacement variation with the anchor bolt length demonstrate that, increase of anchor bolt length from 12 m to 14 m has a great effect on reduction of displacement of the sheet pile. However increase of the anchor bolt length from 14 to 16 m has no more effect on reduction of displacement. Also by comparing sheet pile displacement history for different anchor bolt length it shows that by decreasing the anchor bolt length, initiation time of infinite displacement occurrence due to soil liquefaction is lessened and instability occurs sooner, however in analyses with higher anchor bolt length (L≥14m) it is seen that instability and infinite displacement does not occur.
3- Increase of maximum earthquake acceleration causes increase of sheet pile displacement. Study on displacement history of the sheet pile for different earthquake accelerations reveals that almost to the seventh second, liquefaction does not occur extensively for any of the cases; however after then the sheet pile behavior differ at different earthquake accelerations. Increase of dynamic pressure to the sheet pile and loosing soil resistance in higher accelerations due to extensive liquefaction in soil around the sheet pile and the penetrated length in the time lapse of t=7 Sec to t=l0 Sec causes instability and in finite displacements, however this problem does not occur at lower accelerations
- Dynamic vibration period has a great impact on sheet pile behavior and as seen in most cases the displacement of sheet pile at the tenth second is noticeably larger than that at the eighth second.
- The results also show that soil improvement has a great positive impact on sheet pile behavior. Hence it is suggested to take structural measures along with one of the methods of soil modification to decrease damages.
6- Soil stiffness reduction due to pore water pressure increase and the occurrence of liquefaction during dynamic loading causes an increase in dynamic active soil pressure to sheet pile and reduction of passive pressure of soil as resisting pressure to sheet pile and penetrated length. Hence, for dynamic analysis of sheet pile wall, in areas where there is a potential of liquefaction in soil around the wall, including coastal districts, the effect of soil liquefaction should be considered.

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