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# Numerical analysis of liquefaction-induced lateral spreading phenomenon and investigation of the effect of ground slope and liquefiable soil thickness on lateral displacement

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## ABSTRACT

Lateral spreading of liquefied granular soils induces large displacements and because of that it is one of the destructive phenomena which causes great damages to the buildings, roads, pipelines, and piles. Maximum ground displacement and its variation with depth are the most necessary parameters for seismic design of earthworks and foundations, so this paper focuses upon these parameters. In this paper after validating numerical simulation with experimental observation, the verified model is used for parametric study. For parametric study the ground surface inclination and thickness of the liquefiable soil are selected as variable parameters and their effects on maximum lateral displacements which occurs at the ground surface are investigated. This study shows that ground surface inclination is a very important parameter on lateral displacement, its increase leads to increase in the amount of lateral displacement; however the amount of normalized lateral displacement is independent of the value of ground surface inclination.

## RÉSUMÉ

La propagation latérale des sols granulaires liquéfiés induit de grands déplacements et en raison de celle elle est l'un des phénomènes destructifs qui endommagent grands les bâtiments, les routes, les canalisations, et les piles. Le déplacement au sol maximum et c'est variation par rapport à la profondeur sont les paramètres les plus nécessaires pour la conception sismique des terrassements et des bases, ainsi foyers de ce document sur ces paramètres. En ce document après validation de la simulation numérique avec l'observation expérimentale, le modèle vérifié est employé pour l'étude paramétrique. Pour l'étude paramétrique l'inclination et l'épaisseur extérieures au sol du sol liquéfiable sont choisies en tant que paramètres variables et leurs effets sur des déplacements latéraux maximum qui se produit sur la surface au sol sont étudiés. Cette étude prouve que l'inclination extérieure au sol est un paramètre très important sur le déplacement latéral, son augmentation mène pour augmenter dans la quantité de déplacement latéral ; cependant la quantité de déplacement latéral normal est indépendante de la valeur de l'inclination extérieure au sol.

## 1. INTRODUCTION

The lateral movement of a liquefiable soil layer on gently slopes is the most visible and devastating type of liquefaction-induced ground failure. Occurrence of liquefaction in sloping grounds causes large deformations on ground surface, which may reach to several meters in some cases (Wang & Rahman 1999). Recent earthquakes have shown that this phenomenon causes severe damages to coastal structures, piers of bridges and life-lines, by exerting large lateral forces.

Due to the significance of these failures during liquefaction, a number of research activities have been done in various categories such as physical tests, sliding block analysis, artificial neural networks, and numerical simulation.

In the group of physical research, a wide range of centrifuge and shaking table tests have been employed. One of the most comprehensive and well-known experimental studies tests in this field is the laboratory tests conducted on Nevada sand by the Earth Technology Corporation in the course of Verification of Liquefaction Analysis by Centrifuge Studies (VELACS). Besides, Taboada and Dobry (1995), and Sharp and Dobry (1999)

had investigated the effects of the important parameters on lateral displacement with experiments conducted at Rensselaer Institute of Technology. Also some researches like Cubrinovski et al (2005) and Bethapudi (2008) simulated lateral spreading phenomenon by shaking table tests.

Empirical methods utilize ground inclination and liquefiable ground layer thickness as the fundamental parameters that affect the amount of lateral displacement using regression data analysis. The amount of surface ground movement can be estimated with these formulas easily. Hamada et al (1986-1999), Bardet et al (1999), Youd et al (2003), and Valsamis et al (2010) proposed different relations based on data obtained from field observations.

In addition to this, various numerical methods have been employed to simulate lateral spreading phenomenon. Here, some numerical studies are briefly explained: Uzuoka et al (1998) predicted the lateral spreading of liquefied subsoil based on fluid dynamics; they simplified the behaviour of liquefied soil with Bingham model, which is a model for viscous fluids. In this model shear stress has a linear relation with shear strain. Also, Hadush et al (2000) used similar methods for

simulating lateral spreading. They assumed that liquefied soils behave as a pseudoplastic fluid (Hamada et al 1998). Although by this method liquefaction cannot be simulated exactly, the results of this simulation show that this is a good assumption.

Besides, several researches have used various constitutive models for liquefiable soil. Elgamal et al (2002) numerically simulated VELCAS number 2 and their results for excess pore water pressure and lateral displacements were consistent with experimental observations. Kanibir et al (2006) and Mayoral et al (2009) also simulated the lateral spreading phenomenon. Valsamis et al (2007-2010) simulated VELACS number 2 with FLAC.

In this paper coupled dynamic field equations of extended Biot's theory with u-p formulation are used and soil behavior is modeled by using a critical state two-surface plasticity model (Manzari & Dafalias 1997) for sands. The finite element program, PISA is used for numerical analysis. Furthermore, in the numerical simulations a variable permeability coefficient is used instead of a constant coefficient.

## 2. NUMERICAL FORMULATION

In this research, a fully coupled two-dimensional dynamic analysis, with u-P formulation has been used to simulate the lateral spreading phenomenon and to evaluate the magnitude of deformations occurred in liquefiable soils. In this formulation pore pressures and displacements are computed simultaneously at each time step. Momentum balance for the soil-fluid mixture, momentum balance for the fluid phase, and finally mass balance for the whole system of soil and fluid are satisfied in this method. The primary unknowns are displacement of the solid phase ( $u$ ) and pore fluid pressure ( $P$ ). The  $u$ - $P$  formulation is applicable for dynamic problems in which high-frequency oscillations are not important, such as soil deposit under earthquake loading. Using the finite element method for spatial discretization, the  $u$ - $P$  formulation becomes (Zienkiewicz and Shiomi 1984):

$$M\ddot{U} + \int_V B^T \sigma' dV - QP - f^{(s)} = 0 \quad [1]$$

$$Q^T \dot{U} + H\dot{P} + S\dot{P} - f^{(p)} = 0 \quad [2]$$

Where  $M$  is the mass matrix,  $U$  is the solid displacement vector,  $B$  is the strain-displacement matrix,  $\sigma'$  is the effective stress tensor,  $Q$  indicates the discrete gradient operator coupling the motion and flow equations,  $P$  is the pore pressure vector,  $S$  is the compressibility matrix, and  $H$  is the permeability matrix. The vectors  $f^{(s)}$  and  $f^{(p)}$  include the effects of body forces, external loads, and fluid fluxes.

Numerical integration of the above-mentioned equations and their solution are carried out in a Finite element program PISA. The first version of this program

was developed at the University of Alberta, known as SAGE. Later, a commercial version of this program was released with the name of PISA. Pak (1997), shahir (2001), and Taiebat (2003) further increased the capabilities of this program by completing the formulation to simulate THM (Thermal Hydro-Mechanical) and dynamic problems. In this research, the possibility of variation in the coefficient of permeability for saturated sands has also been implemented to the program.

### 2.1 Constitutive modeling

The critical state bounding surface elastic-plastic sand model, proposed by Manzari and Dafalias (1997), which possesses the simulative ability of the behavior of drained or undrained saturated sands under monotonic and cyclic loadings, is used. This model has 17 parameters divided into 5 categories based on their functions. The calibrated parameters of this model for Nevada sand are shown in Table 1. (Manzari & Dafalias 1997, Taiebat et al 2007)

### 2.2 Numerical modeling procedures

Results from centrifuge model test No. 2 from VELACS project, conducted by Taboada and Dobry (1995) at Rensselaer Polytechnic Institute (RPI), are used to demonstrate the capability of the numerical program for reliable analysis of dynamic response of a saturated soil layer.

#### 2.2.1 Centrifuge test

The model consists of a 20 cm high, uniform Nevada sand layer with approximately 45% relative density. It is fully saturated with water, inclined 2° to the horizontal. The laminar box is spun at a centrifugal acceleration of 50g, so the dimension of test box and soil permeability in prototype is 50 times greater than the dimension and permeability of soil specimen. A sketch of the laminar box and the instruments for the foregoing model test in prototype are shown in Figure 1. The sand box is simultaneously excited laterally at the base with the target prototype accelerogram shown in Figure 2.

Table 1. Material parameters used for Constitutive Model (Manzari and Dafalias 1997)

Parameter Function	Parameter Index	Value
Elasticity	$G_0(kPa)$	31400
	$k_0(kPa)$	31400

	$a$	0.6
Critical State	$M_c$	1.14
	$M_e$	1.14
	$\lambda$	0.025
	$\epsilon_{c,ref}$	0.8
Dilatancy	$A_0$	0.6
	$C_f$	100
	$F_{max}$	100
Hardening	$h_0$	800
	$m$	0.05
	$C_m$	0
State Parameters	$k_c^b$	3.975
	$k_e^b$	2
	$k_c^d$	4.2
	$k_e^d$	0.07

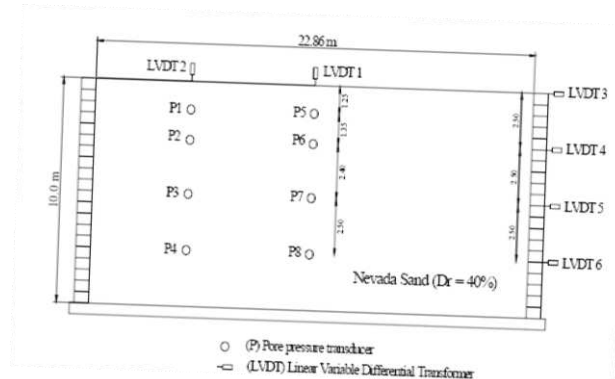


Figure 1. Schematic view of VELACS centrifuge model test No. 2 (Prototype scale).

## 2.2.2 Numerical simulation

In this research, soil layer is modeled by rectangular 8-noded elements with  $u$ - $P$  formulation in which each node has three degrees of freedom: two for soil skeleton displacements and one for pore water pressure. In this study, variation of permeability coefficient has been considered in numerical modeling of liquefiable layer. For this the formulation for the variation of permeability which is first suggested by Shahir (2009) and modified by Ghasemi Fare (2010) is employed. Properties of Nevada Sand used in the numerical model are presented in Table 2. Figure 3 shows the finite element mesh, 64 rectangular elements, which is used for numerical simulation. Boundary conditions due to experimental circumstances are set in the following way:

- Base of the mesh is fully fixed in all directions.

- Nodes at equal depths in two side of the box are constrained to have equal displacements in  $x$  and  $y$  direction to simulate the laminar box.
- Pore water pressures are free to develop for all nodes except the ones at the ground surface.

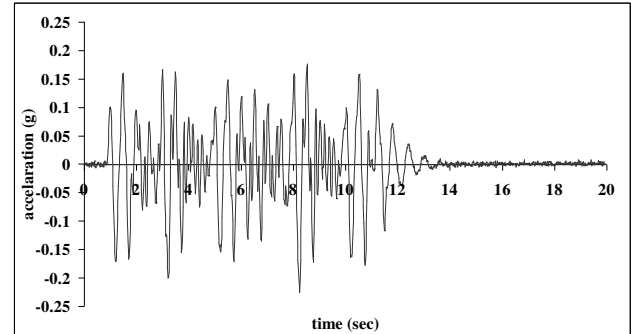


Figure 2. Lateral input acceleration at the base of the laminar box (Prototype scale).

Table 2. Material parameters for Nevada sand (Taiebat et al. 2007)

Parameter	Unit	Value
Porosity ( $n$ )		0.42
Saturated Unit weight	KN/m <sup>3</sup>	20.05
Permeability Coef.	m/s	$6.6 \times 10^{-5}$
Permeability Coef. in Prototype scale ( $k_{st}$ )	m/s	$3.3 \times 10^{-3}$

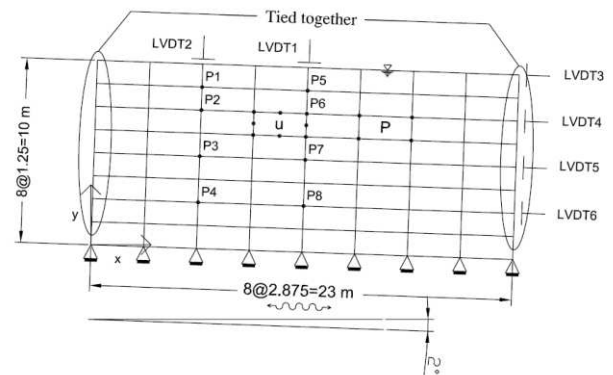


Figure 3. Finite element discretization and boundary conditions.

Simulations are carried out in two loading stages. In the first stage of loading, self-weight, including both the soil skeleton and the pore water weight, are applied on soil elements. In this stage the initial stress state, void ratio and soil fabric evolve. These values are used as initial values for the next stage of loading. Then, at the second stage, an acceleration time history (shown in Figure 2) is applied to the model base as an input motion, and dynamic analysis is performed.

### 3. VALIDATION OF NUMERICAL MODEL

#### 3.1 Pore pressure

Figure 4 shows that excess pore water pressure which is predicted by numerical model is compatible with experimental records. The maximum value of excess pore water pressure, initial rate of generation and its dissipation have been simulated very well at different locations of pore pressure transducers in the soil depth.

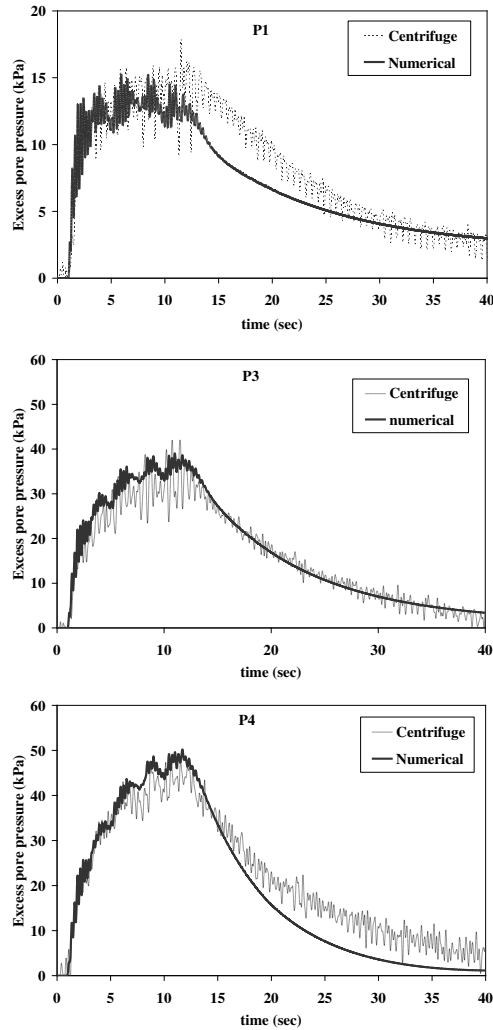


Figure 4. Numerical and Experimental Excess pore pressure time histories

#### 3.2 Displacement

In this section vertical and lateral displacements, which are obtained by numerical simulation, are compared by experimental observations.

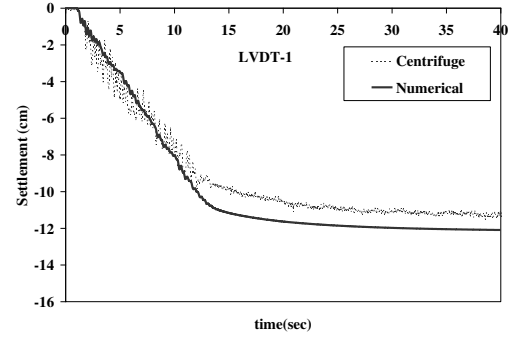


Figure 5. Measured and computed vertical displacement time histories at the ground surface (LVDT 1)

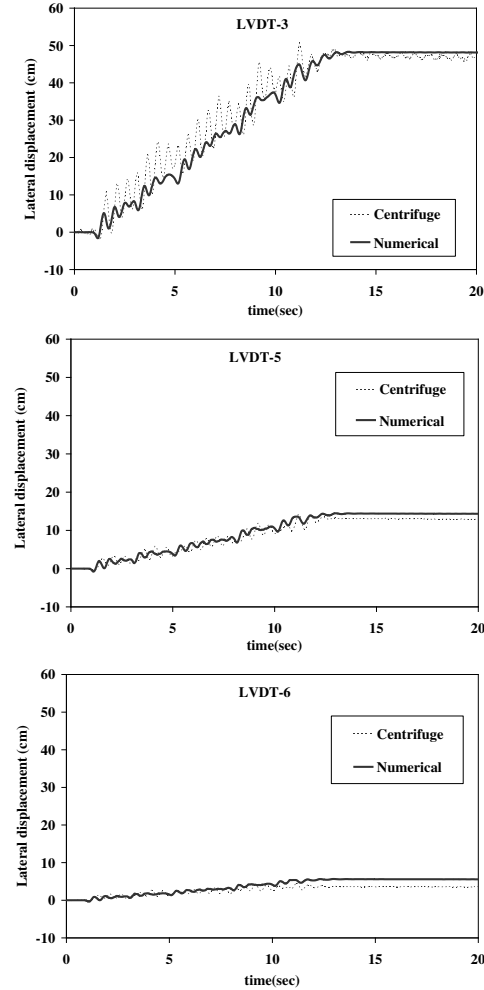


Figure 6. Measured and computed lateral displacement time histories at different locations of LVDT

As it is stated on figures 5 and 6, Numerical predictions of vertical and lateral displacements are consistent with experimental observations. Due to consider the variation of permeability during liquefaction the amount of displacements especially the amount of vertical displacement, as shown in Figure 5, is simulated very well.

Comparisons of the numerical results with experimental observations (figure 4-6) demonstrate that developed numerical program is reliable to simulate lateral spreading.

#### 4. PARAMETRIC STUDY

After validating stage, effect of inclination and thickness of the liquefiable soil layer are investigated in order to provide better understanding of lateral spreading phenomenon.

All parameters in this stage except ground surface inclination and thickness of liquefiable soil are similar to those which have been used for the validation stage. However, the excitation of model in this stage is different. A horizontal sinusoidal excitation with the maximum amplitude of 0.15g and frequency of 2 has been used for all of simulations. Also the duration of the excitation is considered to be 10 second.

##### 4.1 Investigation of the effect of ground surface inclination

The amount of ground surface inclination is changed from 0.5 to 5 degree. The different cases of numerical analysis and their results are shown in table 3.

Figure 7 shows that the maximum lateral displacement occurred on the ground surface, increased with increasing of the ground surface inclination and this increasing ratio will be approximately equal to the increase of ground surface inclination ratio. For example with increasing ground surface inclination from 1 to 2 degree, the maximum lateral displacement increased from 24.12 to 47.94 centimeter. It is to be noted that just some of the numerical results are shown in figure 7, but all of them are shown in table 3.

As figure 7 shows, in all cases lateral displacement increase during excitation and after excitation (time > 10 sec) the value of lateral displacement do not changed. It is important to note that this result is compatible with experimental observations.

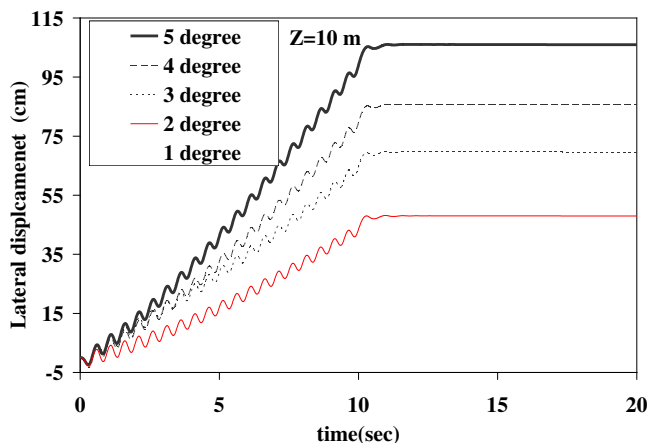


Figure 7. Maximum lateral displacement time histories

Figure 8 shows the normalized lateral displacement. In this figure, the amount of lateral displacements is divided by maximum lateral displacement in each simulation and the depth of soil layer is divided by soil layer thickness. This figure shows that the amount of normalized lateral displacement is independent of the value of ground surface inclination. So just with having the maximum of the lateral displacement, lateral displacement of all depth for any inclination can be predicted.

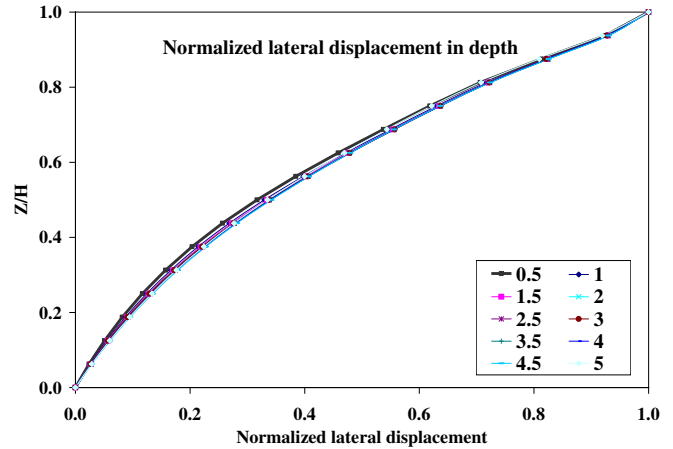


Figure 8. Normalized lateral displacement in depth

Variation of excess pore water pressure at different depth for models number 4 and 13 are shown in Figure 9. The  $r_u$  (excess pore water pressure ratio) is defined as the ratio of the difference of current pore pressure and hydrostatic pore pressure over the initial effective vertical stress  $r_u = \Delta u / \sigma'_{v0}$ . As figure 9 demonstrates, the value of  $r_u$  for elevations near the ground surface are approximately 1 and with passing down to depth the value of  $r_u$  will be reduced. It shows that liquefaction is occurred near ground surface. It is to be noted that this is consistent with the results of Sharp & Dobry (2002).

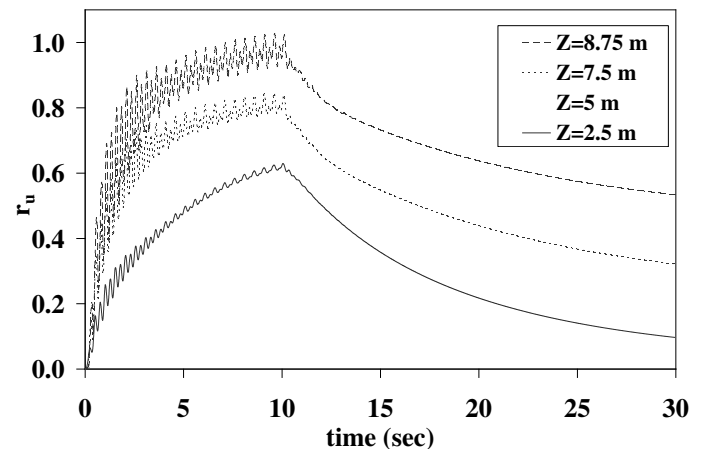


Figure 9. Excess pore water pressure at various depths for models number 4 and 13

#### 4.2 Investigation of the effect of the thickness of the liquefiable soil

After investigating the effect of ground surface inclination, the other important geometric parameter, thickness of liquefiable soil, is studied. In this paper the value of this parameter is changed from 5 to 15 meters to investigate its effect on the amount of the surface ground lateral displacement.

Maximum lateral displacements for different soil layers which occurred at the ground surface are shown in figure 10.

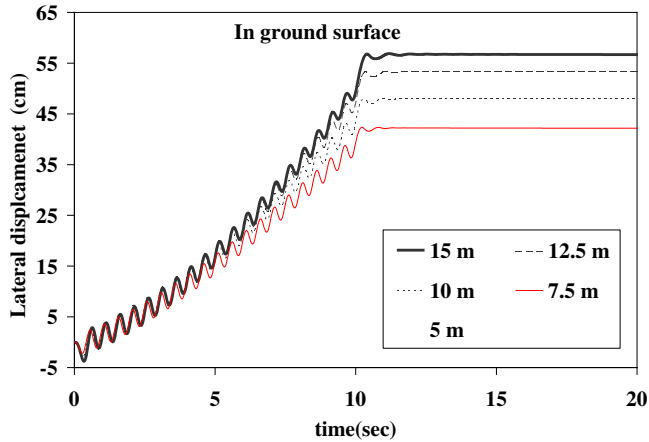


Figure 10. Maximum lateral displacement time histories

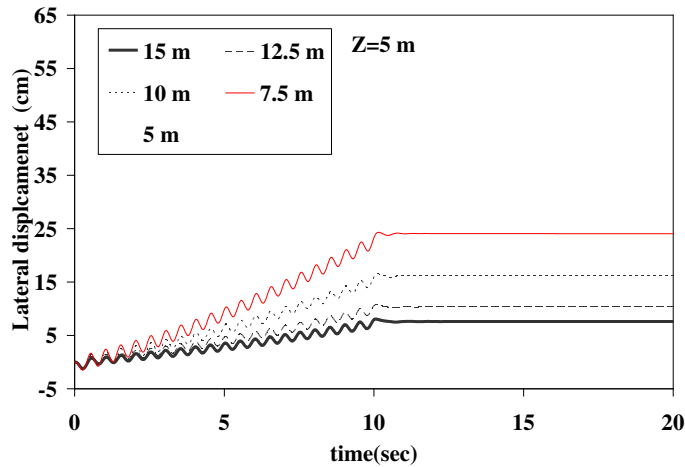


Figure 11. Lateral displacement time histories at specified depth

Figure 10 demonstrates that increasing the thickness of the liquefiable soil causes the value of the maximum lateral displacements to increase. But as the figures show, the effect of the ground surface inclination on maximum lateral displacement is more than the effect of the liquefiable soil thickness. Although maximum lateral displacement elevates with increasing thickness of the liquefiable soil layer but its value for a specified elevation demonstrates a different manner. As figure 11 shows,

lateral displacement which is occurred at 5 meter above the bottom of sand box ( $Z=5$ ) is maximum for the model that has the lowest thickness. Because the value of  $r_u$  (as shown in figure 9) decreased by soil depth increase.

Figure 12 demonstrates that thickness of the liquefiable soil layer affects the value of the normalized lateral displacement; this is in contrast with the effect of ground inclination where a unique curvature was obtained.

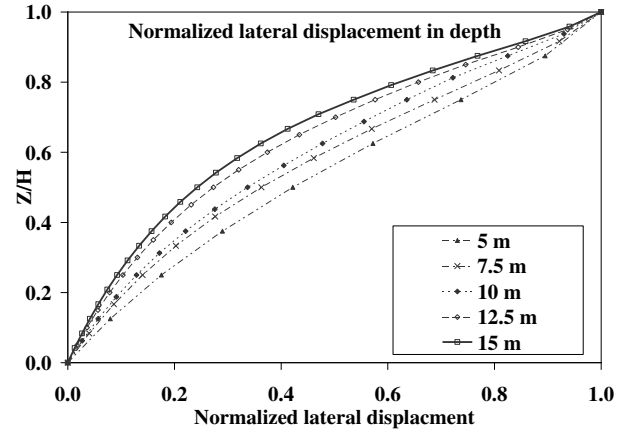


Figure 12. Normalized lateral displacement in depth

Table 3. Different cases of numerical analysis and Results

Number	$\theta^\circ$	H	LD (cm)
1	0.5	10	12.77
2	1	10	24.12
3	1.5	10	35.28
4	2	10	47.94
5	2.5	10	56.61
6	3	10	69.59
7	3.5	10	76.15
8	4	10	85.64
9	4.5	10	94.69
10	5	10	105.9
11	2	5	27.82
12	2	7.5	42.15
13	2	10	47.94
14	2	12.5	53.22
15	2	15	56.76

#### 5. CONCLUSIONS

In this paper the effects of two important parameters on the amount of lateral spreading are investigated by employing a fully coupled dynamic finite element program, PISA, which applies a bounding surface critical state elastic-plastic model. The following results are reached:

- 1) Ground surface inclination plays a key role on the amount of lateral displacement which occurs during lateral spreading, and the value of lateral displacement will be increased approximately with same ratio as increasing in ground surface inclination.
- 2) Normalized lateral displacement is independent of the amount of ground surface inclination.
- 3) Although the value of pore pressure at lower depth are more than the upper ones, the value of  $r_u$  will be reduced in depth.
- 4) At a specified depth, soil layers with smaller thickness show greater lateral displacements.

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