EFFECTS OF GROUND WATER ON SEISMIC RESPONSES OF BASIN

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SUMMARY

It has long been recognized that the local soil and geology conditions may affect significantly the nature of earthquake motions, resulting in the large amplification and spatial variation of seismic motions. In this study the effects of ground water on the seismic response of a basin are investigated using a nonlinear coupled effective stress two-dimensional finite element model. For larger earthquakes, the presence of ground water tends to decrease the horizontal acceleration response on the surface of basin, while the opposite trend is observed for horizontal displacement response. For earthquake of smaller intensity the seismic response of a basin is almost not affected by the presence of ground water. Thus the presence of ground water will have larger effects on the seismic response of a basin for larger earthquakes than for small earthquakes.

INTRODUCTION

It has long been recognized that the local soil and geology conditions, such as the depth of soil layers above bedrock, variation of soil properties and types with depth, lateral irregularity and surface topography, may affect significantly the nature of earthquake motions, resulting in the large amplification and spatial variation of seismic motions. In fact the dramatic damages incurred in recent earthquakes such as the 1994 Northridge earthquake in California and the 1995 Great Hanshin earthquake in Japan further provide new evidence of their importance. Therefore, it is imperative that the site effects on the seismic motions be accounted for in seismic regulations, land use planning and design of critical structures.

Both instrumental approach and theoretical and numerical approach are currently available for investigating the site effects [Bard 1995]. The instrumental approach studies the site effects through the *in situ* observation and/or measurements. Based on the available geotechnical information, different models accounting for wave type, geometry of ground and mechanical behavior of soil have been proposed for the analytical and numerical approach to analyze some aspects of site effects. The analytical and numerical approach can be classified into four groups: analytical methods, ray methods, boundary based techniques and domain based techniques. These methods have been applied to the study on effect of subsurface and surface topography on the seismic motions [Sanchez-Sesma 1987].

The previous studies using two-and three-dimensional finite element or finite difference models have found pinpointed the importance of effect of alluvial valley and sediment basin on the seismic motions [Ohtsuki and Harumi, 1983, Rassem, Ghobarah and Heidebrecht, 1997, Vidale and Helmberger, 1988]. In these studies it is found that the generated local surface waves and their subsequent trapping in the soft soil layers leads to the increased amplifications with respect to the classical one-dimensional analysis often adopted in practical engineering applications.

However, for most of the studies the two-phase nature of soil is not modeled. It has been reported that the increase in pore water pressure in the soil during the earthquake may lead to the reduction in the horizontal acceleration and increase in the lateral displacement. As a result, to be more realistically investigate the effect of basin on the seismic motion, the effective stress based model should be adopted. In this study the effects of

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ground water on the seismic response of a basin are investigated using a nonlinear coupled effective stress two-dimensional finite element method.

METHOD OF ANALYSIS

In this paper a nonlinear coupled effective stress two-dimensional finite element method based on Biot's equations is adopted to examine the seismic motions on the surface of a basin. In this method, the solutions for soil displacement and the pore pressure can be obtained directly from the solution of equations. The constitutive relation for the soil is the cap model [Sandler, Dimaggio and Baladi 1976, Chen and Baladi 1985]. The pore pressure model adopted is the one proposed by Pacheco et al. [Pacheco, Altschaeffl and Chameau, 1989], which is developed based on the cap model. In addition, the viscous boundary accounting for the two-phase nature of soil is used to model the lateral infinite extent of the soil stratum [Akiyoshi, Fuchida and Fang, 1994].

Pore pressure model

As stated previously, the effective stress method based on Biot's equations can provide the solutions for soil displacement and the pore pressure directly from the solution of equations. However, it should be pointed out that in Biot's theory the pore pressure is due to the volume change of soil skeleton only; as a result, the change in pore pressure due to the shear deformation of soil , which is a typical phenomenon for saturated soil during earthquakes, can not be simulated.

To overcome such a problem, many pore water pressure models has been proposed. Since in this study, the cap model is used to model the non-linear behavior of soil, in order to be consistent, the pore pressure model proposed by Pacheco et al. is adopted for pore pressure prediction, which includes simultaneous effects of normal and shear stresses. For the original cap model, when the stress state lies inside the elliptical cap and the failure envelope, the behavior is considered elastic and no plastic deformation will occur. Nevertheless, the experiments indicated that during the unloading-reloading process the soil will still undergo plastic deformation. In order to realistically describe this behavior, a sub-yielding surface is introduced such that during unloading the yielding surface (stationary cap) remains constant, while the sub-yielding surface is compelled to retreat by the current state of effective stress; however, if at any point in the sub-yielding surface the increment of effective stress satisfies the loading condition, then the plastic deformation will occur. With this modification, the increment of total pore pressure is then computed as the sum of increment of pore pressure due to mean normal stress and that due to shear stress. However, in computing the increment of pore water pressure due to shear stress, a calibrating function and a calibrating constant, denoted respectively as f_1 and C_2, have to be assumed.

U-W form of Biot's equations

The Biot's equations consist of three sets of equation: overall equilibrium equation, equilibrium for fluid (generalized Darcy's law) and continuity equations. In general finding the close-form solution of these three sets of equation is not an easy work and the finite element method is frequently used. Zienkiewicz and Shiomi [Zienkiewicz and Shiomi, 1984] have presented several forms for the solution, and the most frequently used forms are the U-P form and U-W form, where U is the displacement of the soil skeleton, P is the pore pressure and W is the fluid displacement. In this paper the U-W form of Biot's equation is adopted to formulate the effective stress method. By following the finite element formulation procedure and using the four-node quadrilateral finite elements for the soil displacement, U, and the fluid displacement, W, the following equations of motion can be obtained for the case when seismic input is given at the bedrock.

$$\begin{bmatrix} M_{uu} & M_{uw} \\ M_{wu} & M_{ww} \end{bmatrix} \begin{Bmatrix} \ddot{U} \\ \ddot{W} \end{Bmatrix} + \begin{bmatrix} C_{uu} & 0 \\ 0 & C_{ww} \end{bmatrix} \begin{Bmatrix} \dot{U} \\ \dot{W} \end{Bmatrix} + \begin{bmatrix} K_{uu} & K_{uw} \\ K_{wu} & K_{ww} \end{bmatrix} \begin{Bmatrix} U \\ W \end{Bmatrix} = -\begin{bmatrix} M_{uu} & 0 \\ 0 & 0 \end{bmatrix} \{J\} \ddot{Y} \tag{1}$$

The detailed procedure for deriving the above equations and the definition of each submatrix on the left side can be found elsewhere[Zienkiewicz and Shiomi, 1984]. On the right side of Eq.(1) the {J}is a vector of 0 and 1, depending on the direction of input motion and $\ddot{Y}$ is the acceleration of earthquake input at bedrock. The Eq.(1) is then solved using the Newmark method.

It should be pointed out that in this study the pore pressure is computed using the model described in section 2.1. Therefore, the fluid displacement W determined from the equation (1) has to be modified. Assuming that the equation has been solved for time $t=t_{k+1}$, and the pore pressure P_{k+1} is determined using pore pressure model, the modification of W is computed as follows by writing the generalized Darcy's law at $t=t_{k+1}$.

$$\nabla P_{k+1} + \rho_f \{g\} + [K]^{-1}\{\ddot{w}\}_{K+!} + \rho_f \{\ddot{u}\}_{k+1} + (\rho_f / n)\{\ddot{w}\}_{k+1} = \{0\} \tag{2}$$

where = is gradient vector, {g} is the gravitational acceleration vector, [K] is the permeability matrix, n is the porosity and ρ_f is the mass density of fluid. Since the pore pressure is computed at the center of each finite element, the pore pressure at each node is thus obtained by interpolating the pore pressure at the elements surrounding the node with linear interpolation function. The equation (2) is also solved using the Newmark method. Thus obtained fluid displacement is then substituted into Eq. (1) and the process is repeated until convergence is achieved.

RESULT AND DISCUSSIONS

Based on the theory described in previous section, a computer program "undyn1" is developed. To verify the validity of the program, a one-dimensional model consisting of ten soil layers analyzed in a previous study under the 1940 El Centro earthquake records in NS direction normalized to 0.1g was adopted for comparison [Pastor and Zienkiewicz, 1985]. The results for the displacement response on the surface and the distribution of excessive pore water pressure along the depth of soil stratum are shown in Figures 1 and 2. It can be seen that although the constitutive models for the two studies are not the same, the trend predicted by both studies are very similar.

To investigate the effects of ground water on the seismic response of a basin, in this study, a basin of trapezoidal shape with 6 soil layers surrounded by rock is employed and assumed to be symmetric. Three different angles of basin edge, 27^o, $45^o$and 63^o are considered, while keeping the width of the surface of basin constant with a value of 450m. When the ground water is considered, it is located at 3m below the surface. Shown in Fig.3 is an example of basin model. In the analysis, the peak acceleration of the 1940 El Centro earthquake records in NS direction is normalized to 0.05g and 0.20g, respectively, which are then adopted as the input motions to represent earthquakes of different intensities. Table 1 shows the values of parameters used in this study. The results computed with and without presence of ground water are then compared for the peak horizontal acceleration ratio (PHAR) defined as the ratio of peak acceleration on the surface to that of input motion and peak horizontal displacement (PHD). It should be noted that the vertical acceleration and displacement on the surface also present but with less magnitude due to the generation of local surface waves. Their values on the surface are largest for the region where rock slope and soil intersects and decrease toward the center of basin [Ho 1998].

Figures 4 and 5 are the PHAR along the surface of basin for peak input motions of 0.05g and 0.2g, respectively. For earthquake of small intensity the PHAR will almost not be affected by the presence of ground water, but the PHAR will be reduced when ground water is considered and the earthquake motion is strong. In addition, the PHAR on the surface atop the rock slope increase with increasing angle of slope and increases with decrease in angle of slope on the surface between the center of basin and the bottom of rock slope. For all the cases the maximum PHAR occurs near the surface atop the bottom of rock slope. Also larger values of PHAR are obtained for small earthquakes.

The PHD for different intensities of earthquakes is shown in figures 6 and 7. When the earthquake is strong, the presence of ground water will affect the seismic motion on the surface more and give larger displacement. The PHD on the surface atop the rock slope increase with increasing angle of slope and increases with decrease in angle of slope on the surface between the center of basin and the bottom of rock slope but with insignificant differences. Unlike the acceleration, the maximum PHD occurs at the region near the basin center.

CONCLUSION

In this study the effects of ground water on the seismic response of a basin are investigated using a nonlinear coupled effective stress two-dimensional finite element model. For the PHAR the values on top and near the basin edge are larger than those near the central region of the basin, while the trend is opposite for PHDR. For larger earthquakes, the presence of ground water tends to decrease the horizontal acceleration response on the surface of basin, while the opposite trend is observed for horizontal displacement response. For earthquake of smaller intensity the seismic response of a basin is almost not affected by the presence of ground water. Thus the presence of ground water will have larger effects on the seismic response of a basin for larger earthquakes than for small earthquakes.

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Table 1: Values of parameters used in the analysis

Parameters	Depth (m)						
	0-3 (no water)	3-9	9-12	12-15	15-18	81-21	21-24 (rock)
S wave velocity(m/sec)	133	167	201	234	329	360	1000
Poisson ratio	0.4	0.4	0.4	0.4	0.4	0.4	0.2
Soil density(t/ m^3)	1.7	2.0	1.9	2.0	2.0	2.5	3.0
Bulk modulus of soil particle (kN/m^3)	$2.5x10^7$	$2.5x10^7$	$2.5x10^7$	$2.5x10^7$	$2.5x10^7$	$2.5x10^7$	$2.5x10^{15}$
Coefficient of earth pressure at rest	0.65	0.68	0.71	0.74	0.77	0.80	1.0
Water density(t/ m^3)	1.0e-15	1	1	1	1	1	1
Coefficient of Permeability (m/sec)	Evaluated in program	$1.0x10^{-8}$	$1.0x10^{-8}$	$1.0x10^{-8}$	$1.0x10^{-8}$	$1.0x10^{-8}$	$1.0x10^{-15}$
Porosity	0.45	0.45	0.45	0.45	0.45	0.45	0.2
Bulk modulus of water (kN/m^3)	$2.0x10^6$	$2.0x10^6$	$2.0x10^6$	$2.0x10^6$	$2.0x10^6$	$2.0x10^6$	$2.0x10^6$
Degree of saturation	0.5	1	1	1	1	1	1
Parameter of water retention curve (u)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Parameter of water retention curve (v)	2	2	2	2	2	2	2
Parameter of water retention curve (Ω)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Parameter of water retention curve (θ_s)	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Parameter of water retention curve (θ_r)	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Damping ratio	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Parameter of pore pressure model (D_1)	5	5	5	5	5	5	5
Parameter of pore pressure model (D_2)	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Parameter of pore pressure model (D_3)	1.43	1.43	1.43	1.43	1.43	1.43	1.43
Cohesion (kN/m^2)	1	2	3	4	5	6	1.0e5
Angle of friction(degree)	22.5	25	27.5	30	32.5	35	45
Cap model parameter R	5	5	5	5	5	5	5
Cap model parameter W	0.18	0.18	0.18	0.18	0.18	0.18	0.0018
Cap model parameter D (1/kN)	$5x10^{-6}$	$5x10^{-6}$	$5x10^{-6}$	$5x10^{-6}$	$5x10^{-6}$	$5x10^{-6}$	$5x10^{-8}$

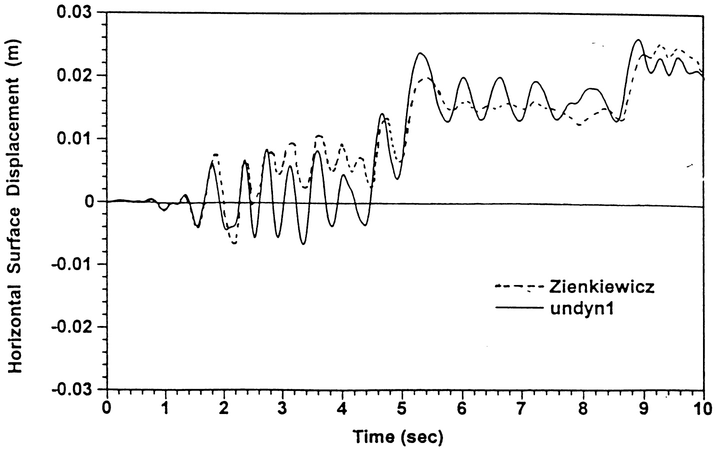

Figure 1: Comparison for displacement response on the surface

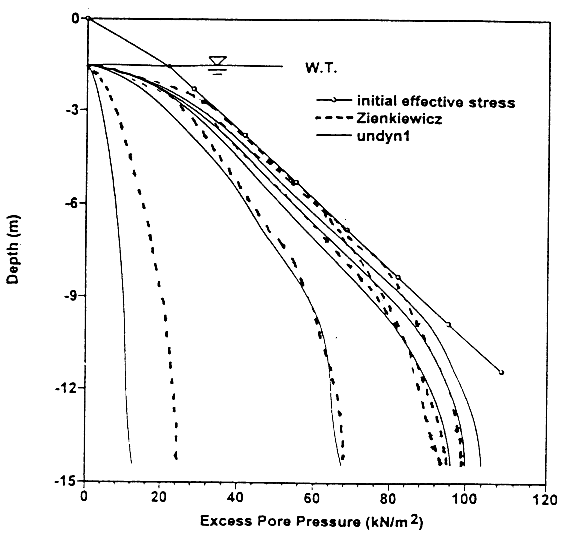

Figure 2: Comparison for distribution of excessive pore water pressure

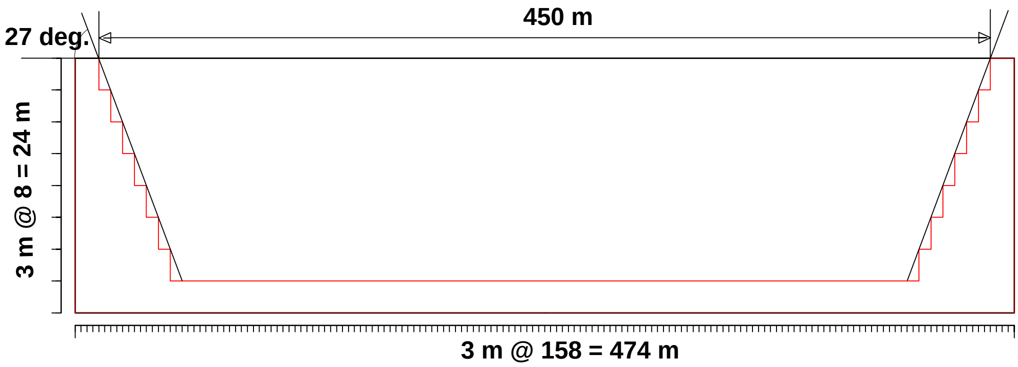

Figure 3: Basin model used for analysis

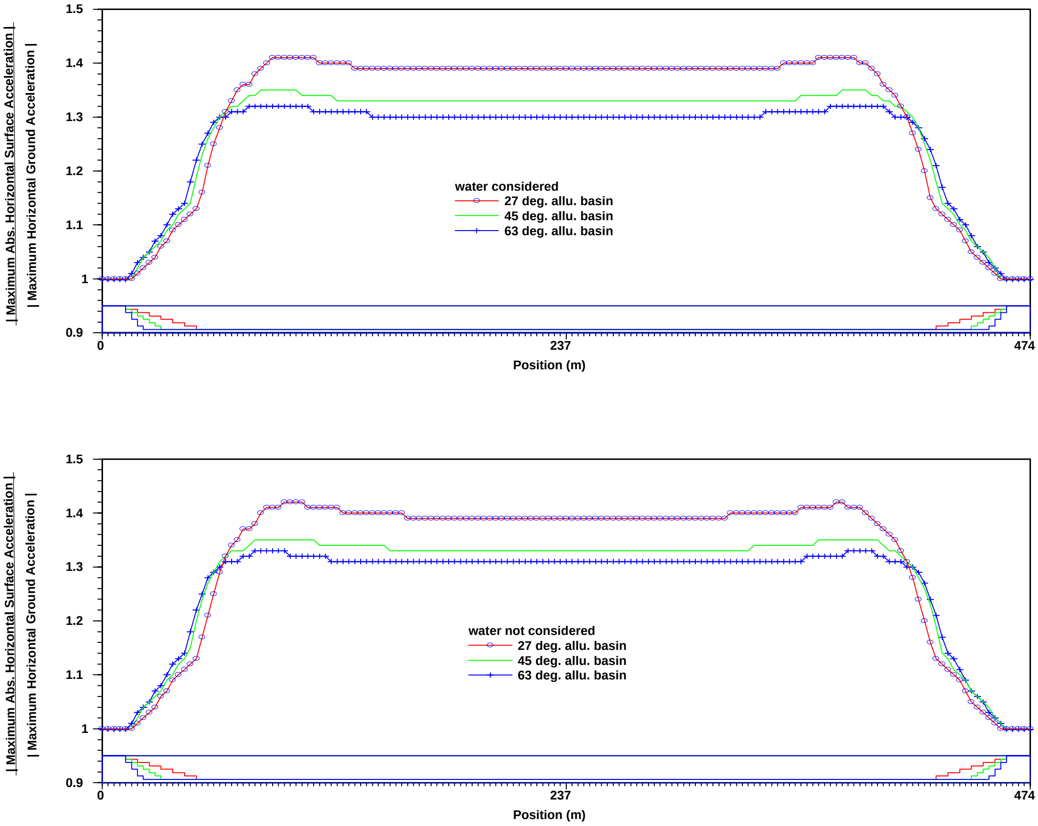

Figure 4: Peak horizontal acceleration ratio for basin with different slopes (PGA=0.05g)

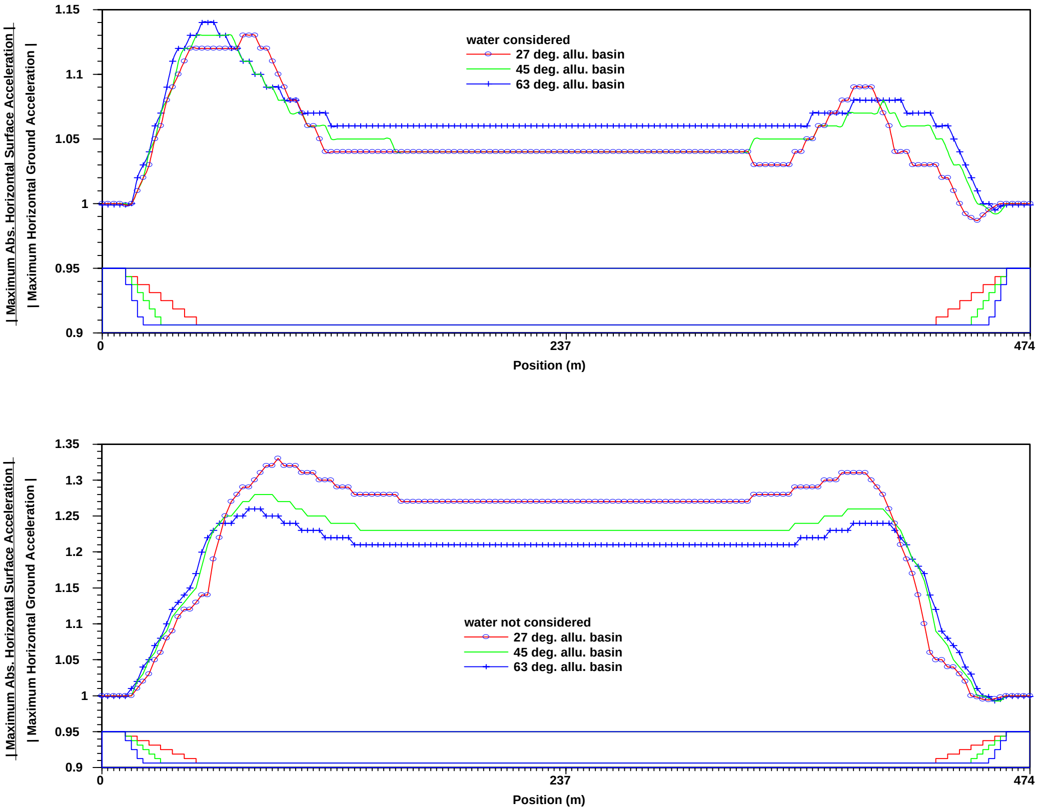

Figure 5: Peak horizontal acceleration ratio for basin with different slopes (PGA=0.2g)

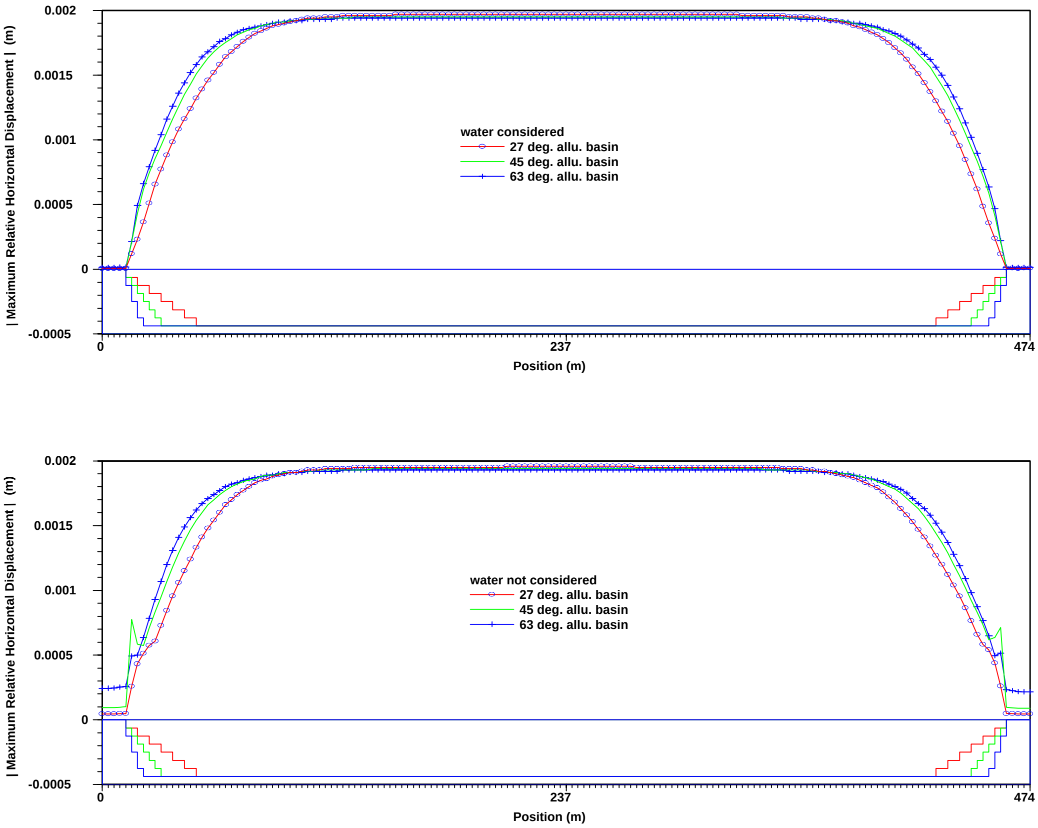

Figure 6: Peak horizontal displacement for basin with different slopes (PGA=0.05g)

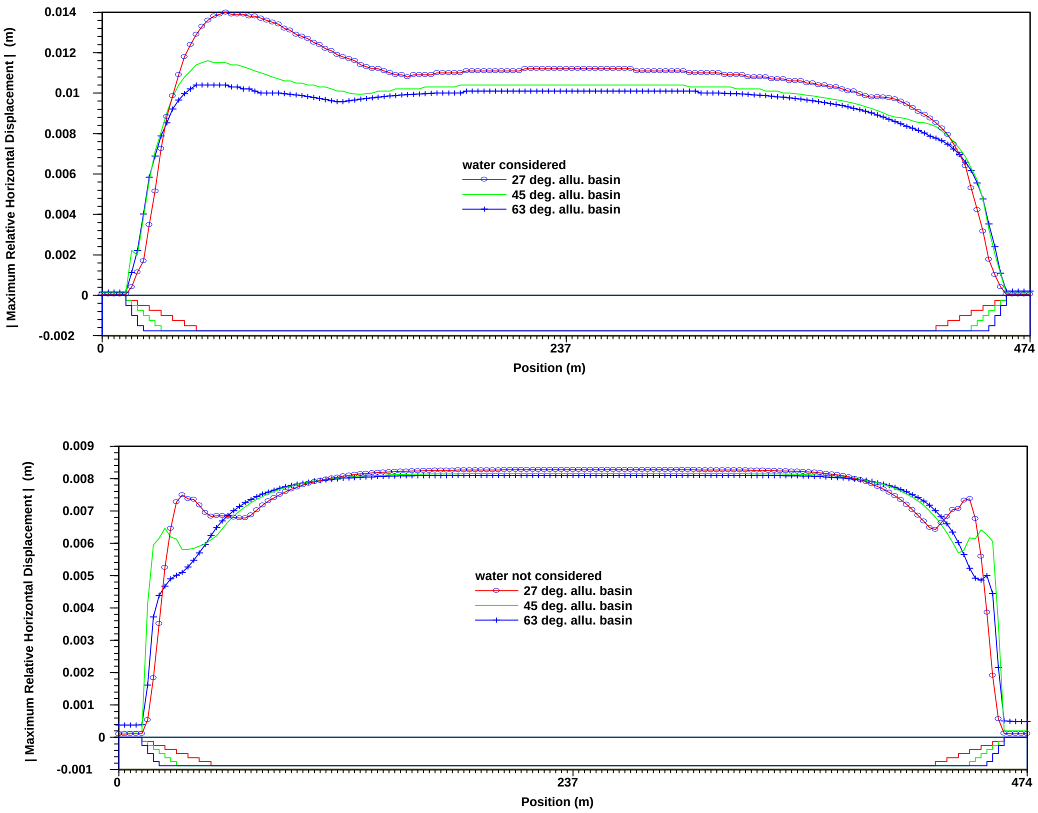

Figure 7: Peak horizontal displacement for basin with different slopes (PGA=0.2g)