Seismic response analysis of Earth Dam using PLAXIS

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Abstract. Earthen dams are the most common type of dams built since early civilization because these are mostly made up of locally available materials which require minimum processing and the problems of overturning and sliding are avoided due to their increased self-weight. Many earthen dams have been performing well under different environmental conditions and some have undergone failures. Overtopping, Slope instability, foundation failure, piping, seepage, erosion and earthquake are some common causes for these failures of these structures. Failures due to earthquake of several earth dams are already reported in India and all over the world. The damage suffered by these earth dams include longitudinal and transverse cracks on the crest of the dam, failures of both upstream and downstream slopes, subsidence of the dam, Loss of alignment and even lifting up of a portion of the dam. Previous studies have brought out that the weakening of the subsoil during earthquake could be one of the major causes for distress in dams during earthquakes. In the present study, an attempt has been made to analyze the deformation pattern, acceleration at different locations and stresses developed in earth dams in response to earthquake ground shaking by conducting parametric studies (With changed properties of soil and water level in reservoir, ground water table and composition of foundation material etc). The present study is made using finite element software, PLAXIS which is widely used in geotechnical engineering for analyzing 2D plane strain problems.

Keywords: Earth-dam, Earthquake, Failure, Finite element analysis, PLAXIS

1 Introduction

Dams are huge structures generally used to store water. They are important structures because they provide water for irrigation, domestic and industry purposes. They also provide river navigation and help hydroelectric power production. Dam failure is one of the most important hazards to both infrastructure and human life. An earthen dam has a core consisting of an impervious material to prevent seepage of water from the upstream side to the downstream side mainly made up of clay and surrounded by two shells which are permeable on either side of core.

There have been many instances of failure to earth dams during earthquake loading in recent times. A study by USCOLD suggested that earthquake is the second largest cause for the failure of earth dams (Chandradhara,2008).

Here, stability analysis of an earth dam is presented using PLAXIS software (version 8) using 2D representation of a 3D problem. PLAXIS is found to be more reliable compared to limit equilibrium method of evaluating the safety factors and for conducting parametric analysis (Shivkumar et al., 2015). Clough and Chopra (1966) introduced the finite element method for two-dimensional plane-strain analysis to find out the dynamic response of an embankment. Advanced soil models can be used to provide accurate predictions for static and dynamic loading conditions and have successfully been used in analyses of earth dams (Griffith et al., 1988). By conducting the parametric sensitivity analysis, importance of the overall dam stability has been found out through this study. In PLAXIS, it is easy to undertake the parametric sensitivity studies (Shivkumar et al., 2015). Behavior of dam under seismic loading is studied by analyzing the effective stresses and displacements. This analysis through finite element method allows to study the behaviour of the dam considering changes in stresses, strains, accelerations and displacements at different locations in the body of the dam.

2 Problem Configuration

Analysis is carried out by idealizing the problem as a two dimensional plane strain system, best suited for geo-materials with thick cross-section, using PLAXIS and hence the strain in the thickness or z direction of the 2D model is zero. By examining Hooke's Law in 3 dimensions, it is possible to obtain the stresses in the z direction. The earthen dam is modelled using 15-node element triangle with clay and sand material in model. Material parameters of the earth dam are given in Table 2 and Table 5. The mesh consists of 515 nodes and 660 stress points. To analyse any problem, it is necessary to first develop geometry of the model which is a 2D representation of a real 3D problem consisting of lines, points and clusters and it should indicate the various subsoil divisions with its layers, structural objects, stages of construction, and loads. Also the model must be sufficiently large enough such that the results are not affected.

Table 1. Dam details

Parameters	Details
Dam length	24 m
Height	15 m
Boundary	44 m
Loads	Standard fixities , Standard earthquake boundaries Dynamic load system – load system A Prescribed displacements
γ_{water}	10 kN/m^3

Pre-failure cross sections are prepared (Fig. 1) using data from Table 1. The mesh used in the present analysis is shown in Fig.3 with different colors indicating areas of varying shear strengths.

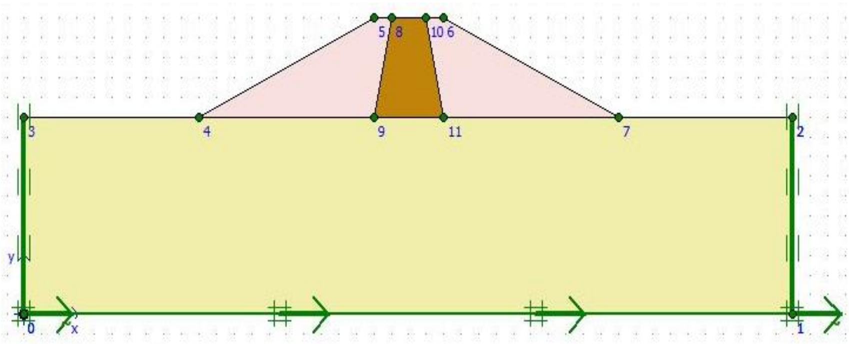

Fig. 1. Problem configuration

3 Parametric study of dam

The performance of earthen dam is analysed and studied by varying the parameters such as Water level, foundation material property and Young's Modulus of soil mass. Effect of above parameters on the structure of the dam, such as variation or changes in the dam stability, deformation of the dam, variation of pore pressure within the dam and variation of stresses within the soil mass have been analysed and tabulated.

The numerical calculations using PLAXIS software involve 3 phases. First phase is plastic analysis of dam conducted for the time when the construction is over. Second phase includes plastic analysis of dam under own body load and finally the last step consists of dynamic analysis under earthquake loading. Dynamic analysis is carried out using harmonic load multiplier, as shown in Fig. 2, taking a suitable time interval of 10 seconds. The load frequency and magnitude are given by Frequency and amplitude multipliers respectively and load phase angle is defined in the Initial phase angle. The value of Amplitude multiplier, Frequency and Initial phase angle are taken as 1, 1 Hz and 1° respectively, using an assumed input motion and changing parameters and arriving at a value wherein the deformation and stresses are least. This can be adopted by using materials possessing those properties and to determine the possibility of generation of pore pressure and if developed to identify the zones where the pore pressures have been developed. The soil properties for the sandy foundation are shown in Table 2. For the clayey foundation only the properties of Foundation soil have been changed, keeping the properties of Shell and Core the same. Value of angle of shearing resistance (ϕ) is reduced to 10 degree and the value of cohesion (C) is increased to 40 kPa.

Table 2. Properties of Sandy foundation

	γ_{unsat} (kN/m^3)	γ_{sat} (kN/m^3)	E (kN/m^2)	ϕ (degree)	C (kPa)
Shell	18	20	50,000	30.5	9.8
Core	20	22	70,000	0	50
Foundation	18	20	50,000	50	2

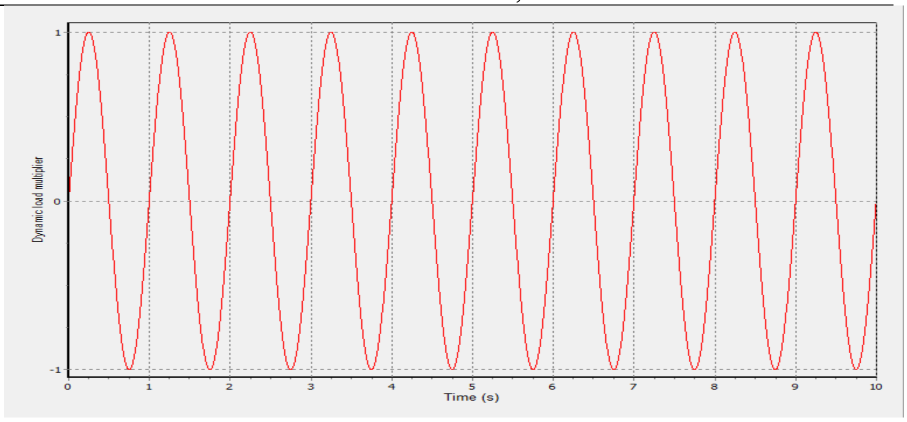

Fig. 2. Input harmonic load multiplier

3.1 Convergence test

The dam is a three zoned section consisting of central core and outer shells. Based on convergence test it is found that the results were least affected when using medium sized mesh. Beyond medium size mesh i.e., for fine and very fine the results remained the same as that of medium mesh. Similarly, it was seen that as the dam length was increased, the displacement also increased. Three boundary conditions were considered with two different materials as foundation - (1) Clay and (2) Sand. Boundary length was considered as 44m, 34m and 24m. Hence to know the maximum displacements, a boundary length of 44m has been fixed for the study using medium sized mesh. For the parametric study a representative earth dam was considered having a length of 44m, 15m height and 10m deep subsoil as shown in Fig1.

3.2 Change in Length / Boundary of Dam

The length of the dam indicates the distance between the left abutment and the right abutment or the distance between the left and right toe. The length of the dam is helpful in determining the boundary of the dam. In this study three boundaries have been considered namely full length of dam which is 44m and reduced every 10m to 34m and then 24m. The deformation was observed for each of the mesh sizes available in the PLAXIS software. The variation of deformation with respect to the mesh sizes have been obtained as shown below

Table 3. Variation of displacement with length for different meshes with clay as foundation material

Mesh size	Displacement (Sand foundation)		
	24m	34m	44m
Very coarse	0.00339	0.00507	0.00588
Coarse	0.00339	0.00508	0.00588
Medium	0.00340	0.00509	0.00590
Fine	0.00340	0.00509	0.00590
Very fine	0.00340	0.00509	0.00590

Table 4. Variation of displacement with length for different meshes with sand as foundation material

Mesh size	Displacement (Clay foundation)		
	24m	34m	44m
Very coarse	0.0044	0.00568	0.00648
Coarse	0.00445	0.00569	0.00648
Medium	0.0045	0.00571	0.00649
Fine	0.0045	0.00571	0.00649
Very fine	0.0045	0.00571	0.00649

3.3 Water Level

The pore water pressures and the external water pressures are generated based on phreatic level. This phreatic level indicates or gives series of points wherein water pressure is zero. In PLAXIS program the unit weight of water is 10 kN/m^3. Variation of pore pressures and stresses that are generated within the dam and the displacement occurred with varying height or position of water level in the dam for both materials is observed and presented below. Fig. 5 Shows the deformed mesh. From the fig it is seen that extreme total displacement is 2.07*10^{-3} m when the phreatic line is at the base of the dam. Fig.6 shows the deformed mesh. From the fig it is seen that extreme total displacement is 6.16*10^{-3} m when the phreatic line is at 1m below the dam**.**

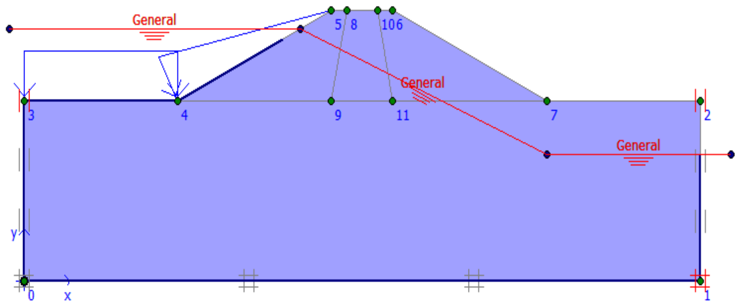

Fig. 4. Phreatic line (1m below the dam)

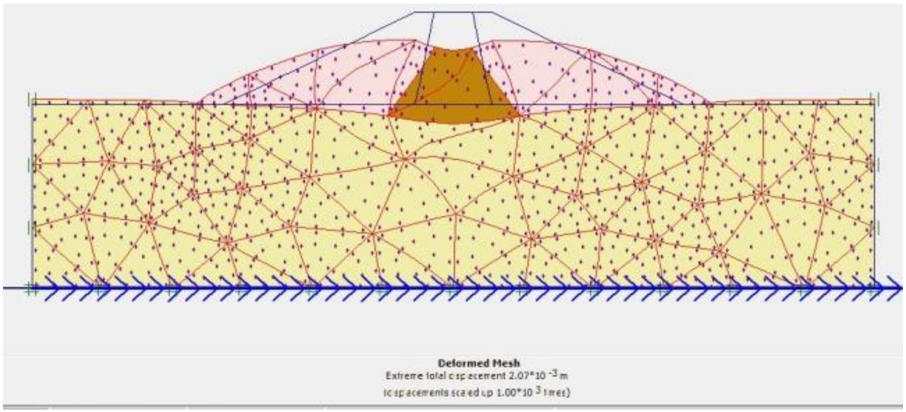

Fig. 5. Deformed mesh when the phreatic line is at the base of the dam.

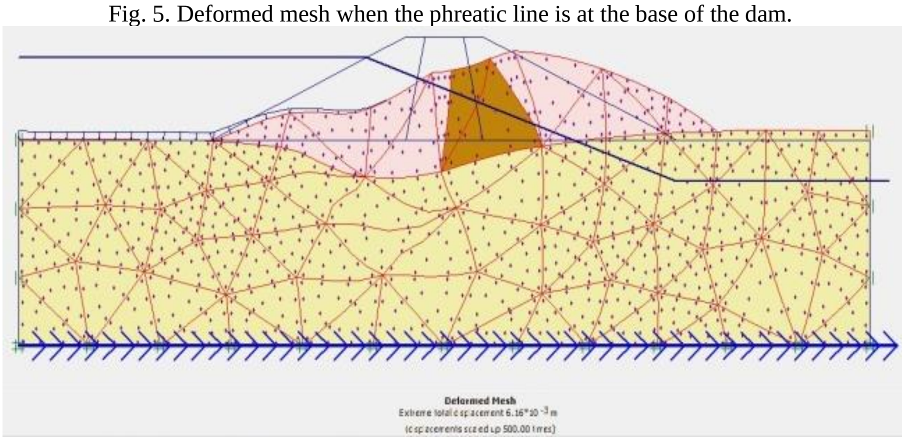

Fig.6. Deformed mesh when the phreatic line is at 1m below the dam**.**

Table 5. Variation of deformation with change in water level for different properties of soil

Water level	Deformation (for Clay foundation)	Deformation (for Sand foundation)
At base of Dam	2.07×10^{-3}m	***1.58*** $\times 10^{-3}$m
At midlevel of dam	5.00×10^{-3}m	***4.52*** $\times 10^{-3}$m
At 1m below freeboard of dam	6.16×10^{-3}m	***7.12*** $\times 10^{-3}$m

Table 6. Generation of excess pore water pressure and total displacement (Sandy foundation)

Mesh size	Before shaking			After shaking			Total displacement
	Effective principal stress kN/m²	Total stresses kN/m²	Active pore pressure kN/m²	Effective principal stress kN/m²	Total stresses kN/m²	Excess pore pressure kN/m²	
Medium	184.67	303.63	139.36	190.71	311.03	20.37×10^{-3}	6.51×10^{-3}m
Coarse	180.80	302.08	138.85	187.65	304.54	5.62×10^{-3}	6.44×10^{-3}m
Very coarse	180.80	301.27	138.65	187.65	304.53	4.56×10^{-3}	6.44×10^{-3}m

Table 7. Generation of excess pore water pressure and total displacement(Clayey foundation)

Mesh size	Before shaking			After shaking			Extreme total displacement m
	Effective principal stress kN/m²	Total stresses kN/m²	Active pore pressure kN/m²	Effective principal stress kN/m²	Total stresses kN/m²	Excess pore pressure kN/m²	
Medium							

3.4 Young's Modulus

Modulus of Elasticity is the ability of a body to withstand or resist the deformation when it is subjected to stress. The elastic modulus of the object is given by the slope of stress-strain curve. A material having a higher elastic modulus will be stiff (Modulus of Elasticity for the central core is kept more than that of other two zones). And in case of soils, if the soil particles are closely packed, they tend to have a high modulus. The effects on displacement and effective stresses in the dam with increase in Modulus of Elasticity of the material are presented below.The dam considered is a three zoned section consisting of central core (Modulus of Elasticity EC), Foundation (Modulus of Elasticity EF) and outer shell (Modulus of Elasticity ES). It is seen that with the increase Modulus of Elasticity the displacement has reduced significantly.

Table 8. Variation of Modulus of Elasticity (E) (For Clay)

Young's Modulus E (kN/m^2)			Effective Principal stress (kN/m^2)	Displacement (*10^{-3} m)
Central Core (EC)	Outer Shell (ES)	Foundation (EF)		
30000	50000	40000	-223.32	16.69
40000	60000	50000	-178.12	7.08
50000	70000	60000	-172.18	7.60
60000	80000	70000	-172.16	6.51
70000	90000	80000	-172.13	5.70

Table 9.Variation of Modulus of Elasticity (E) (For Sand)

Young's Modulus E (kN/m^2)			Effective Principal stress (kN/m^2)	Displacement (*10^{-3} m)
Central Core (EC)	Outer Shell (ES)	Foundation (EF)		
30000	50000	40000	-190.49	9.72
40000	60000	50000	-190.40	7.81
50000	70000	60000	-189.93	6.51
60000	80000	70000	-189.78	5.60
70000	90000	80000	-190.08	4.91

In the dam section three points A,B and C were chosen at different levels. The accelerations and deformations were observed at these points keeping the phreatic line at 1m below dam, and at the base of the dam.

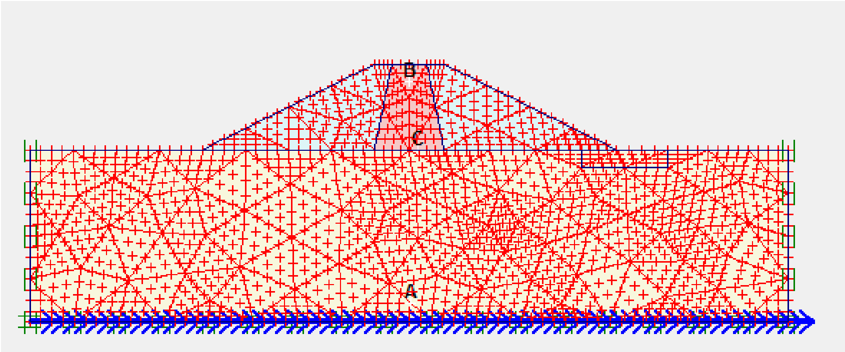

Fig.*7.* Points A, B and C chosen at different locations of the dam section

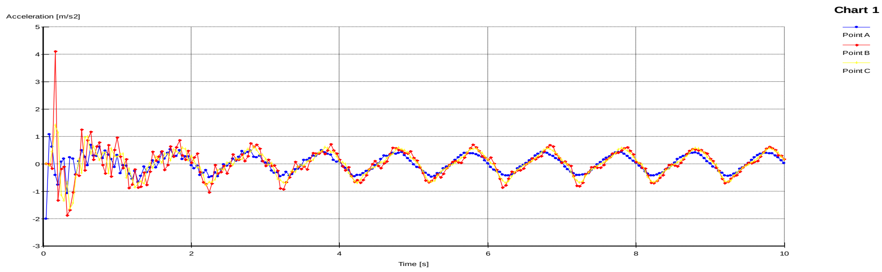

Fig.8. Time vs Acceleration (a_x) graph at points A,B and C for Clay foundation (Phreatic line 1m below dam)

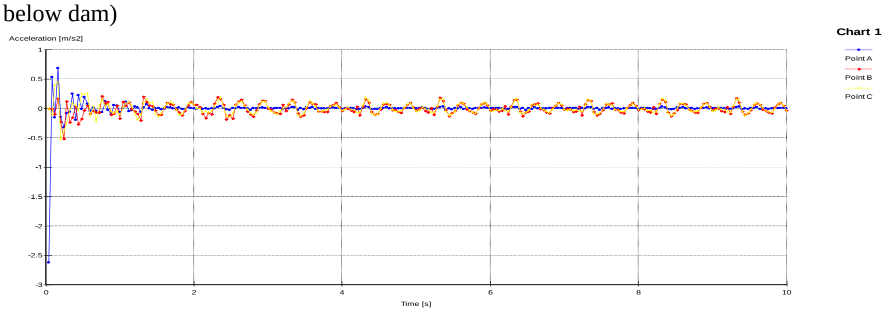

Fig.9.Time vs Acceleration (a_y) graph at points A,B and C for Clay foundation (Phreatic line 1m below dam)

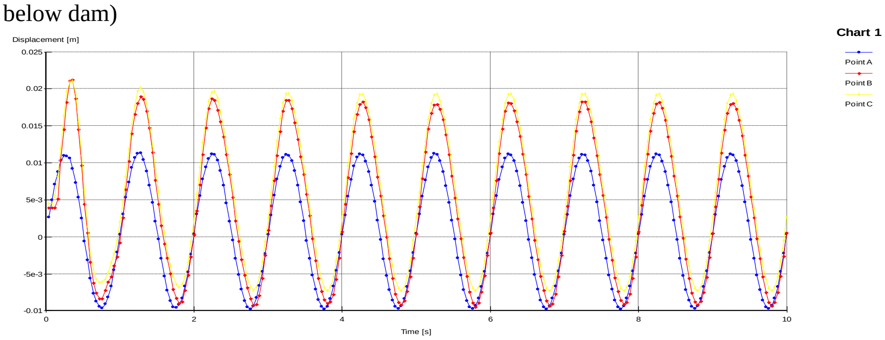

Fig.10 Time vs Displacement (u_x) graph at points A, B and C for Clay foundation (Phreatic line 1m below dam)

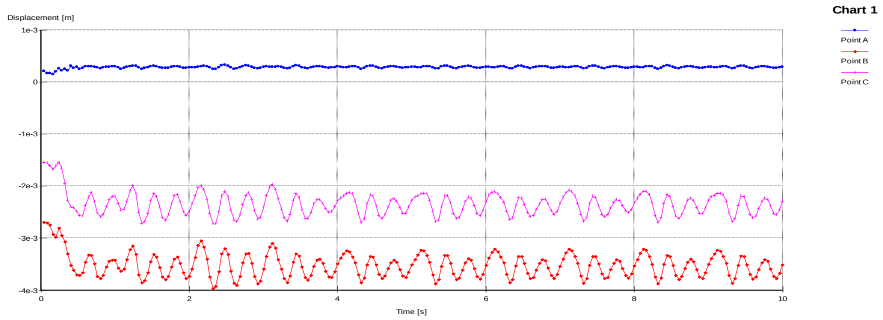

Fig.11. Time vs Displacement (u_y) graph at points A,B and C for Clay foundation (Phreatic line 1m below dam)

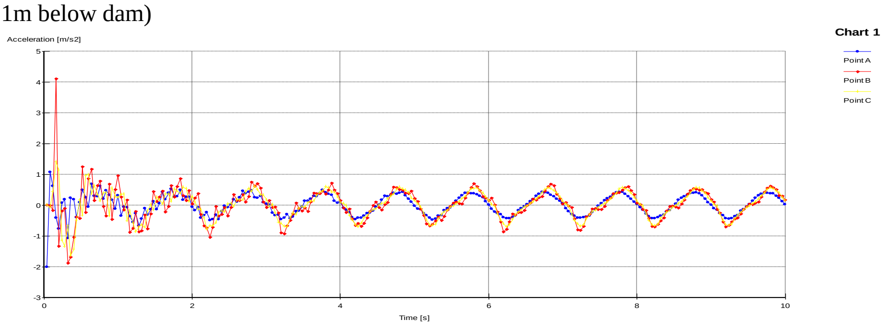

Fig.12. S***hows*** Time vs Acceleration (a_x) graph at points A,B and C for Clay foundation (Phreatic line at base of dam)

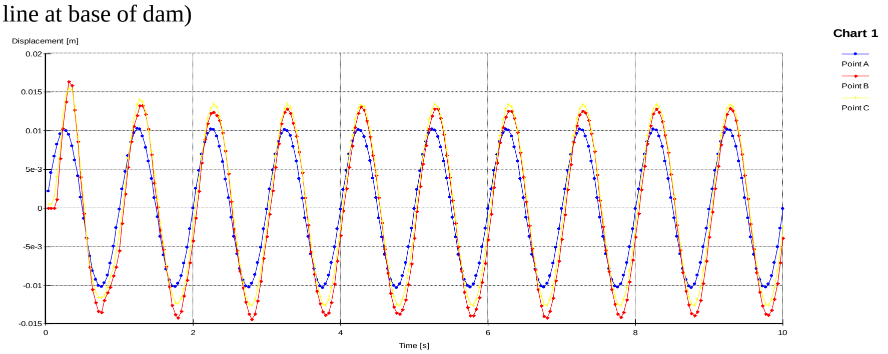

Fig.13.Time vs Displacement (u_x) graph at points A,B and C for Clay foundation (Phreatic line at base of dam)

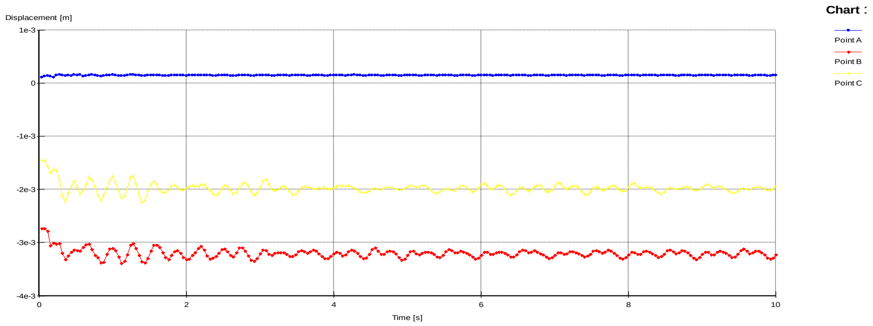

Fig.14. Time vs Displacement (u_y) graph at points A,B and C for Clay foundation (Phreatic line at base of dam)

4 Discussions

The performance of the implemented finite element formulation using PLAXIS is analysed. The influence of the selected boundary conditions on the stability of dam was studied. Three finite element models were developed with three different boundary conditions at the sides namely 44m, 34m and 24m. Deformation and stresses were observed for each dam length and different size mesh. It was observed that the results of deformation were least affected by keeping the boundary length at 44m, as the distance from the dam towards boundary was increasing, and the size of the mesh as medium and the deformation remained constant after medium size for both clay and sand. Hence a dam length of 44m and medium size mesh was taken as the convergence point for further analysis.The displacement increased with the increase in water level of the dam for both the materials.The parametric study was carried out for a dam with two types of foundation materials namely clay and sand, by varying the water level, and by changing Young's modulus.

For clay the shear strength parameter of the soil (C) is increased and it is seen that clay performed better with increase in cohesion. Drastic reduction in the displacement was observed when the Young's modulus was increased by every 10 kN/m^2 for shell (30 to 70 kN/m^2), core (50 to 90 kN/m^2) and foundation (40 to 80 kN/m^2) material from $16.69x10^{-3}$ m to $5.6x10^{-3}$ m for clay as increase in Young's modulus increases the elasticity of the soil and hence the displacement decreases. Whereas for sand the displacement gradually reduced from $9.72x10^{-3}$m to $4.38x10^{-3}$m and the effective principal stresses were found to be decreased more for clay compared to sand with increase in E value. Based on observation it can be said that the displacement can be reduced using clay material possessing a higher value of Young's modulus of elasticity. The deformed mesh (after the 10s earthquake), when Phreatic line is at the base of the dam, ***is*** shown in Fig. 5 and when Phreatic line is 1m below the dam is shown in Fig. 6. The displacements are the permanent deformation after the earthquake simulation. The dam mostly deformed toward the upstream side with a maximum displacement of 6.16`$x10^{-3}$ m**.**

A potential sliding surface is located at two-thirds of the height of the dam in the upstream shell. Larger discrepancies appear at the mid-height of the upstream and downstream shells. Relative displacement differences between the clay and sand foundation are depicted in Table 5. The maximum horizontal displacement is observed for sand foundation (7.12 x10^{-3}m) when the phreatic line is 1m below dam.

The dynamic analysis is carried out to determine if the pore-pressures are developed in the dam and if so developed, to identify the zones.Three points A, B and C were considered. A at the crest, B at the centre and C at the base of the dam and displacement, acceleration and stress were noted at those points. Duration of the dynamic analysis is 10 s. To establish a reasonable stress state for the dam before dynamic analysis, the initial static equilibrium stress state was obtained.The horizontal and vertical acceleration time histories for clay foundation are shown in Fig. 8 and Fig. 9, when the phreatic line 1m below dam. It is seen that maximum horizontal acceleration is observed at the top of the dam (4kN/m^2), whereas maximum vertical acceleration is observed at the base of the foundation (0.7kN/m^2).

The maximum accelerations during the 10 s of earthquake were calculated. For horizontal movement, higher accelerations are mainly located at the top portion of the dam. For vertical movement, higher accelerations are located at the mid-height of the upstream and downstream shells and horizontal accelerations are generally larger than vertical acceleration.

It is true that earthquake force is transient and random. However from the point of view of understanding the behaviour of earth material of dam, it is always better to study initially with harmonic vibration and later transient motion can be applied.

As it is the preliminary work, it was decided to understand the changes in excess pore water pressure and deformation characteristics when the applied excitation is harmonic.

Further, for many of the shaking table tests conducted, the generated ground motion will be harmonic.

5 References

1 Chandradhara, G. P. (2008).Seismic Performance study of earth embankments.Ph.D thesis submitted to Kuvempu University, Karnataka, India.
2 Griffiths D.V., Prevost J.H. (1988). Two and three dimensional dynamic finite element analyses of the long valley dam. Geotechnique;38:367–88.
3 Clough, R.W. and Chopra, A.K., (1966). Earthquake stress analysis in earth dams. J. Eng. Mech.,ASCE.
4 Rampello, S.,Cascone, E. and Grosso N. (2009). Evaluation of the Seismic Response of a Homogenous Earth Dam, Soil Dynamics and Earthquake Engineering, 29 782–798.
5 ShivkumarS.A., Shivamanth, Solanki C.H. and Dodagoudar, G.R. (2015). Seepage and Stability analysis of earth Dam using finite element method Aquatic Procedia 4 876 – 883.
6 Earthquake Spectra, (2002), 2001 Bhuj, India Earthquake Reconnaissance Report, EERI Publication No. 2002-01.
7 Mestat, Bourgeois, E. and Riou, Y. (2004),Numerical Modelling of Embankments and Underground Works,Computers and Geotechnics, Vol. 31, No. 3, pp. 227-236.
8 Newmark N.M, (1965). Effects of earthquakes on dams and embankments, Rankine lecture- Geotechnique 15(2), 139-160.
9 Towhata, I., Prasad, S.K., Honda, T. and Chandradhara, G. P., (2002).Geotechnical Reconnaissance study on damage caused by 2001Gujarat earthquake, India- Soils and Foundations, Vol.42, No. 4, pp 77 – 88.
10 Sarma, S. K. (1975). Seismic Stability of Earth Dams andEmbankments.Geotechnique, Vol. 25, No. 4, pp. 743-761.
11 Huang, T.K.(1996). Stability analysis of an earth dam under steady state seepage. Comput. Struct. 58(6), 1075–1082.
12 Plaxis, 2D. (2010). Tutorial Manual, Delft University of Technology & PLAXIS bv, The Netherlands.