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Original Research Article

SEISMIC BEHAVIOR AND STABILITY ANALYSIS OF AN EMBANKMENT DAM ON A PERMEABLE FOUNDATION

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Abstract

This study analyses the behaviour of an embankment type homogenous earth dam with a plastic clay core subjected to an earthquake excitation and its deformation with time. The displacement vs time graph has been plotted under the earthquake excitation and deformation for the structure is found out. The analysis tries to depict the real-life performance of the dam under earthquake excitations for its additional safety consideration. GeoStudio has been used to perform the QUAKE/W analysis on the dam. QUAKE/W models the dynamic stresses arising from earthquake shaking and simulates the impact of these stresses on the earth's structures. The software is based on the finite element method. The study also consists of seepage analysis of the dam body with impervious clay core and generation of the zero-pressure line along with the flow lines and generation of flow vectors within the body of the dam. The SEEP/W analysis has been used for the generation of the seepage across the dam body which may be further used to check the stability of the dam. In addition to that, a slope stability analysis has also been performed using SLOPE/W analysis to get the desired value of the factor of safety.

Keywords: QUAKE/W, GeoStudio, Earthquake excitations, SEEP/W, SLOPE/W, Embankment dams

1. INTRODUCTION

Embankment dams are large hill like structures constructed for various purposes which may be ponding or other irrigation purposes. They are created by compaction of plastic composition of clays or a mixture of gravel and clay with a central impervious core either of clay or concrete. A crucial component of embankment dams is the diaphragm wall, which is constructed to safeguard against piping and seepage. Horizontal or vertical filters are also provided at the downstream end of the dams to drain out the seepage

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water and provide additional safety to the dams. Bureau of Indian Standards suggests guidelines on the procedure to be followed for the construction of earthen dams[1], [2]. An Earthquake is what happens when two blocks in the earth tend to slip across or over one another and cause movements in the earth, the other reason for the occurrence of earthquakes may be the presence of faults in the rocks. Some of the lesser intensity earthquakes may also be due to anthropogenic activities such as blasting and bomb tests carried out significantly across the globe. Mejia et al. presented a detailed report and guidance for seismic analysis under U.S society on dam's article 'Analysis of seismic deformations of Embankment dams [3]. In the current scenario, adequate emphasis is put on designing earthquake resistant structures to minimize human losses and property damage. In this regard, engineers and geologists carry out detailed investigations on the history of the earthquakes at the proposed sites of construction to maintain the required degree of safety. The study of effect of the artificial and natural seismic records on the reinforced concrete frames is predicted with the nonlinear seismic structural response [4]. With advancements in the field of technology it has been possible to conduct seismic analyses and record seismic activity all over the globe, further, this information has been adequately used to carry out the earthquake analysis of any structure and design buildings or dams for higher degree of safety including the earthquake resistant designs.

This study aims to narrate the ordeal of the dam subjected to earthquake excitations with a maximum peak acceleration of 0.8g. In this study, adequate emphasis has been laid on the analysis of an embankment dam with a homogenous earth clay core subjected to earthquake excitation with a peak acceleration of the eightieth percentile of acceleration due to gravity. An investigation on the peak ground acceleration and earthquake characteristics of the Turkish earthquake and the effect of fault lines on earthquake intensity and magnitude has been performed [5]. The QUAKE/W analysis tool of the GeoStudio stimulates the earthquake excitation as per the spreadsheet data of the quake and even the seismogram records can be directly imported into the software for the analysis. QUAKE/W dynamic analysis uses the initial stresses obtained from the initial static analysis; therefore, it may be necessary to perform an initial static analysis before dynamic analysis to obtain the initial stresses. Investigation on the settlement profiles of earth dams and framework for interpreting along cross section of the earth dams and their use [6].Seepage analysis predicts the behaviour of a dam while designing other perimeters of dams. A seepage and slope stability analysis of the dam using finite element-based software [7]. Numerical earth dam modelling using the finite element method and study of the variation of pore water pressure using a transient analysis of the dam, description about a six-month time period requirement for pore water to reach an equilibrium condition in the core [8]. Use of FEM technique by using SEEP/W analysis for the case study of the Al-Adhaim dam, various seepage control measures and techniques to reduce the exit gradient at the downstream end of the dam. Effect of the clay core within the dam and its effectiveness in decreasing the exit gradient and thereby improving the overall performance of the dam and seepage control [9]. A steady-state seepage analysis using SEEP/W has been performed for the embankment dam in this regard in this study. It provides basic information about the rate of flow and an idea of flow direction using flow vectors and their variation within the body of the dam. Several analyses have been performed to depict the flow paths of water particles in the soil, especially dams. A numerical analysis of the dam in this regard and permeability ratio's role in determining the exit gradient of the dams [10]. Use of limit analysis method for the analysis of slopes reinforced with piles in non-homogenous and anisotropic soils [11]. The limit equilibrium analysis is a highly accurate and widely accepted method for the analysis of stability of slopes. The technique evaluates the stability of the complex geometry very accurately. The response of piles and use of limit equilibrium solutions for the evaluation of slope stability[12].

Analysis of the behaviour of a geosynthetic-reinforced embankment with the help of a 2D numerical model, and slope stability improvement by a significant amount and deformation reduction with use of the reinforcements in the embankments [13].Experimental and numerical study regarding the use of geogrids and geotextiles, and use of geogrid layers in improving the slope stability thereby reducing the deformations significantly than geotextiles [14]. An investigation on the influence of geosynthetic strength and vertical limits on geosynthetics for slope protection. Further, a slope stability analysis of the embankment dams with the application of geosynthetics has also been performed using the limit equilibrium analysis which improves the factor of safety against sliding and the slope may become more stable [15]. The analysis has been done using GeoStudio trial version.

Currently, the researchers are focused more on using finite element analysis (FEA) and computational fluid dynamics (CFD) analysis to simulate the highly complex interactions between the dam structure, foundation materials and seismic forces. The methods are highly advanced and use high computing power for generation of simulations. Furthermore, there is a growing emphasis on probabilistic seismic hazard assessment (PSHA) and performance-based seismic design approaches. These methods take into account uncertainties in seismic hazard, soil properties, and dam behaviour to assess the safety and performance of embankment dams under seismic loading.

In addition, innovative retrofitting techniques and advanced monitoring systems are being developed to enhance the seismic resilience of the dams. These may include methods such as soil stabilization and induction of seismic sensors for real time monitoring of the dam behaviour. Inclinometers, settlement gauges, strain gauges, seismic sensors, temperature sensors, optical fibre sensors and remote sensing techniques are some of the latest instruments and ways to monitor the dam behaviour which are currently in use. Data collection and processing of the dam collected using data monitoring systems is highly useful in improving the dam safety and resilience against natural disasters. Exploratory data analysis (EDA) such as statistical analysis and visualization techniques helps to identify patterns and anomalies.

2. METHODOLOGY FOR QUAKE/W ANALYSIS

QUAKE/W software analyses various earth structures which may be subjected to earthquake excitations and other blast loadings to compute the relative displacements and may also provide the permanent deformations associated with it, moreover, it may also compute the slope stability of the required structure using procedure given by Geo Studio modelling.

The software is based on the finite element technique. The governing equations used in the finite element method can be expressed by Eqs. (2.1), (2.2), (2.3), (2.4), and (2.5).Where, Eq. (2.1) and (2.2) represent the equation of motion and the equation for mass matrix respectively.

$$[m]\{\ddot{u}\} + [c]\{\dot{u}\} + [k]\{u\} = \{F\} \tag{2.1}$$

Where [m] is the mass matrix, [c] is the damping matrix, [k] is the stiffness matrix, and [F] is the vector of loads and $\{\ddot{u}\}$,$\{\dot{u}\}$,{u} correspond to nodal acceleration, nodal velocity and nodal displacement respectively.

$$[m] = \int_V \rho[\psi]\, dV \tag{2.2}$$

Where, [m] is the mass matrix and ρ is the mass density and $[\psi]$ is the diagonal matrix of mass distribution factors.

QUAKE/W uses a stiffness matrix equation and ground excitation force equations as mentioned in Eqs (2.3) & (2.4):

$$[k] = \int_V [B]^T [C][B]\, dv \tag{2.3}$$

Where, [k] is the stiffness matrix, [B] is the strain displacement matrix and [C] is the constitutive matrix.

The force $[F_g]$ due to earthquake load can be expressed as: -

$$[F_g] = [m]\{\ddot{u}_g\} \tag{2.4}$$

Where, [m] is the mass matrix and $\{\ddot{u}_g\}$ is the applied nodal acceleration.

QUAKE/W is based on Gauss – Legendre numerical integration for the generation of stiffness matrix [k]. The evaluation of variables is firstly done at discrete points within a particular element, these points of attention are known as Gauss points, and then follows the summation of all the Gauss points within the element. For this, QUAKE/W uses the Eq. (2.5) as mentioned below: -

$$[k] = \int_A [B]^T [C][B]\, dA \tag{2.5}$$

2.1 Modelling on QUAKE/W

Fig. 1describes the variation in acceleration with respect to time and it describes the maximum value of acceleration recorded at a station. In the figure, maximum acceleration is limited to eightieth percentile of the acceleration due to gravity. The software tool QUAKE/W uses the equivalent linear dynamic method and Cholesky factorization technique to solve the finite element equations, which is closely related to Gauss Elimination method. In GeoStudio, dynamic analysis such as seismic analysis is performed using time-domain method rather than modal analysis or mode superposition analysis. The software also provides tools and capabilities for analysing dynamic behaviour and soil-structure interaction under seismic and other transient loading conditions. The acceleration has a huge impact on the destruction that is associated with earthquakes. A study on the seismic deformation and displacement of the earth dams using limit equilibrium design and circular slip surfaces for slope instability [16]. Shojaeian conducted seismic reliability investigation of bearing capacity of foundations based on the limit equilibrium method. With the increase in the horizontal acceleration, the destruction associated with the earthquakes approaches a higher value, and therefore it's better to design the structures based on the study of the earthquakes for enhanced safety. Larger variations in the earthquake accelerations are directly associated with huge displacements and more the distortion in the values greater impact occurs on the structures [17].

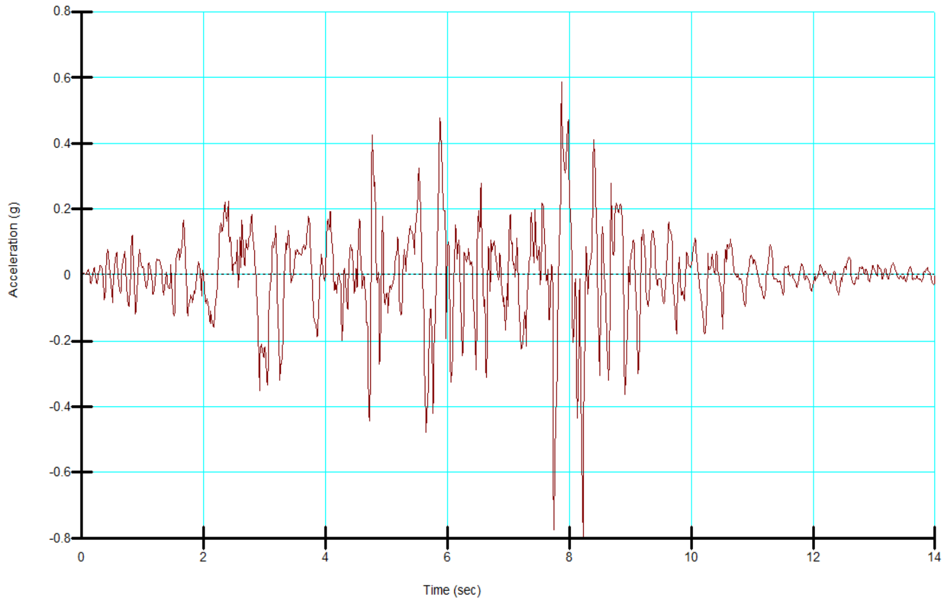


Fig. 1. Acceleration vs. time graph

3. GENERATION OF GEOMETRY AND MESHING BY QUAKE/W

Meshing of any structure involves discretizing it into a number of finite elements. Further, their behaviour is analysed by the reconnection of these into a continuum as a whole. In this QUAKE/W analysis, the geometry of the model is created using the create regions tool in the software. In this analysis, an initial static analysis is performed to obtain the shear stresses required for the dynamic analysis of the dam by assuming 15 meters of water head at upstream of the dam. The geometry consists of a dam foundation depth of 10 meters with an embankment height of 18 meters from the top of the foundation. The width of the crest is assumed as 6 meters with an upstream slope of 1:3. The foundation of the dam consists of dense sand with a poison's ratio of 0.3 and the embankment is comprised of impervious stiff clay core and dense sand casing. The filter media is loose sand and is used at the downstream end as shown in Fig. 2. Table 1 represents the materials used in this analysis in different dam components along with their properties.

Table 1. Materials and their properties used

Type of soil	**Dam component**	**Material model**	**Unit weight**	**Colour code**	**G$_{max}$**
Dense silty sand	Foundation	Linear Elastic	17kN/m^3	Green	40,000 kPa
Gravelly clay	Core	Linear Elastic	16kN/m^3	Red	8,000 kPa
Silty sand	casing	Linear Elastic	17kN/m^3	Yellow	40,000 kPa
Sand	Filter	Linear Elastic	18kN/m^3	Blue	15,000 kPa

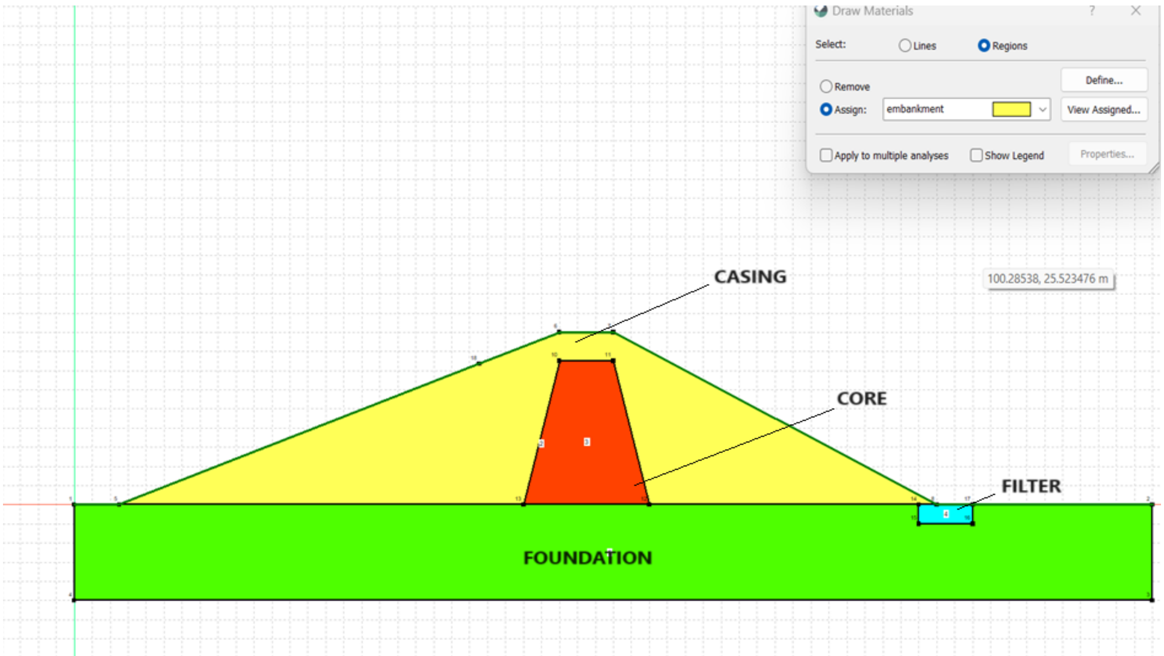


Fig. 2. Dam geometry after assigning materials

Fig. 3 shows the meshed structure of the whole dam with the rectangular elemental size of 1 meter, it also shows the irregular sized mesh element. The figure also depicts the phreatic line and throughout the dam, the pressure is atmospheric at the phreatic line. Quake modelling describes the proper procedure that is followed for the generation of mesh and the mesh element sizes.

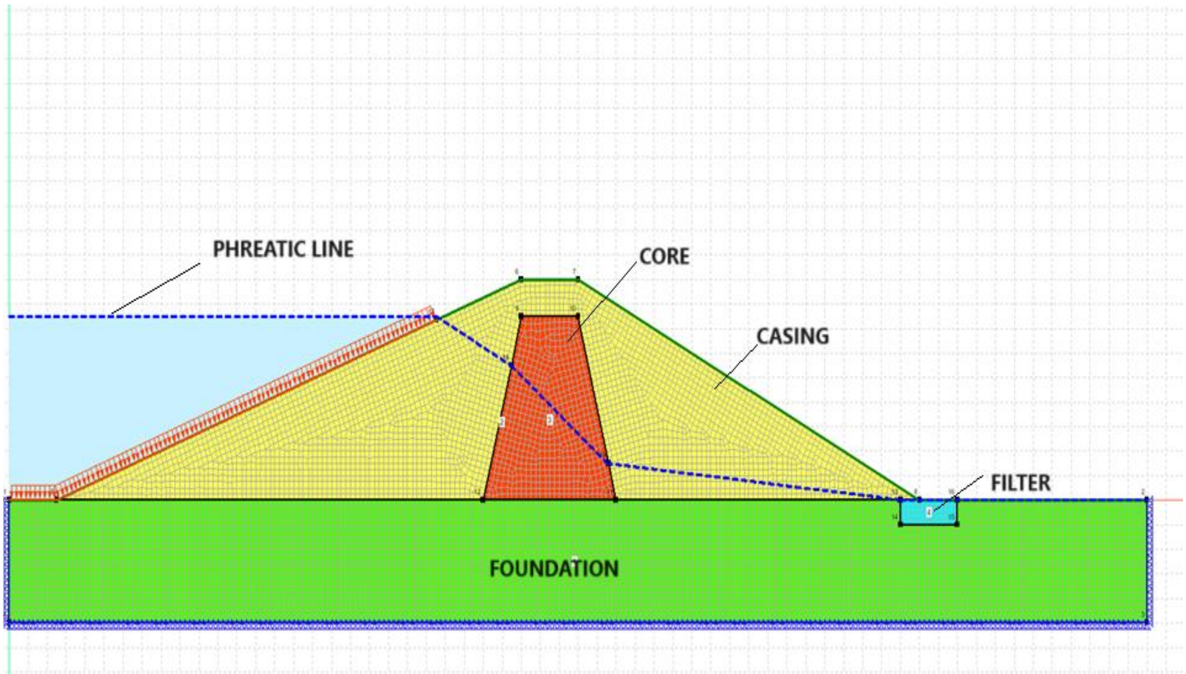


Fig. 3. Dam body after meshing

4. BOUNDARY CONDITIONS

QUAKE/W is a boundary condition-based analysis and hence, needed to be specified for this analysis. In the definition of dynamic analysis, the pre-recorded seismogram files can be directly imported as per the analysis requirements. The values can further be modified according to the peak value of the acceleration desired for running the analysis. In this analysis, a 14-second earthquake excitation has been used with the peak value of acceleration as 0.8 times the acceleration due to gravity.

In the initial static analysis of the embankment dam, the boundary conditions applied to the analysis consist of hydrostatic pressure which is applied to the upstream face up to a height of 15 meters with restriction on lateral movement of the foundation both at upstream and the downstream faces and restriction on both vertical and horizontal displacement at the bottom of the foundation of the dam as shown in Fig. 4. In addition, a zero-pressure boundary condition has also been applied at the downstream toe. Table 2 displays all the boundary conditions used for initial static and dynamic analyses. A dynamic ratio of 0.1 has been taken into consideration in the analysis as it is important for the dissipation of seismic energy.

Table 2. Boundary conditions

Boundary conditions	Category	Colour code
Zero Rotation	Rotation	Purple
Hydro pressure	Stress/Strain	Red
Fixed X	Stress/Strain	Blue
Fixed Y	Stress/Strain	Brown
Fixed X/Y	Stress/Strain	Light Blue

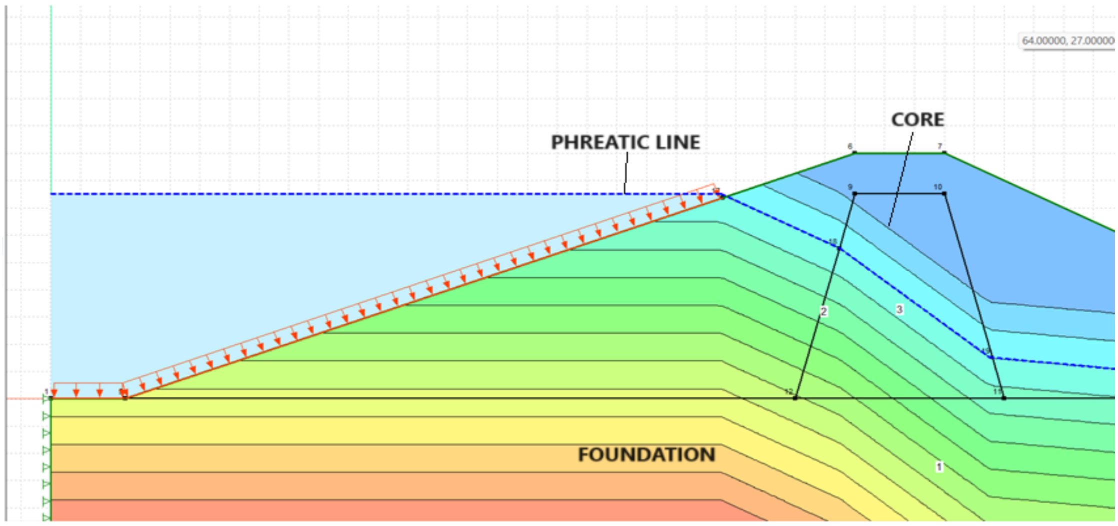


Fig. 4. Initial Static boundary conditions

In the case of the dynamic analysis, the boundary conditions consist of the upstream slope with a water head of 15 meters and restraint against vertical displacement in both the upstream and downstream faces of the foundation along with the fixed base of the foundation. The vertical movement of the foundation has been restricted during the earthquake excitation and is allowed to move in the lateral direction to get the horizontal relative displacement for the imported seismic excitation. Thereafter a displacement vs time graph has been plotted for the seismic excitation. The boundary conditions for the dynamic analysis are shown in Fig. 5.

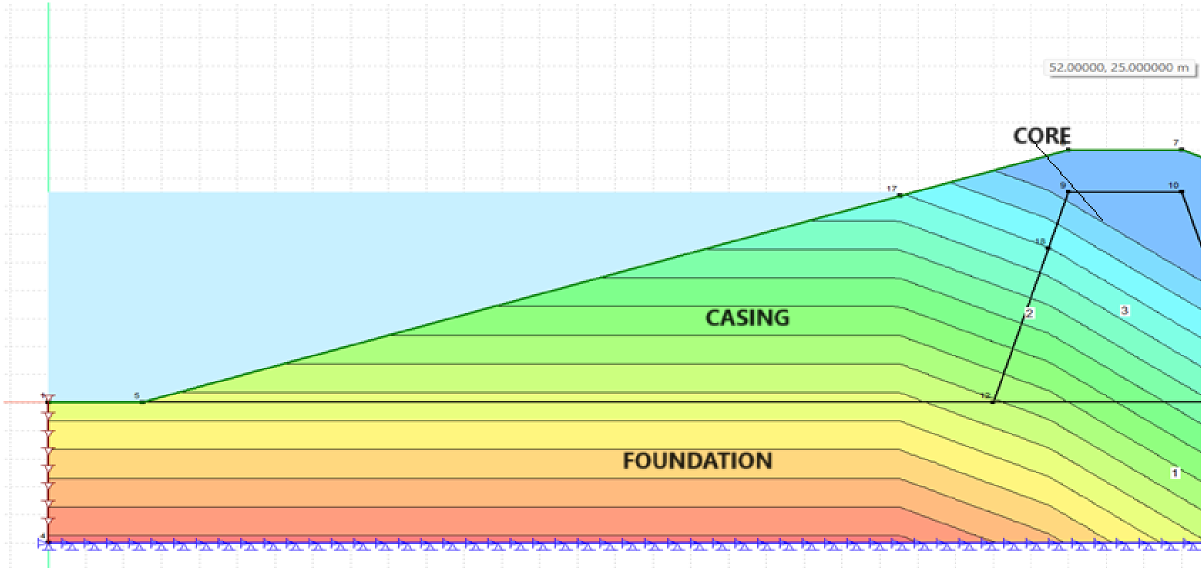


Fig. 5. Dynamic boundary conditions

5. SEEPAGE ANALYSIS

Seepage analysis provides the steady state seepage of the dam and is fully useful in the analysis of the stability of the dams. Steady-state seepage analysis generates seepage vectors, as determined by the software based on the materials' properties. The soil behaviour is assumed to be linear and elastic in nature. Earth dam failures occurring due to seepage and with a study on Mandali dam's safety results that the rapid drawdown case was the most critical case [18]. Generation of a numerical model for the seepage analysis of the embankment dams and results for the seepage tests [19]. Fenton et al. studied statistics of free surface flow through the stochastic earth dams. This study considers a numerical model of the dam formed by different materials consisting of silty sand, clay and gravel with different properties [20]. The geometrical model used for this analysis is the same model that has been analyzed in the earthquake analysis, with the consideration of the core of the dam being purely impervious.

The methodology used in the seepage analysis consists of the generation of the physical model as per the considered dimensions and thereafter creation of different regions in the dam and assigning properties of materials as per Table 3. The regions of the dam represent the various materials with different properties, Thereafter the SEEP/W analysis solver provides results in the form of flow vectors representing the rate of flow and the flow paths if desired.

GeoStudio uses various material models in its analysis and we can define the soil behaviour as saturated/unsaturated as per the conditions or the field data available. In this study we have defined the foundation in saturated condition and based on it a sample water content function and hydraulic conductivity function has been applied. The saturated only soil model is useful for defining a soil region that will always remain below the phreatic surface. Besides the software provides four estimation methods for estimating the volume and water content functions. Here, sample function method has been used in the analysis for the seepage. Other methods include (Fredlund and Xing) and (Modified Kovacs). Van Genuchten is another important method for predicting the parameters of soil.

In this steady state analysis using SEEP/W since there is no change occurring in the storage of the domain and therefore internal estimation algorithms have been used for generation of volumetric water content function which provides the hydraulic conductivity function for the desired soil. In the study Volume WC data point function has been created with the help of tool within the software to estimate the hydraulic conductivity by defining the sample material such as silt, sand, clay as per the materials designated in the model. This estimation provides us with a volumetric water content curve based on previously published literature as per the selected soil. Using the edit data point tools in the software we can delete or modify the data pints in the curve but no modification in this analysis has been done. The value of the coefficient of compressibility can be added here in the estimation window of the software.

Again, based on the volumetric water content function the hydraulic conductivity function of the different components of the structure such as embankment, casing, core are generated using the internal estimation techniques in the software while adding the values of permeability as per the soil used in different structures. In this analysis the casing and the foundation are made of silty sand therefore same properties have been used. The hydraulic conductivity function is based on the Van Genuchten method of analysis which generates the similar curve based on the previously published literature. The data can be modified using the edit data tools in the software and additional data may also be added. The function volumetric data function and hydraulic conductivity function are defined for all the components of the structure based on the type of the soil used in the structure. Van Genuchten proposed a four-parameter equation for predicting the volumetric water content function. The governing equation is as follows:

$$\Theta_\omega = \Theta_r + \frac{\Theta_S - \Theta_r}{\left[1 + \left(\frac{\psi}{a}\right)^n\right]^m}$$

where:

Θ_ω= the volumetric water content.

Θ_r= the saturated volumetric water content

ψ = the negative pore-water pressure, and

a, n, m = curve fitting parameters (note: "a" has units of pressure)

In this analysis anisotropy i.e. (k_y/k_x) ratio is 1 as hydraulic conductivity is same in both directions.

5.1 Generation of the model

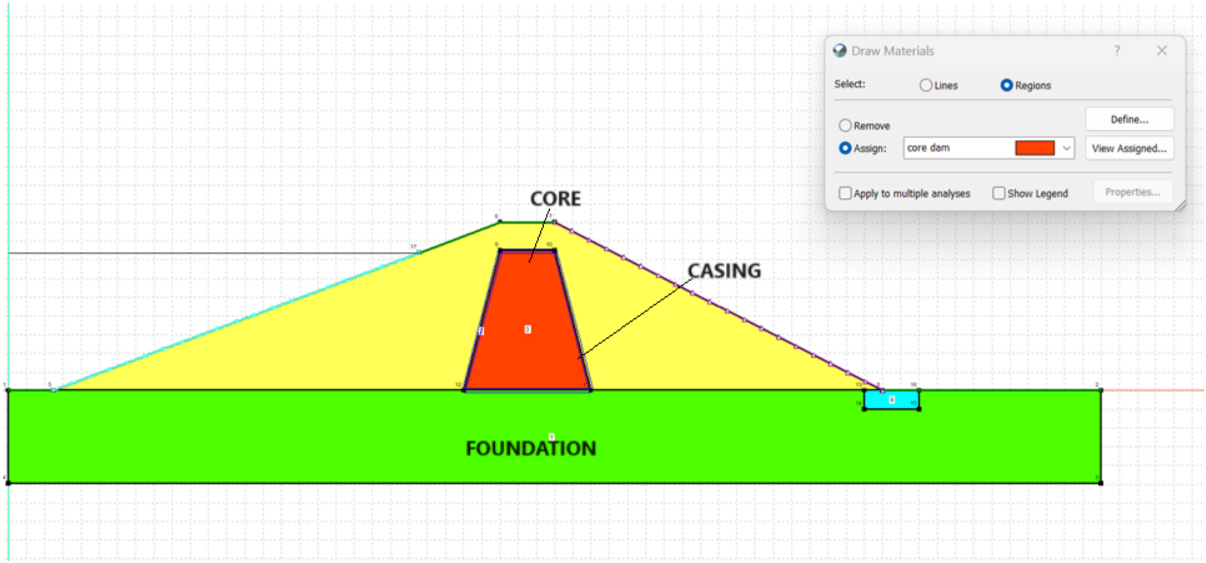


Fig. 6. Seepage model with assigned materials

The model consists of the dam 18 meters in height with a total water head of 15 meters resting on a pervious sand foundation with an impervious clay core, (the impervious layer of the core has been generated using the add impervious barrier option in the SEEP/W analysis) and pervious casing. The model of the dam so constructed is further analyzed by assigning materials, the model after assigning different materials and its properties is as shown in Fig. 6.

Table 3. Materials and its properties for seepage analysis

Dam component	Material conditions	Compressibility(/kPa)	Permeability (K_x) (m/sec)
Foundation	Saturated/Unsaturated	0.0005	1e-03
Core	Saturated/Unsaturated	0.0002	1e-09
Casing	Saturated/Unsaturated	0.0005	1e-03
Filter	Saturated/Unsaturated	0.0005	1

GeoStudio provide several “typical” water content functions for different types of soils. In using these sample functions, we specify the saturated water content and the residual water content (if any) based on our understanding of field conditions. The above-mentioned properties estimate a volume and water content function as shown in Fig. 7 & 8.

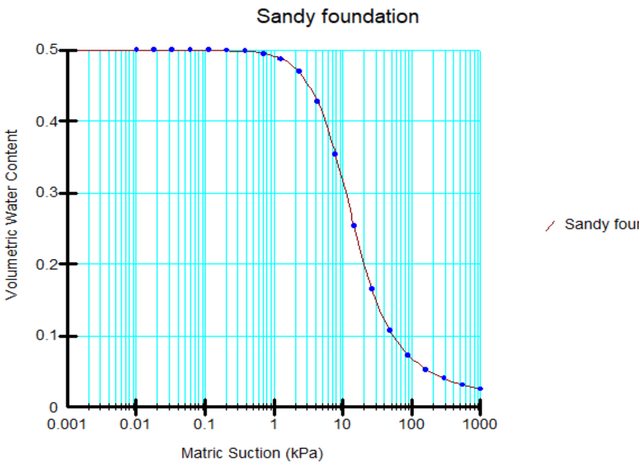


Fig. 7. Vol. Water content function foundation

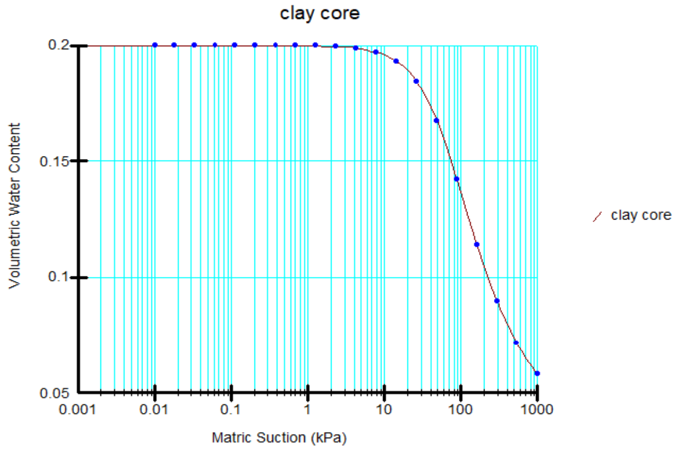


Fig. 8. Vol. Water content function core

Fig. 7 & 8 represent the volume water content function convergence graphs for the foundation and core respectively as estimated by the software automatically as per considered values of compressibility and permeability. Data points should be in a line as in the above figures, the data point values can also be manually inserted into the solver window as per the required analysis.

5.2 Boundary conditions and meshing

The boundary condition of the analysis consists of a constant total water head of 15 meters assigned to the upstream side of the dam with a second drainage condition that has been assigned to the downstream slope of the dam. Table 4 shows the boundary conditions for the analysis. The meshing consists of a unit size of each element with several elements and nodes. Meshing plays a significant role in the analysis proper meshing results in accurate and improved accuracy of the analysis. The generated mesh and the applied boundary conditions of the water head up to 15 meters are shown in Fig. 9.

Table 4. Boundary conditions for seepage analysis

Boundary conditions	Category	Colour code
Zero pressure	Hydraulic	Red
Reservoir level	Hydraulic	Blue
Drainage	Hydraulic	Purple

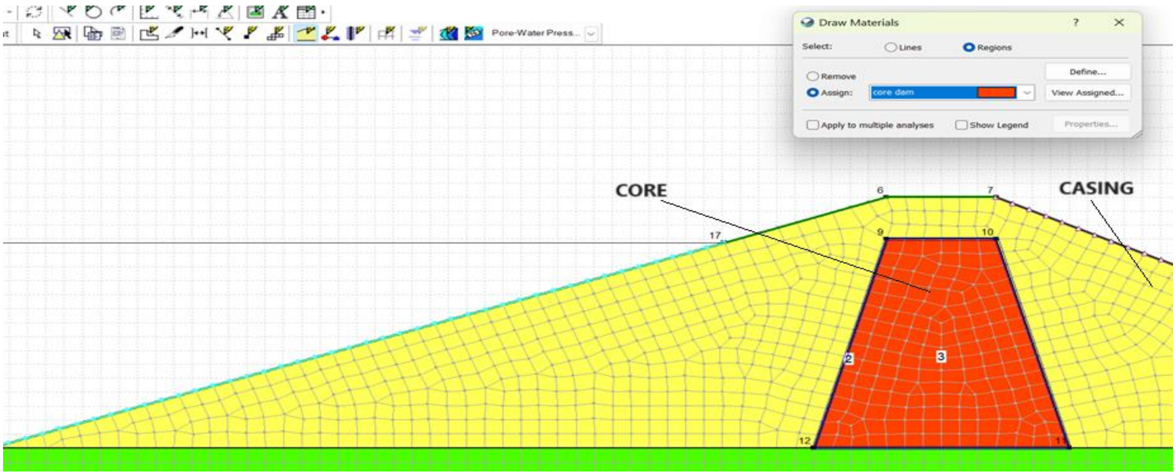


Fig. 9. Meshed structure with boundary conditions

6. SLOPE STABILITY ANALYSIS WITH GEOSYNTHETIC SLOPE PROTECTION

In this analysis of the slope of the dam, a consideration of a dam model with 18-meter height has been made and the steady state analysis of the same dam has been performed. The model consists of a dam with a clay core and a relatively silty sand casing has been used. Slope stability analysis is highly recommended for checking the stability of the dams. The analysis has been done using SLOPE/W analysis within the GeoStudio software. A detailed static and pseudo static stability analysis of an earthen embankment of Nagarjuna Sagar dam by GeoStudio [21]. A study on the seismic slope deformation of the earth dams and damage associated with it [22].The methodology deals with the generation of the numerical model for the analysis and thereafter defining materials and their properties. In addition to that a surcharge load has been applied and the behaviour of the slope with the use of geogrids has also been checked. This analysis examines the effectiveness of nailed slopes and the significance of nails in enhancing slope stability [23]. Use of crumb rubber in dry sand to stabilize the soil and enhance soil stability, an ideal solution for the sequestration of waste products such as rubber to reduce its negative environmental impacts [24].

Fig. 10 represents the typical model of the dam for the analysis of the slopes using the geogrids. The 2D model consists of a foundation, an embankment casing of silty sand, and a clay core. Geogrids of 13 meters in length have been used for slope stability. Moreover, Entry and exit lines have been defined in the model as shown in Fig. 10. The entry and exit lines as shown in the same figure define the range of the slip surfaces both at the crest and the downstream end of the slope.

Table 5 represents the properties of the different materials used in the slope stability analysis. The properties consist of unit weight, cohesion value, and angle of phi. In this analysis, maximum cohesion is provided in the clay core of the embankment dam.

6.1 Generation of numerical model

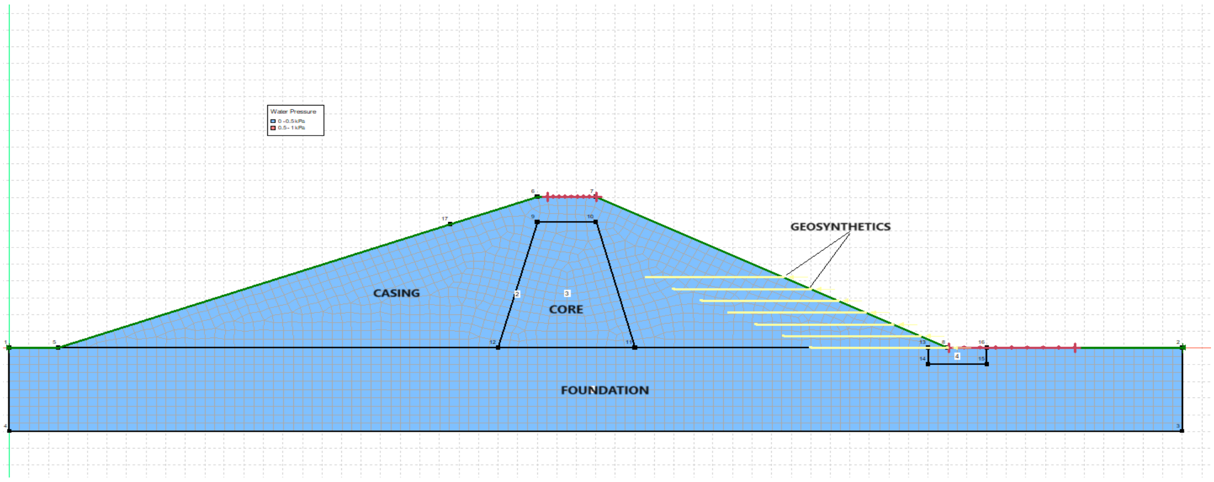


Fig. 10. Model for slope analysis

Table 5. Material properties for slope analysis

Name	Unit weight	Cohesion
Foundation	17 kN/m^3	0 kPa
Core	16 kN/m^3	20 kPa
Casing	17 kN/m^3	10 kPa

Fig. 11 shows the typical representation of the dam model with a surcharge acting at its crest. A surcharge load of 16 kN/m has been defined in the analysis. The surcharge load directly influences the geogrid and its capacities in many cases. Here the slope provided is not too steep therefore lesser number of geogrids are sufficient for safety. Otherwise, if the surcharge load is more with a steep slope tension failure may occur leading to failure of the geogrids. In the generation of slip surfaces entry and exit method has been used and other values have been taken as default values by the software itself. In case of geogrids the reduction factor of 1 has been used.

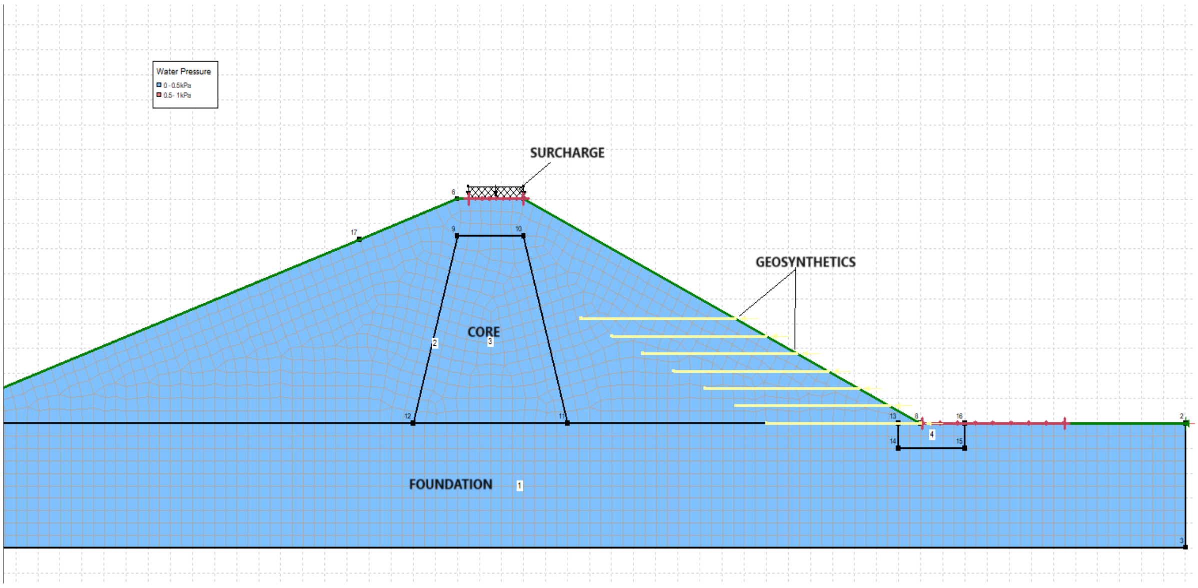


Fig. 11. Model with surcharge load at the top

6.1.1 Characteristics of geosynthetics

Table 6. Geosynthetics properties

Properties	Values/Perimeters
Reduction factor	1
Factored tensile capacity	150 kN/m
Nature of force	Distributed
Pull out resistance	40kPa

The detailed study on the role played by the geosynthetics in the slope stability and soil improvement [25]. The slopes of sandy soils can be improved and better protected by the use of geosynthetics [26].

6.1.2 Crest deformation

The dynamic analysis generates mesh deformations, with varying deformed meshes displayed at each time step, as illustrated in Figs. 12 and 13. The deformation varies with the time and the ground excitation. A history point is located on the crest of the dam body in this case and the relative displacement of that point is depicted in the graph. Various such points can be located on the numerical model to know the displacement at those points or the necessary points whose displacements are required to be found.

Figure 12 shows the typical deformation of the dam body and its mesh. The vectors represent the direction of the mesh deformation, the longer vectors describe higher deformation occurring in the respective direction. The peak acceleration of the seismic excitations and the time of the occurrence of seismic excitations greatly influence the degree of deformation associated with mesh. Computation of the earthquake induced deformations at the crest of the earth dams using finite element method and earthquake induced deformations being almost symmetrical at the center line of the dam [27]. Fig. 12 indicates almost symmetrical deformation of the dam occurring at the center line of considered dam model and is more varied as we move away from the dam axis.

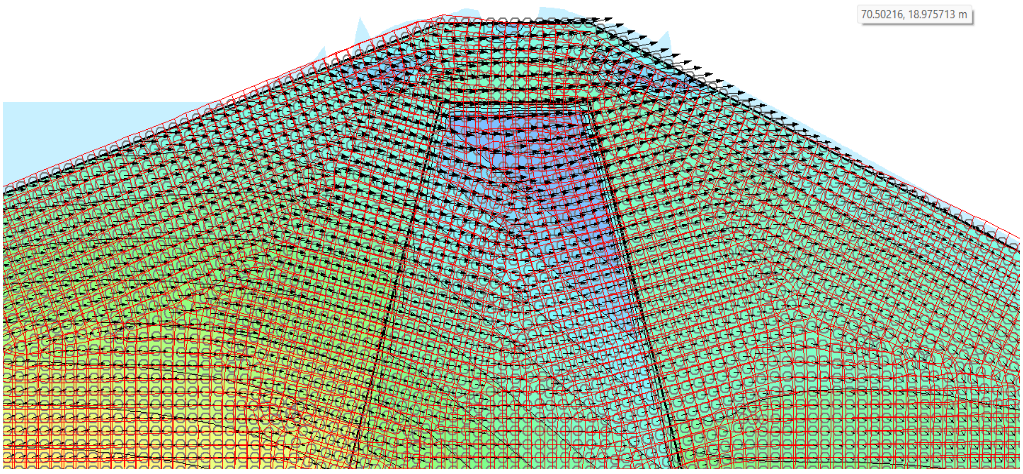


Fig. 12. Crest mesh deformation

6.2 Relative displacement vs time graph for crest

A relative displacement vs time graph has been plotted for the crest deformation occurring due to horizontal earthquake excitation causing the crest to disintegrate. Fig. 13 depicts the displacement of the crest with time. A history point at the crest was considered and its displacement with time and peak horizontal acceleration was predicted using the QUAKE/W analysis. The result clearly indicates the influence of peak horizontal acceleration and time step on the displacement of crest. The peak horizontal acceleration significantly influences the crest settlement whereas the influence of vertical component of seismic excitation has comparatively smaller influence on the crest displacement [28].

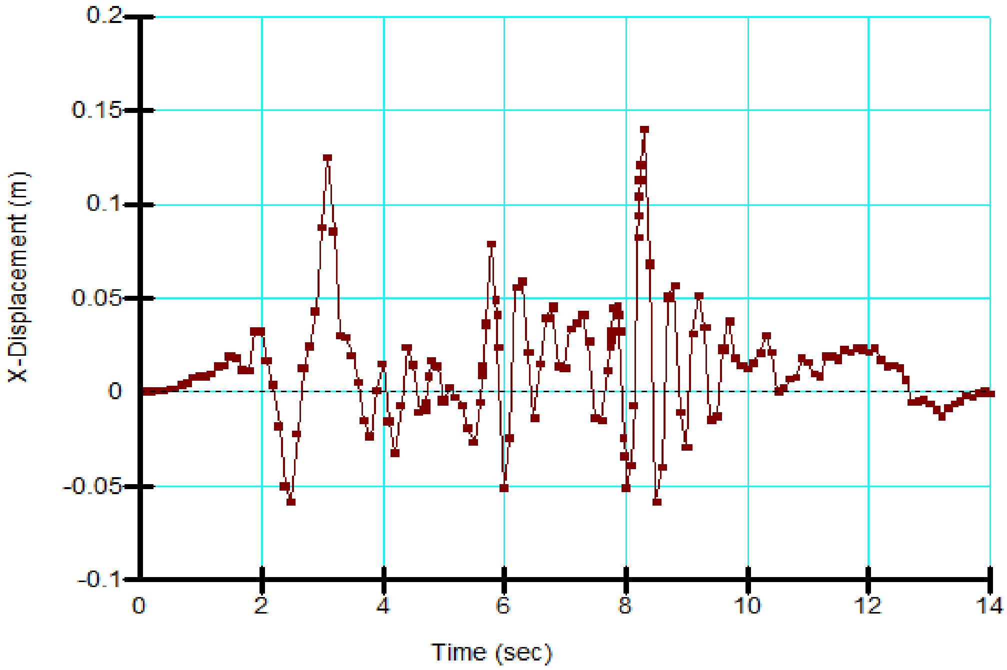


Fig. 13. Relative displacement vs time graph

6.3 Variation of shear stresses in crest

Fig. 14 shows the graph representing the variation of maximum shear stress with time. The shear stress for the crest reaches its maximum value at the range of 8-10 seconds with a maximum value of 53 kPa. The shear resistance of soils is desirable but the accumulation of water within the dam body decreases the shear strength of the soils which results in loss of shear strength and therefore such condition is not desirable, hence the water must be removed through proper passage. Fig. 14 also establishes the fact that the maximum displacement occurs in the regions having maximum values of shear stresses, also it is clearly evident that shear stress values and displacement values are inter dependent in this case.

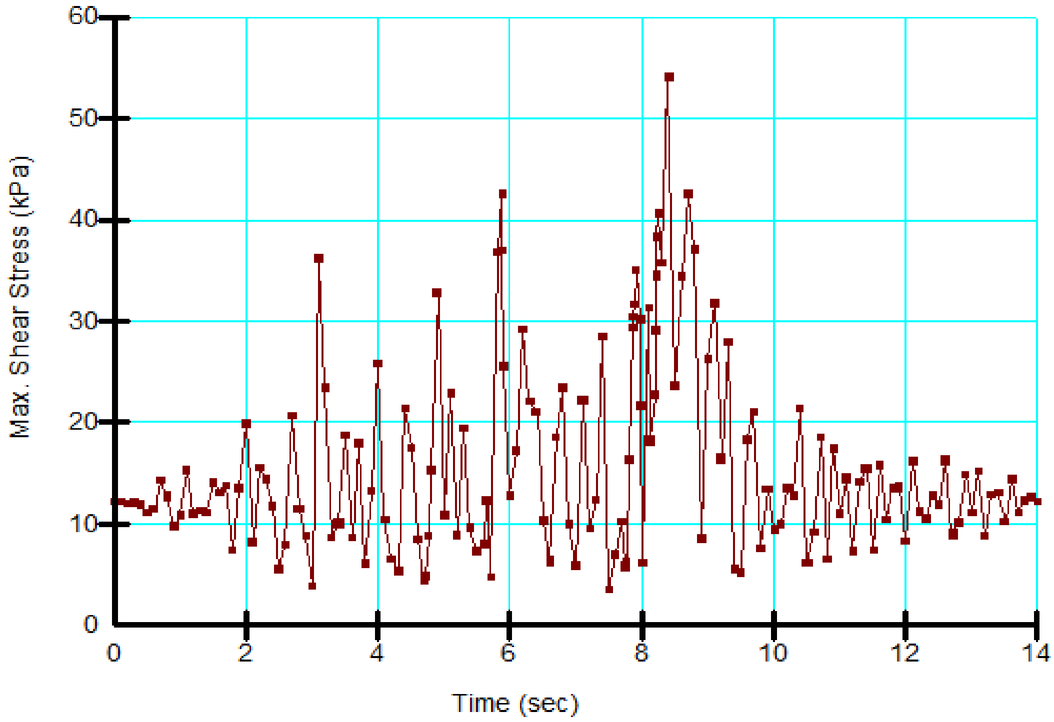


Fig. 14. Maximum shear stress vs time graph

6.4 Seepage vectors through embankment

Fig. 15 represents the seepage vectors within the body of the dam and these vectors are representative of the direction of the excess pore water pressure within the body of the dam. These also represent the rate of flow and the longest vectors highlight the highest flow rate and the smallest ones represent the low flow rate. The phreatic line falls due to presence of the core in the dam body; therefore, it may be concluded that the impermeable clay core greatly influences the phreatic surface and seepage within the dam body. Study of various equations and their comparison with software results to compute seepage within the body of earth dams, also the influence of the clay core in lowering the seepage within the body of earth dams [29].

Water seeps through the dam body and reaches the filter provided at the downstream end to exit through the toe drain provided. Pressure below the phreatic line is positive hydrostatic and above it is atmospheric.

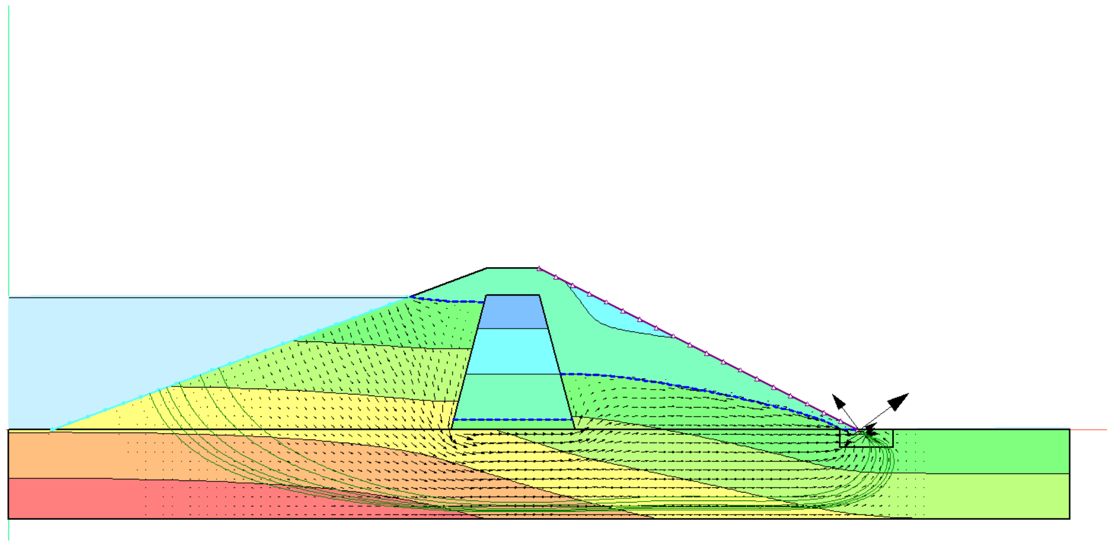


Fig. 15. Seepage vectors through dam body

6.5 Flow paths within the embankment

Fig. 16 represents the flow paths within the dam body, these are indicative of the path followed by a water droplet through the embankment dam body. Use of anti-seepage walls for the control of seepage using innovative solutions and conducted a seismic response of the earth rock dams [30]. These flow paths are perpendicular to the equipotential lines in the dam. Above the phreatic line, the flow paths indicate the capillary zone.

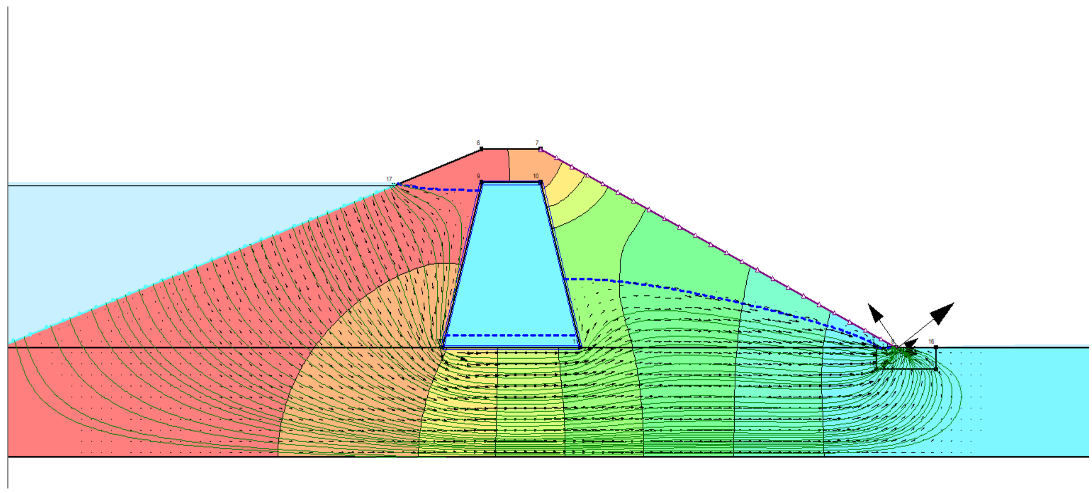


Fig. 16. Flow paths within the dam body

6.6 Pore water pressure through embankment

Fig. 17 represents the water pressure variation in the dam body with distance. Positive hydrostatic water pressure represents the water pressure below the phreatic line whereas the negative pressure is representative of the water pressure above the phreatic line. Pore water pressure distribution is directly impacted by change in the total stress distribution in case of nearly undrained conditions. Study of Zoccolo dam and importance of pore water pressure distribution to know well in time about the water tightness problems occurring within the dams [31] .

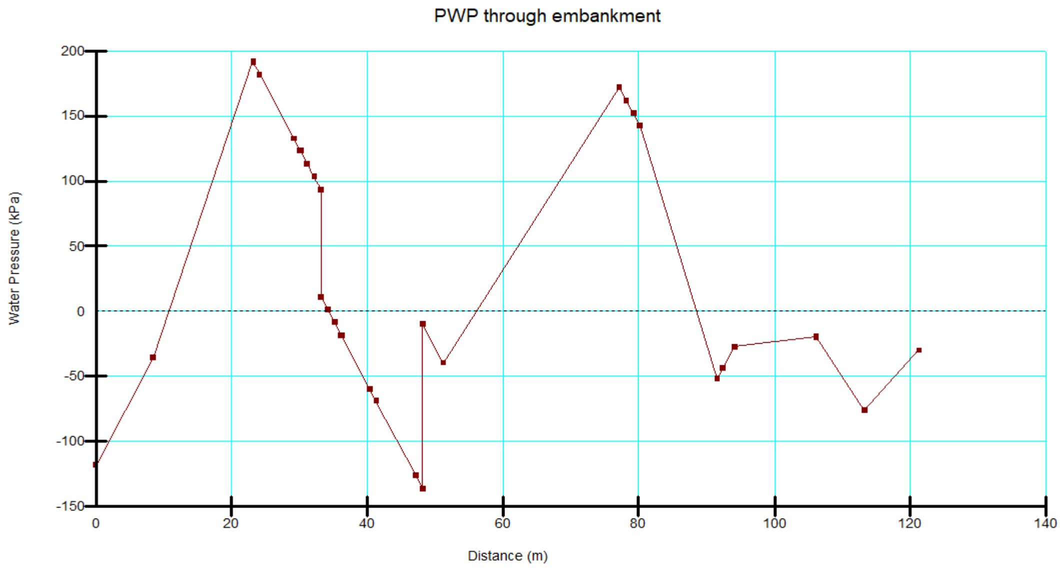
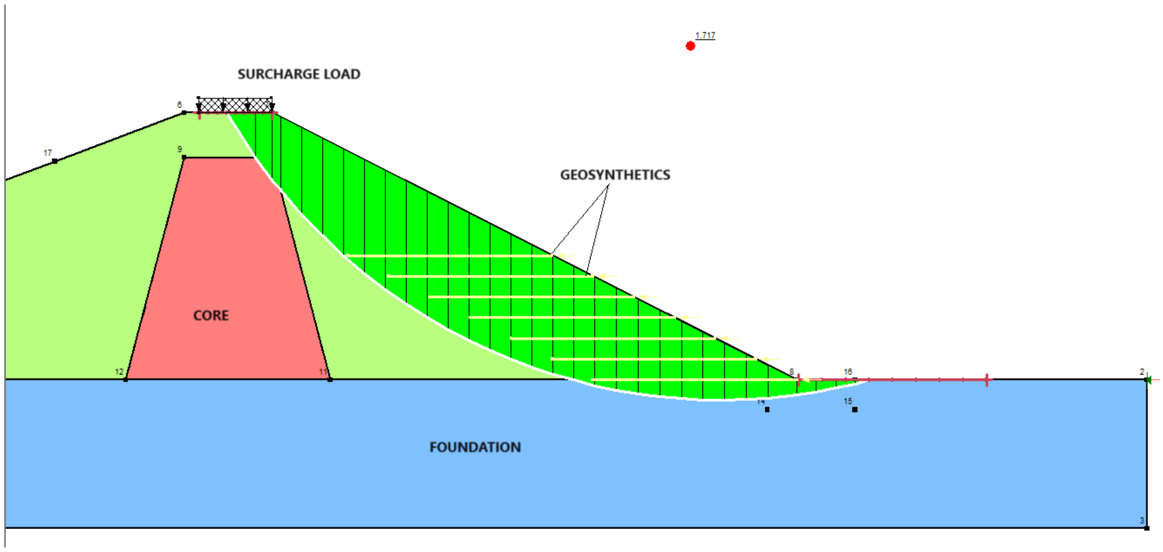


Fig. 17. Water pressure vs distance graph

6.7 Slope stability with geosynthetics

Fig. 18 shows the slip surface of the dam under the stability analysis using geogrids. While using geogrids we get a factor of safety of 1.717 in this analysis which is sufficient for the steady state analysis of the stability of the slopes. The corresponding values of the factor of safety with the slip surfaces vary and therefore for every slip surface there is a unique value of factor of safety. The maximum value of factor of safety here is 1.717 as shown in this figure. In no slip surface the values of factor of safety are lesser than the 1.5, therefore the slope protection is ensured and there is significant improvement in the slope stability with the use of geosynthetics. The use of continuous geosynthetics in high multi slope embankments, resulted in generation of factor of safety greater than 1.3, which was desirable [32].



. Fig. 18. Dam body with slip surfaces

6.8 Discussion

In QUAKE/W analysis the deformation at the dam axis as compared to the upstream and downstream end of the dam is lesser, and therefore it may be concluded that under the seismic action an earth dam can be made more seismic resilient using retrofitting techniques and reinforced materials. In SEEP/W analysis seepage through the dam body can be minimized using cut off walls and diaphragm walls. The cut off walls provide additional stiffness to the dam body and it also introduces seismic resilience and reduction in pore water pressure and shear stresses in the dam body. In slope stability analysis the geosynthetics are helpful in the slope protection of the dams.

Advanced data visualization techniques play a crucial role in understanding and communicating complex data related to earth dam safety. It is highly suggested to use data visualization techniques in monitoring the dam behaviour, the techniques may include geospatial visualization, time series analysis, multivariate analysis, data fusion analysis and integration [33].

The use of advanced data visualization techniques by engineers, and regulators can be helpful in gaining deeper insights into the complex factors influencing earth dam safety and effectively communicate risk information to stakeholders for informed decision-making and risk management[34], [35].

7. CONCLUSION

This study predicts how an embankment dam will behave when subjected to earthquake excitations, including deformation of the dam body and steady-state seepage. The study also provides adequate information on the use of GeoStudio QUAKE/W, SEEP/W and SLOPE/W analyses for the dams or slopes. In this analysis, a graph representing the relative displacement for the crest and showing the maximum deflection of the crest occurring within the 8-10 seconds time step range of seismic excitation. Though the analysis uses a 0.8g value of horizontal acceleration which is very high and therefore such a condition may not arise in actuality, for more safety additional stiffness can be provided in the crest using reinforcement of soil slope or by providing impermeable barriers perpendicular to the seepage. The seepage analysis of the dam body shows the flow path and flow vectors beneath the impervious core thereby reducing the seepage failure due to the presence of clay core. The graph in Fig. 17 shows the water pressure variation at the dam axis section. The water pressure is positive hydrostatic below the phreatic line and negative above the phreatic line. The study also concludes that a filter along with a toe drain is necessary for the downstream protection of the dam and to avoid piping and seepage failure.

A slope analysis using geogrids has also been performed thereby resulting in getting a value of factor of safety. The geogrids provide a good amount of stability to the slopes thereby increasing the overall durability of slopes. A factor of safety of 1.717 has been computed using 5 geosynthetics at downstream of the dam slope. The calculated factor of safety is adequate for safety criterion and therefore it may be concluded that under dry conditions the geosynthetics provide adequate safety to the embankment dams.

Resilience of earth dams to seismic events can be improved by using innovative materials and construction techniques specifically tailored to their unique characteristics. Some of the methods deployed for enhancing safety are such as addition of soil stabilization additives such as polymers, fibres and cementitious binders, dynamic compaction techniques, seismic isolation and damping systems. Use of flexible facing systems, such as geosynthetic-reinforced vegetated slopes or articulated concrete blocks, can be done to protect the dam slopes from erosion and slope instability during seismic events. Installation of accelerometers, piezometers, inclinometers, and GPS sensors to monitor ground motion, pore water pressure, deformation, and structural response in real-time might also be fruitful.

Moreover, structure of earth dams can be modified for additional resilience against seismic activity using measures such as toe buttressing, seismic reinforcement and using internal stability measures such as filter layers, geotextiles or construction of upstream face blankets to dissipate seismic energy and improve slope instability[36].

REFERENCES

1. Indian Standards 8826-1978: Guidelines for design of large earth and rockfill dams, Bureau of Indian Standards (BIS), New Delhi.
2. Indian Standards 9429-1999*:* Drainage System for Earth and Rockfill Dams, Bureau of Indian Standards (BIS), New Delhi.
3. Mejia, Lelio and Abbaszadeh, Sam and Armstrong, Richard and Beaty, Michael and Montgomery, Jack 2022, Analysis of Seismic Deformations of Embankment Dams, U S Society on Dams.
4. F, Qin 2023 Simulation analysis of structural nonlinear seismic response, *International Journal for Simulation and Multidisciplinary Design Optimization* **14**,18.
5. Y, Duan, J, Bo, P, Da, Q, Li, W Wan and W, Qi 2023 Analysis of Peak Ground Acceleration and Seismogenic Fault Characteristics of the Mw7.8 Earthquake in Turkey, Applied *Sciences* **11436** 13-20.
6. L, Pagano, A, Desideri and F, Vinale 1998, Interpreting Settlement Profiles of Earth Dams, *Journal of Geotechnical and Geoenvironmental Engineering* **124**, 923–932.

7. A, Zewdu, Belew, D, Yigezu, Tenagashaw, W, Tadesse Ayele and T Gebrie 2021, Modelling of Seepage and Slope Stability Analysis of Ribb Embankment Dam, Preprint (Version 1) available at *Research Square.*
8. GR, Rakhshandehroo, M, Vaghefi and ARH, Zadeh 2011, Three dimensional Seepage Analyses in Mollasadra Dam after Its Impoundments, *Journal of Applied Sciences and Environmental Management*, **15**.
9. AA, Jawad, WH, Hassan and MY, Fattah 2021, Numerical analysis of a zoned earth dam considering hydrodynamic force during the earthquake excitation, *Journal of Physics: Conference Series,* IOP Publishing Ltd.
10. NJH, Al, Mansori, TJM, Al-Fatlawi, NY, Othman and Al, Zubaidi 2020, Numerical analysis of seepage in earth-fill dams, *Civil Engineering Journal* **6**,1336-1348.
11. TK, Nian, GQ, Chen, MT, Luan, Q, Yang and DF, Zheng 2008, Limit analysis of the stability of slopes reinforced with piles against landslide in nonhomogeneous and anisotropic soils, *Canadian Geotechnical Journal* **45**,1092-1103.
12. HG, Poulos 1995, Design of reinforcing piles to increase slope stability, *Canadian Geotechnical Journal* **32**, 808–818.
13. YJ, Park, MA, Gabr, RH, Borden, KJ, Kim and CA, Kreider 2007, Limit equilibrium and deformation analyses of a geogrid-reinforced embankment, *Geosynthetics in Reinforcement and Hydraulic Applications* **1-12**.
14. MI, Onur, M, Tuncan, B, Evirgen, B, Ozdemir and A Tuncan 2016, Behavior of Soil Reinforcements in Slopes, *Procedia Engineering*, *Elsevier Ltd* 2016,483–489.
15. DR, Shiwakoti, TBS, Pradhan and D, Leshchinsky 1998, Performance of geosynthetic-reinforced soil structures at limit equilibrium state, *Geosynth Int* **5**,555-587.
16. SK, Sarma 1981, Seismic Displacement Analysis of Earth Dams, *Journal of the Geotechnical Engineering Division* **107**,1735-1739.
17. A, Shojaeian and F, Askari 2020, Seismic Reliability Investigation of Bearing Capacity of Foundations Based on Limit Analysis and Limit Equilibrium Methods, *Geotechnical and Geological Engineering,* **38**, 6329–6342.
18. BA, Zeidan, M, Shahien and M, Elshemy 2017, Combined Seepage and Slope Stability Analysis of Failed Earthen Dams.
19. G, Kheiri, H, Javdanian and G, Shams 2020, A numerical modeling study on the seepage under embankment dams, *Model Earth Syst Environ* **6**, 1075–1087.
20. GA, Fenton and DV, Griffiths 1996, Statistics of Free Surface Flow through Stochastic Earth Dam, *Journal of Geotechnical Engineering* **122**, 427–436.
21. KB, Jyothi and UK, Singh 2023, Static and pseudo-static stability analysis of right earthen embankment of Nagarjuna Sagar dam by GeoStudio, *E3S Web of Conferences*, EDP Sciences.
22. H, Javdanian, M, Zarei and G, Shams 2023, Estimating seismic slope displacements of embankment dams using statistical analysis and numerical modeling, *Model Earth Syst Environ* **9**, 389–396.
23. Srinivas, C, Padmavathi M 2021, Static and Dynamic Analysis of Nailed Slope, *Proceedings of the Indian Geotechnical Conference 2019. Lecture Notes in Civil Engineering,* **133.**
24. RK, Pathak, G, Kumar Chaturvedy and UK, Pandey 2023, Geotechnical Behaviour of Sandy Soil Mix with Rubber Crumb, *Recent advances in Civil, mechanical and Electrical Engineering*,335-343.
25. Niroumand, Hamed and Kassim, Khairul and Ghafooripour, Amin and Nazir, Ramli 2012, The Role of Geosynthetics in Slope Stability, *Electronic Journal of Geotechnical Engineering* **17**, 2739-2746.
26. T, Viveka, NS, Kumar and KS, Chamberlin 2021, Stabilization of Slopes of Sandy Soils by Using Geosynthetics, *IOP Conf Ser Mater Sci Eng,*1197.

27. E, Taniguchi, RV, Whitman and WA, Marr 1983, Prediction of earthquake-induced deformation of earth dams, *Soils and Foundations* **23**, 126–132.
28. D, Roy and R, Singh 2009, Estimation of Earthquake-Induced Crest Settlements of Embankments, *American Journal of Engineering and Applied Sciences* **2**, 515–525.
29. A, Fakhari and A, Ghanbari 2013, A simple method for calculating the seepage from earth dams with clay core, *Journal of Geo Engineering, Taiwan Geotechnical Society* **8**, 27–32.
30. J, Zhang, X, Chen, J, Li and S, Xu 2023, Seismic Response of Earth-Rock Dams with Innovative Antiseepage Walls on the Effect of Microscopic Fluid-Solid Coupling*, Sustainability Switzerland*, **15.**
31. L, Pagano, E, Fontanella, S, Sica and A, Desideri 2010, Pore water pressure measurements in the interpretation of the hydraulic behaviour of two earth dams, *Soils and foundations* **50**, 295–307.
32. S, Widodo 2015, Case Study on High Multi Slope Embankment reinforced by Geosynthetics, *Seminar National HATTI.*
33. B, Beiranvand, T, Rajaee and M, Komasi 2024, Spatiotemporal clustering of dam settlement monitoring using precision instrument data, *Results in Engineering* **22**.
34. A, Di Pasquale, G, Nico, A, Pitullo and G, Prezioso 2018, Monitoring strategies of earth dams by ground based radar interferometry: How to extract useful information for seismic risk assessment, *Sensors Switzerland*,18.
35. HT, Al, Hudaib and RP, Ray 2023, The Methodologies and Main Challenges of Assessment the Multi-Hazard Interaction and Risk Management Associated with Roads Infrastructures and Dam Safety: A Review*, International Journal of Integrated Engineering* **15**,174-188.
36. Schwager, Markus 2023, Simplified seismic safety evaluation of existing small embankment dams, *International Journal on Hydropower and Dams,* 80-85.