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ASIAN JOURNAL OF
SCIENCE AND TECHNOLOGY

ISSN: 0976-3376

Asian Journal of Science and Technology
Vol. 6, Issue 05, pp. 1447-1454, May, 2015

REVIEW ARTICLE

PHREATIC LINE AND PORE PRESSURE STRESSES IN ZONED ROCKFILL DAM

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ARTICLE INFO

Article History:
Received 05th February, 2015
Received in revised form
15th March, 2015
Accepted 25th April, 2015
Published online 31st May, 2015

Key words:
CPE6MP,
ABAQUS,
Embankment,
Propagation.

ABSTRACT

The position of the phreatic surface influences the stability of the earth dam because of potential piping due to excessive exit gradient and sloughing due to the softening and weakening of the soil mass as it touches the downstream slope or intersects it. The phreatic surface should be kept at or below the downstream toe. In this study, finite element software, ABAQUS, is used to determine the phreatic line within the Jebba dam (zoned rockfill dam) with a drainage system in steady-state condition. The dam model was meshed with a 6-node quadratic plane strain triangle elements (CPE6MP). A total of 401 elements and 872 nodes were generated. This study shows that the drain has restrained the phreatic line almost in upstream side of the dam and the downstream side of the dam is free of pore pressure. Following the finite element modelling, the deformations and stress distributions were determined. From the analysis result, it is observed that the central section of the embankment is free from tensile stresses; however, part of the upstream and the region around the berm of the dam body possess some amount of tensile stresses with no drainage system. These are zones of crack propagation. However, these tensile stresses are reduced and eliminated in some region with the introduction of the drainage system. This implies that positive pore water pressure (i.e. higher phreatic line) increases the tensile stresses in the embankment.

INTRODUCTION

Finite element methods have been used for many years with success in the analysis of complex structures and many aerospace structures are designed on the basis of these analysis. The finite element method is ordinarily used for the feature and final design stages if a more exact stress investigation is required. Finite element models are used for linear elastic static and dynamic analyses and for nonlinear analyses that account for interaction of the dam and foundation. The finite element method provides the capability of modelling complex geometries and wide variations in material properties. The stresses at corners, around openings, and in tension zones can be approximated with a finite element model. An important advantage of this method is that complicated foundations involving various materials, weak joints on seams, and fracturing can be readily modelled. Commercial finite element modelling software includes, Abaqus, ANSYS, ADINA and SAP etc. The construction of dams is a significant investment in the basic infrastructure of any nation. The ability of man to store and channel water is of great importance for his existence and development even from ancient times.

The Kainji Dam built in 1968, Jebba Dam built in 1985 and Shiroro Dam built in 1990; a forth dam built at Zungeru, also in Niger state. These are all hydroelectric dams and generate a potential combined power output of 1900 MW (Kainji and Jebba Dam, 2014). The phreatic surface should be kept at or below the downstream toe. The position of the phreatic surface influences the stability of the earth dam because of potential piping due to excessive exit gradient and sloughing due to the softening and weakening of the soil mass as it touches the downstream slope or intersects it (Moayed *et al*., 2012).

Earth Dams

A dam is a barrier that impounds water or underground streams. Dams generally serve the primary purpose of retaining water, while other structures such as floodgates or levees (also known as dikes) are used to manage or prevent water flow into specific land regions. Hydropower and pumped - storage hydroelectricity are often used in conjunction with dams to generate electricity (The BP Statistical Review of World Energy, 2012). The potential functionality and aesthetics of a dam is brought through good design, thorough planning and investigation and appropriate construction techniques (Doherty, 2009).

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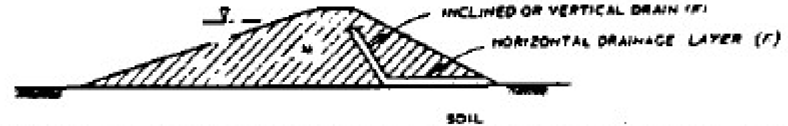
An earth dam is composed of suitable soils obtained from borrow areas or required excavation and compacted in layers by mechanical means. Following preparations of a foundation, earth from borrow areas and from required excavations is transported to the site, dumped, and spread in layers of required depth. The soil layers are then compacted by tamping rollers, sheeps foot rollers, heavy pneumatic-tired rollers, vibratory rollers, tractors, or earth-hauling equipment. One advantage of an earth dam is that it can be adapted to a weak foundation, provided proper consideration is given to thorough foundation exploration, testing, and design (EM, 2004).

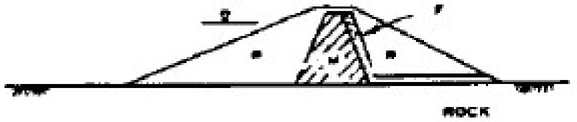
Types of Earth Dam

Some generalized sections of earth dams showing typical zoning for different types and quantities of fill materials and various methods for controlling seepage are presented in Figure 2.1.

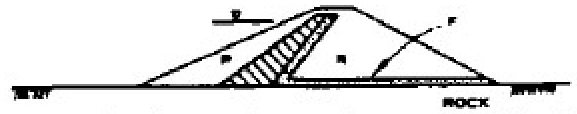
When practically only one impervious material is available and the height of the dam is relatively low, a homogeneous dam with internal drain may be used as shown in Figure 2.1a. The inclined drain serves to prevent the downstream slope from becoming saturated and susceptible to piping and/or slope failure and to intercept and prevent piping through any horizontal cracks traversing the width of the embankment. Earth dams with impervious cores, as shown in Figures 2.1b and 2.1c, are constructed when local borrow materials do not provide adequate quantities of impervious material. For dams on pervious foundations, as shown in Figure 2.1d to 2.1f, seepage control is necessary to prevent excessive uplift pressures and piping through the foundation. The methods for control of underseepage in dam foundations are horizontal drains, cut-offs (compacted backfill trenches, slurry walls, and concrete walls), upstream impervious blankets, downstream seepage berms, toe drains, and relief wells (Walker, 1984).



a. Homogeneous dam with internal drainage on impervious foundation



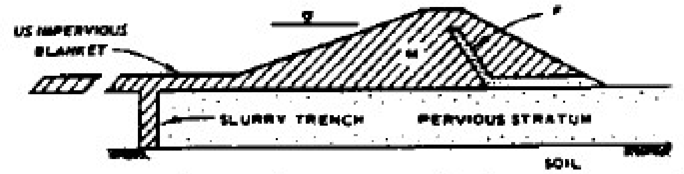
b. Central core dam on impervious foundation



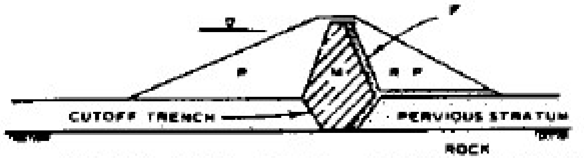
c. Inclined core dam on impervious foundation

LEGEND

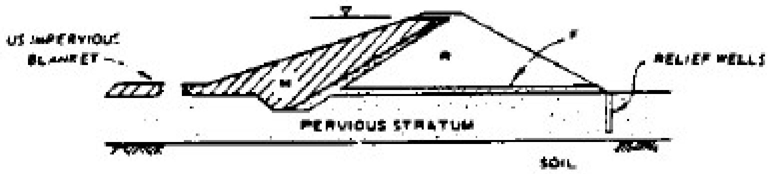
M = IMPERVIOUS
P = PERVIOUS
R = RANDOM
F = SELECT PERVIOUS MATERIAL
US = UPSTREAM



d. Homogeneous dam with internal drainage on pervious foundation



e. Central core dam on pervious foundation



f. Dam with upstream impervious zone on pervious foundation

Figure 2.1 Types of earth dam sections

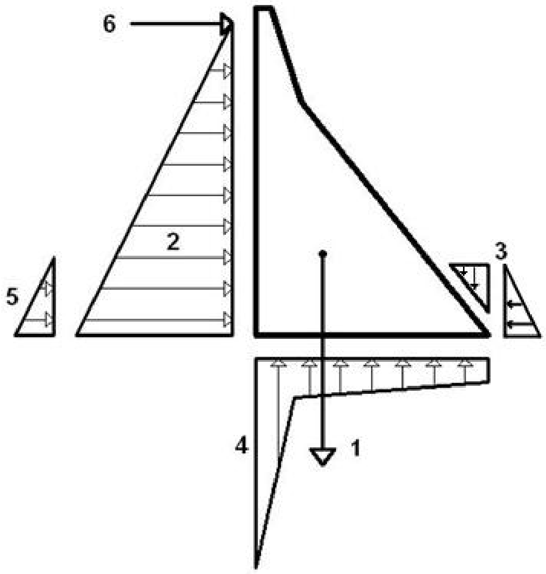


Figure 2.2 Forces acting on a gravity dam: 1. Dead weight, 2. Hydostatic pressure from the Reservoir, 3. Hydrostatic pressure from the Tailwater, 4. Internal hydrostatic pressure, 5. Sand and silt, 6. Ice. Temperature and seismic loads are not displayed in this picture

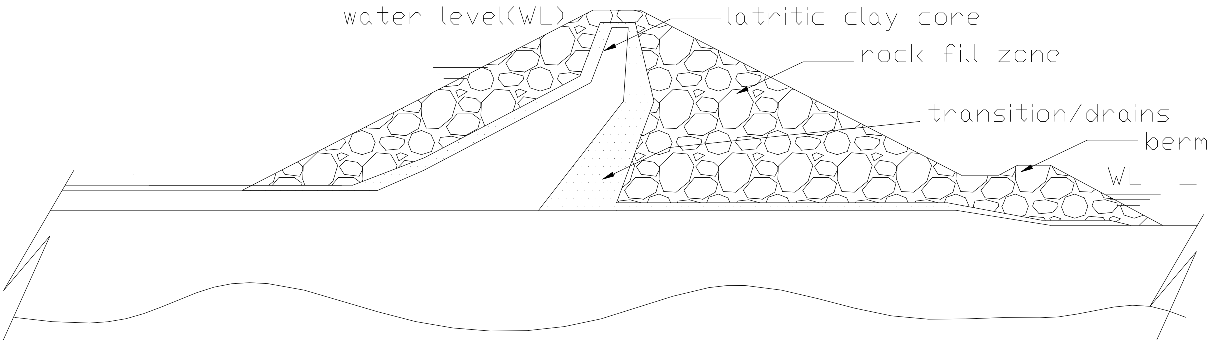


Fig. 3.1: Jebba Main Dam Section

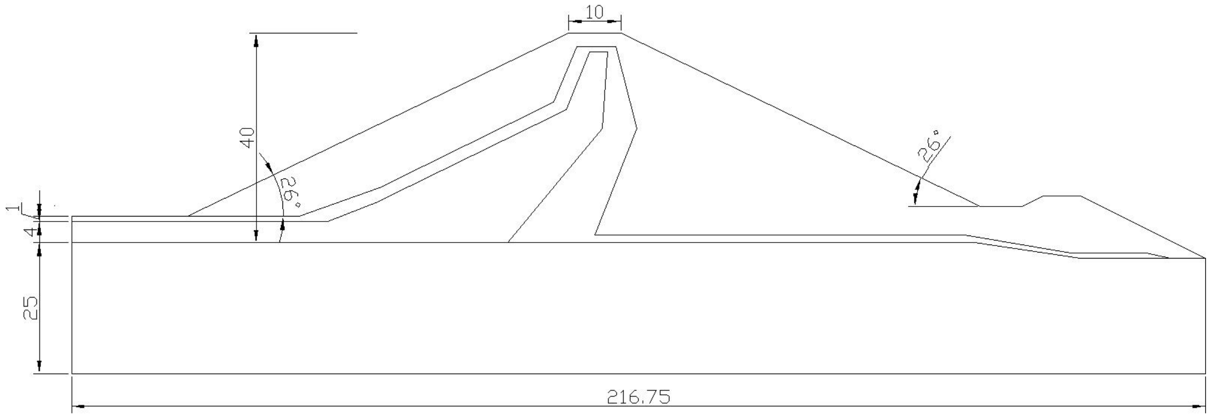


Figure 3.2. Dimensioned Jebba Dam Section

Loads

There are several types of forces acting on dams, the eight that are commonly used are listed and explained in this section. The forces acting on a dam are: Dead weight, Hydrostatic pressure from reservoir, Hydrostatic pressure from tail water, internal hydrostatic pressure (uplift pressure), Sand and silt, Ice, Temperature, Earthquake.

Load Cases

From the loads mentioned above it is possible to create load cases; Usual, Unusual, Extreme. A usual load case occurs often, or even all the time. For example the combination of dead weight, sand and silt load, uplift pressure, hydraulic pressures from reservoir and tail water at a normal level. An unusual load case may be the usual case from above with added ice load and lowest possible temperature.

An extreme load case could be a combination of the worst scenario in all eight load-types, including a nearby earthquake. The reason to use these load cases is to be able to estimate and calculate safety factors, the more usual a load case is, the higher the safety factor should be. This is just an example of how different scenarios can be predicted, in reality these different cases are very thoroughly evaluated, with a lot of different combinations (Boberg and Holm, 2012).

Causes of Failure of Earthen Dams

Earth dams are less rigid and hence more susceptible to failure[9]. Earthen dams may fail, like other engineering structures, due to improper designs, faulty constructions, lack of maintenance, natural causes etc. The various causes leading to the failure of earthen dams can be grouped into the following three classes (Garg, 2006):

- Hydraulic failure
- Seepage failure
- Structural failure

About 40% of earth dam failures have been attributed to hydraulic failure. This failure may occur due to over topping, erosion of upstream face, cracking due to frost action, erosion of downstream face by gully formation and erosion of the downstream toe. Uncontrolled and concentrated Seepage through the dam body or through its foundation may lead to piping or sloughing and the subsequent failure of the dam. More than 1/3rd of earth dams have failed due to these reasons (Garg, 2006). About 25% of the dam failures have been attributed to structural failures (Garg, 2006). Structural failures are generally caused by shear failure, causing sliding.

Phreatic Line in Earth Dams

Line of seepage or phreatic line or saturation line is defined as the line within the dam section below which there are positive hydrostatic pressures in the dam. The hydrostatic pressure on the phreatic line is equal to the atmospheric pressure and hence equal to zero. Above the phreatic line, there is a zone of capillary saturation called capillary fringe, in which the hydrostatic pressure is negative. The appreciable flow through the dam body below the phreatic line, reduces the effective weight of this soil, and thus reduces the shear strength of the soil due to pore pressure. But on the other hand, the insignificant flow through the capillary fringe, leads to greater shear strength, because the capillary tension in water leads to increased intergranular pressure. The effects of the capillary fringe are thus on a slightly safer side and hence neglected.

It is essential to determine the position of the phreatic line, as its position will enable us to determine the following (Garg, 2006):

- It gives us a divide line between the dry (or moist) and submerged soil. The soil above the seepage line will be as dry and the soil below the seepage line shall be taken as submerged for computation of shear strength of soil.
- It represents the top streamline and hence, helps in drawing the flow net.
- The seepage line determination helps to ensure that it does not cut the downstream face of the dam. This is extremely necessary for preventing softening or sloughing of the dam.

The phreatic surface should be kept at or below the downstream toe. The position of the phreatic surface influences the stability of the earth dam because of potential piping due to excessive exit gradient and sloughing due to the softening and weakening of the soil mass as if it touches the downstream slope or intersects it (Moayed *et al*., 2012). About 30% of earth dams had failed due to the seepage failure like piping and sloughing. Recent comprehensive reviews by Foster *et al.* (2000) show that internal erosion and piping are the main causes of failure and accidents affecting embankment dams; and the proportion of their failures by piping increased from 43% before 1950 to 54% after 1950. The sloughing of the downstream face of a homogeneous earth dam occurs under the steady-state seepage condition due to the softening and weakening of the soil mass when the top flow line or phreatic line intersects it. Steady seepage develops after a reservoir pool has been maintained at a particular elevation (e.g., maximum storage pool) for a sufficient length of time to establish a steady line of saturation through the embankment. The seepage forces which develop in the steady state condition act in the downstream direction.

Methods of Seepage Control

All earth and rock-fill dams are subject to seepage through the embankment, foundation, and abutments. Seepage control is necessary to prevent excessive uplift pressures, instability of the downstream slope, piping through the embankment and/or foundation, and erosion of material by migration into open joints in the foundation and abutments. The purpose of the project, i.e., long-term storage, flood control, etc., may impose limitations on the allowable quantity of seepage. The three methods for seepage control in embankments are flat slopes without drains, embankment zonation, and vertical (or inclined) and horizontal drains. The methods of control of underseepage in dam foundations are horizontal drains, cutoffs (compacted backfill trenches, slurry walls, and concrete walls), upstream impervious blankets, downstream seepage berms, relief wells, and trench drains (EM, 2004).

MATERIALS AND METHODS

Finite Element Method

The Finite Element Method (FEM) is a key technology in the modelling and simulation of advanced engineering systems. The behaviour of a phenomenon in an engineering system depends upon the geometry or domain of the system, the property of the material or medium, and the boundary, initial and loading conditions.

Abaqus

Abaqus is a product of Dassault Systèmes Simulia Corp., Providence, RI, USA. It is an indispensable software package due to its abilities of dealing with nonlinear problems. An Abaqus model is composed of several different components that together describe the physical problem to be analysed and the results to be obtained. At a minimum the analysis model consists of the following information: discretized geometry, element section properties, material data, loads and boundary conditions, analysis type, and output requests.

Jebba Hydroelectric Power Station

The Jebba Dam, which was constructed between 1979 and 1984 and commissioned in 1984, has the following feature (NEPA, 1977):

- Normal maximum reservoir operating level -- 103.0m
- Minimum reservoir operating level---------------- 99.0m
- Reservoir draw-down--------------------------------- 4.0m
- Reservoir full supply capacity------------ 3.880 x $10^9 m^3$
- Minimum reservoir capacity-------------- 2.880 x $10^9 m^3$
- *Reservoir flood level---------------------------------- 106m*
- Length of reservoir------------------------------------ 100km
- Width of reservoir------------------------------------- 2-5km
- Average reservoir run-off---------------- 25billion.m^3/day
- Flood control structure----------------

- 6 gates underflow spillway
- Emergency spillway wal
    - Navigation canal-------------------- incorporated
    - Installed generating capacity---------------- 560MW

Modelling the Dam (2-D Plane Strain Assumption)

A three –dimensional problem can be simplified if it can be treated as a two- dimensional (2D) solid. According to Timoshenko and Goodier, 1951, if a long cylindrical or prismatical body is loaded by forces which are perpendicular to the longitudinal elements and do not vary along the length, it may be assumed that all cross sections are in the same condition. The state of plane strain occurs in members that are not free to expand in the direction perpendicular to the plane of the applied loads. If we assume that the applied loads lie in the x-y plane, then w, the displacement in the z-direction is zero and the displacements u and v are functions of only x and y. This set of displacements makes $e_{zz}, e_{xz}, and\ e_{yz}$ each zero. The dam was represented as a 2D solid, where one coordinate (z-axis) was removed. Coupled pore fluid plane strain analysis was used in this dam model. External forces were applied only in the x-y plane.

Material and Section Properties

Material Sources

The embankment materials were all obtained from the vicinity of the dam site. Rockfill material was processed from the rock (gneiss) excavated for the structures while the impervious material was taken from an area located 7km northeast of the construction site (Osuji and Anyata, 2005). The material properties are given in Table 3.1.

Alluvial Foundation

The alluvial foundation underlying the main dam and impervious blanket comprises mostly uniformly graded fine to medium coarse-grained clean quartzitic sands with traces of fine gravel of low to medium high density. This river alluvium is primarily water and / or wind deposited sand. The main dam area was densified by vibro compaction and partially by blasting (Osuji and Anyata, 2005).

Impervious Blanket and Core

The impervious blanket extends some 450m upstream from the upstream toe of the main dam and forms an impervious lining over the foundation sand. It is a continuation of the inclined core and serves to reduce both the quantity of downstream seepage and the uplift pressure under the dam. This medium plastic material consists of lateritic silty sandy clay and has a permeability ranging from $1*10^{-8}$ to $5.1*10^{-6}$cm/s.

Assumptions

To facilitate the transportation of an actual cross-section of a dam to an idealized computer model of the dam, the following assumptions were made.

- The foundation bedrock is considered incompressible and thus becomes the lower limit of the element mesh. Also, the end of 25m densified foundation forms the limit of the element mesh.
- The transition and rockfill materials were assigned the same material properties while the impervious core and the alluvial foundation zones were all considered as distinct material types and as such assigned unique material properties.

Table 3.1. Material Input Parameters

Zone	Construction Material	Shear strength (kPa)	Angle of friction ϕ	Unit weight γ (N/m^3)	Modulus of Elasticity, E (N/m^2)	Shear strength parameter $c^{/}$	Permeability (m/s)	Void ratio
1	Compacted Impervious Fill	34.03	25	1900	25.00E6	11.66	10^{-7}	1.0
2	Filter and Transition Material	0.00	38	1700	64.22E6	0.0	10^{-2}	0.3
3	Compacted Gneiss	0.00	38	1700	64.22E6	0.0	10^{-2}	0.3
4	Alluvial sand (foundation)	0.00	36	1700	53.00E6	0.0	10^{-4}	0.4

Defining the Model Geometry

The dam model was drawn in AutoCAD and then converted to Standard ACIS Text file (.sat extension). This file was then imported as the Abaqus Part model.

Due to the zoned design of the structure and the provision of inclined upstream impervious core, the elements were chosen to reflect the material differences. The elements transiting between materials were made to have their boundaries forming the transiting boundary.

Loads and Boundary Conditions

Forces can be static and/or dynamic. Statics deals with the mechanics of solids and structures subjected to static loads such as the dead weight of the structures. Structures will experience vibration when subjected to dynamic forces varying with time, such as seismic forces generated by an earthquake (Alsuleimanagha and Liang, 2012). The dead weight shall be assigned to the whole earth dam and created by using the mass of the earth dam and the acceleration of -10.0 m/s in the y direction. The upstream face of the dam is exposed to water in the reservoir behind the dam. Since Abaqus uses a total pore pressure formulation, the pore pressure on this face must be prescribed to be $u_w = (H_1 - y)g\rho_w$, where H_1 is the elevation of the water surface, y is elevation, g is the gravitational acceleration, and ρ_w is the mass density of the water. ($g\rho_w$, the weight density of the water, must be given as the value of the specific weight of the wetting fluid as part of the definition of material permeability.) It was assumed that no deformation occurs at the base of the 25m densified foundation.

Meshing the Model

In order to perform 2D finite element analyses, the model was discretized into basic quadrilateral and triangle elements. The dam model was meshed with the 6-node quadratic plane strain triangle (CPE6MP**).**

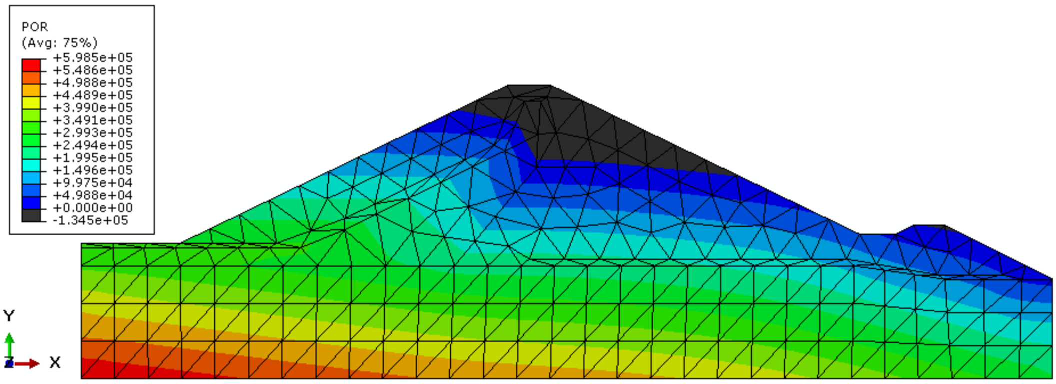


Figure 4.1a Phreatic Line within the Earth Dam with no Drainage System

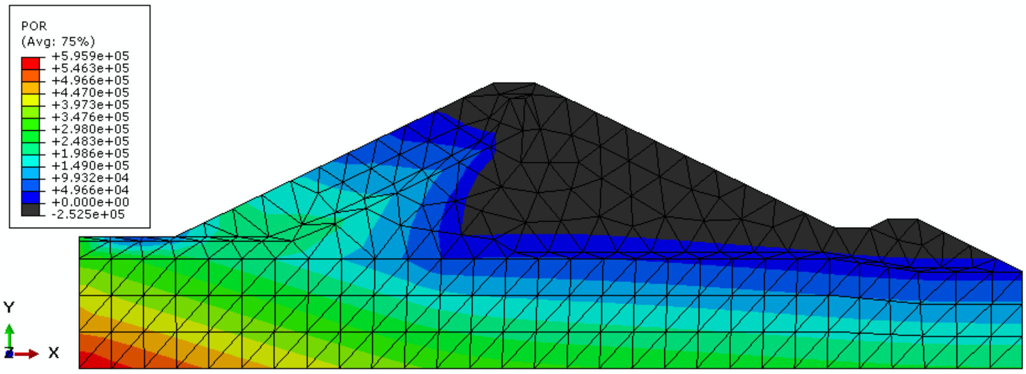


Figure 4.1b Phreatic Line within the Earth Dam with Drainage System

RESULTS AND DISCUSSION

Figures 4.1a and b show the phreatic line within the earth dam that has or has not drainage system. It can be observed from Figure 4.1a that the phreatic surface would intersect the downstream slope if no drainage is installed and the flow lines will reach the downstream face. Figure 4.1b shows the phreatic line within the earth dam with a filter drain around the core, extending towards the base of the upstream and downstream of the dam section. This figure shows that the drain has restrained the phreatic line almost in upstream side of the dam and the downstream side of the dam is free of pore pressure. Seepage is the continuous movement of water from the upstream face of the dam toward its downstream face. The upper surface of this stream of percolating water is known as the phreatic surface. The phreatic surface should be kept at or below the downstream toe. The filter design for the drainage layers and internal zoning of a dam is a critical part of the embankment design. It is essential that the individual particles in the foundation and embankment are held in place and do not move as a result of seepage forces. This is accomplished by ensuring that the zones of material meet “filter criteria” with respect to adjacent materials. Where a large carrying capacity is required, a multilayer drain should be provided (EM, 2004). Figure 4.2a & b shows the maximum principal stresses in the dam. Positive maximum principal stresses (tensile stresses) occur predominantly around the upstream of the dam and slightly around the berm, a maximum value of 0.4888N/mm^2 for the model with no drainage system. However this value (0.3824N/mm^2) is less for the model with drainage system. The minimum principal stresses in the dam (Figure 4.2c and d) are mainly compressive stresses (negative). However positive minimum principal stress (tensile stress) value of 0.1836N/mm^2 occurs in the model with no drainage system and 0.1722N/mm^2 in the model with drainage system (a lower value).

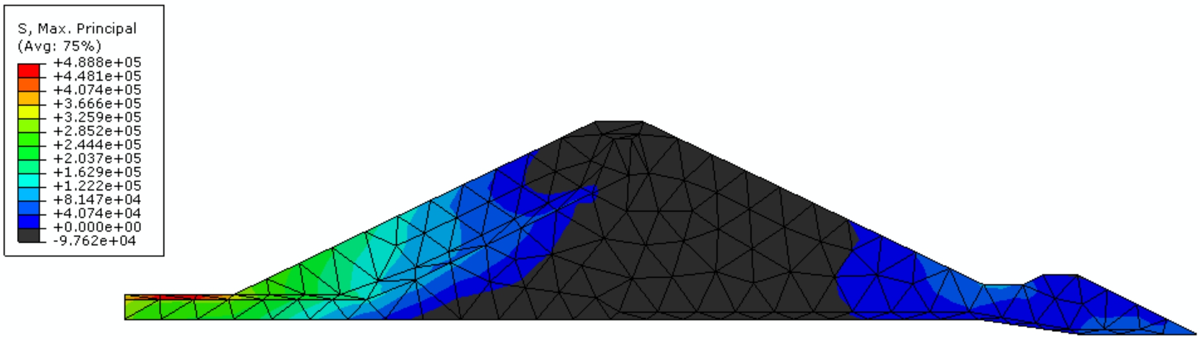


Figure 4.2a. Maximum principal stress distributions in the embankment with no drainage system

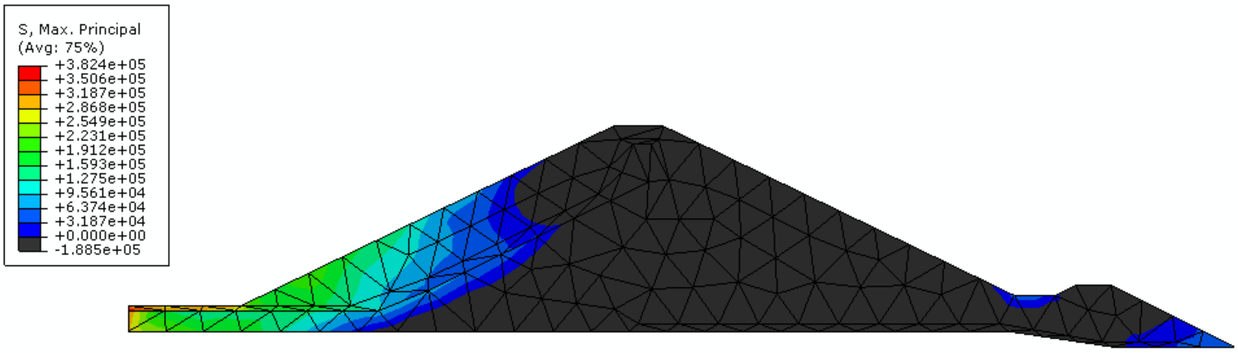


Figure 4.2b. Maximum principal stress distributions in the embankment with drainage system

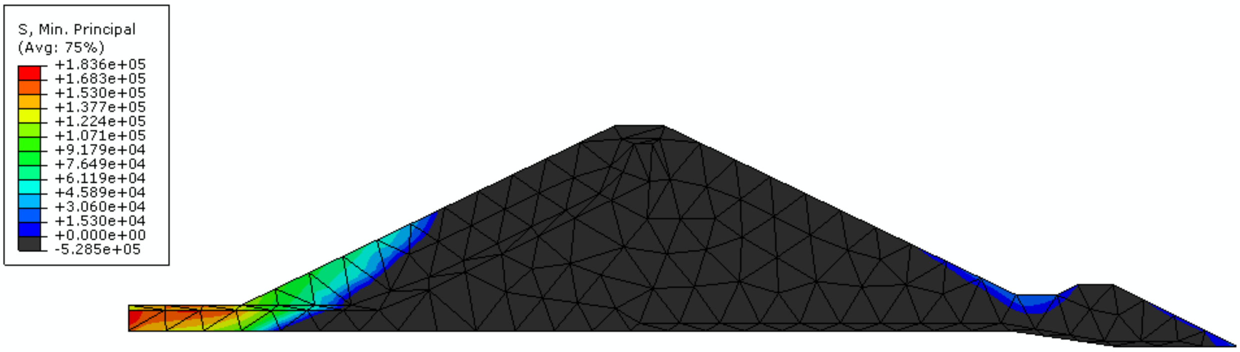


Figure 4.2c. Minimum principal stress distributions in the embankment with no drainage system

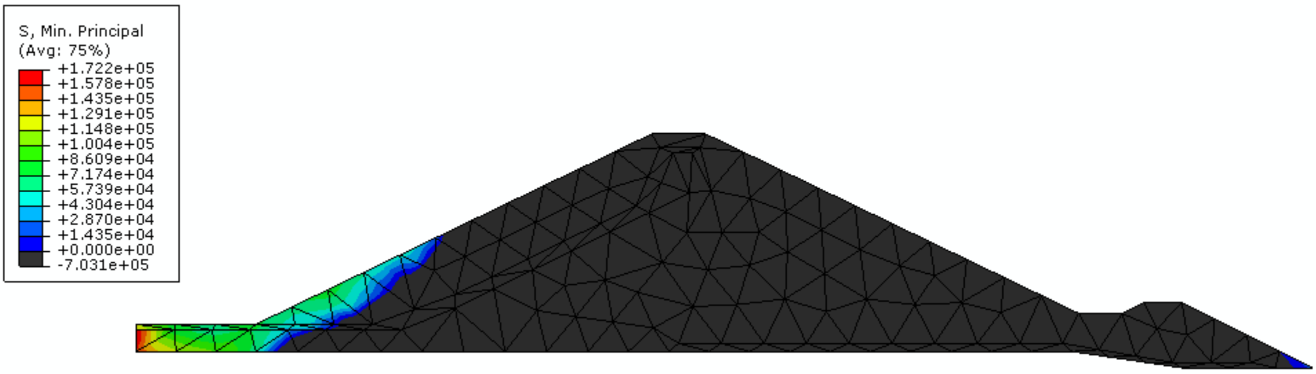


Figure 4.2d. Minimum principal stress distributions in the embankment with drainage system

Following the finite element modelling, the deformations and stress distributions were determined. From the analysis result, it is observed that the central section of the embankment is free from tensile stresses; however, part of the upstream and the region around the berm of the dam body possess some amount of tensile stresses with no drainage system. These are zones of crack propagation. However, these tensile stresses are reduced and eliminated in some region with the introduction of the drainage system. This implies that positive pore water pressure (i.e. higher phreatic line) increases the tensile stresses in the embankment.

Conclusions

All earth and rock-fill dams are subject to seepage through the embankment, foundation, and abutments. Seepage control is necessary to prevent excessive uplift pressures, instability of the downstream slope, piping through the embankment and/or foundation, and erosion of material by migration into open joints in the foundation and abutments. The phreatic surface should be kept at or below the downstream toe. This study shows that the drain has restrained the phreatic line almost in upstream side of the dam and the downstream side of the dam is free of pore pressure. Following the finite element modelling, the deformations and stress distributions were determined. From the analysis result, it is observed that the central section of the embankment is free from tensile stresses; however, part of the upstream and the region around the berm of the dam body possess some amount of tensile stresses with no drainage system. These are zones of crack propagation. However, these tensile stresses are reduced and eliminated in some region with the introduction of the drainage system. This implies that positive pore water pressure (i.e. higher phreatic line) increases the tensile stresses in the embankment.

Recommendations

Based on these findings, the following recommendations are relevant:

- There is need for maintenance of the monitoring or measuring instruments at the Jebba dam and for continuous check and repair of cracks in the dam. This is because the collapse of such structure will be catastrophic.
- The drainage system of the dam should be well monitored and serviced to ensure good performance and restraining of the phreatic line to the upstream of the dam.

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