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Finite element steady state seepage analysis of Kubanni reservoir in Ahmadu Bello University, Zaria, Nigeria

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Abstract
The increase in pore water pressures related to the development of the steady state seepage condition result in an associated decrease in effective stress in the soil of the dam embankment. In this paper, the finite element procedure of seepage analysis method is employed to determine the quantity of seepage flow that passes through an earth dam. The fluctuations of the water level in the kubanni reservoir were used to compute the variation of the seepage value at downstream face caused by increase in depth of the water at the upstream face of the embankment. At the upstream depth of 7.5m high, the total seepage water rate at downstream has been determined to be -0.0642m³/day/m2. The model is established for easy analysis of seepage with different variation of water depth.

Keywords: seepage, Kubanni, element, Zaria, pressures

1. Introduction

The major causes of failure of earth dams can be seepage, piping, foundation instability, deformation and deterioration, and from earthquakes. However, most of the recorded failures around the world are related to seepage problems. The variation of the water depth on the upstream face of the embankment of a dam will leads to saturation and unsaturation of the different regions of the embankment. This will ultimately cause the variation of the degree of saturation, seepage and affect the stability of the embankment. The analysis of flow through saturated and unsaturated soils using numerical models is a highly nonlinear problem that requires iterative techniques to obtain solutions. Perri *et al*., (2012) [1] observed that geotechnical practice has long recognized that increases in pore water pressures associated with the development of the steady state seepage condition result in an associated decrease in effective stress in the soil. This brings about the need for control measures that will minimise the impact of seepage through the dam. The measures to be adopted ranges from effective management of foundation cut-offs, impervious zones, transition zones, drainage material and blankets, upstream impervious blankets, adequate core contact area, and relief wells (U.S.A.C.E, 2004).

The seepage analyses methods that range from analytical, experimental and numerical methods are employed to determine the quantity of seepage flow that passes through an earth dam. They can also be used in the analysis of other parameters such as (a) the phreatic line (b) the pore pressures within the dam's cross section and its foundation and (c) the exit gradient at the downstream embankment of the dam.

Furthermore, the analytical methods comprises Dupuit, Casagrand, conformal mapping and others which were applied by researchers like (Rezk and Senoon, 2012; Rezk and Abo Elela 2015) [6, 7]. While experimental methods employs permeability tank approach as carried out by Passey *et al*., 2006 [1]; Djehiche *et al*., 2014 [9]; and Sachpazis, 2014 [10].

The numerical method uses finite element and finite difference models. These numerical models were used in solving the governing equations of flow through a zoned embankment of an earth dam (Fattah *et al.*, 2014) [11]; the stability and seepage of an earth dam under rapid drawdown condition were analysed by Tung *et al.*, (2015) [12] using sheet piles. They presented the amount of seepage, exit gradient, hydraulic gradient and pressure head of zoned earth dams by considering different values of core permeability and core thickness (Khassaf and Madhloom, 2017) [13]. Mouyeaux *et.al.* (2019) [14] performed a probabilistic analysis of pore water pressures based on field data to represent the permeability with a 2D random field model based on the Finite Element Method (FEM) to establish from statistical and geostatistical analysis and study the influence of the spatial variability of permeability on pore water pressure using Monte-Carlo simulations (MCS).

A major advantage of numerical modelling being that it utilises computer software which consumes less time as compared to experimental methods that require physical settings.

Dam structures are designed to retain surface water and limit water losses and pore-pressures through the embankment. The requirement of the design is complicated by the operation of dam under changing water levels. Therefore, the main aim of this study is to model and analyse the steady state seepage condition under drawdown of an earth dam (Kubanni Dam as a case study) through the application of finite element numerical model software (SEEP/W). The software uses phreatic surface and any other flow that might have existed in the capillary zone above the phreatic line as an upper boundary. The fluctuations of the water level in the reservoir were used to compute the variation of the seepage value at downstream face caused by increase in depth of the water at the upstream face of the embankment by employing a finite element procedure. This leads to the numerical model that can be used to analyse almost any kind of seepage problem.

2. Theoretical Background

The seepage through a heterogeneous, anisotropic, saturated-Unsaturated soil can be analysed by using a partial differential equation derived based on the principle of conservation of mass written as equation 1.

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right)=m_v\left(\frac{\partial h}{\partial t}\right)\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$$

Where, h is the pressure head causing the flow, and k_x, k_y and k_z are the coefficients of permeability in x, y and z directions respectively. M_v is the water storage (slope of the soil-water characteristic curve).

However, in the case of homogeneous soil deposits and anisotropic media equation 1 can be modified as equation 2.

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)=0\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$$

This is Laplacian equation, which is a special case of the Helmholtz equation, one of the most basic partial differential equation known in mathematics. A graphical solution to this equation is a map of contours of equal potential crossed with flow lines known as a flow net. A flow net is a map of contours of equal potential crossed with flow lines. For the flow net to represent a correct solution to the Laplacian equation, the equipotential lines and flow lines must cross the equipotential lines at right angles. The area between two adjacent flow lines is called a flow channel and the flow in each channel has to carry the same amount of flow.

Several researchers have evaluated the performance of the embankment dams, slopes and similar structures subjected to seepage. However, it was noticed that very few attempts have been made to make quantitative predictions of the amount of steady-state seepage conditions passing through kubanni embankment dam and understand the processes and train the thinking of the researchers in that direction.

2. Description of the Study Area

The Kubanni catchment area is located within the Central High Plains of Northern Nigeria guinea savannah region at approximately 670 m above sea level (Jatau, 1999) [3]. It belongs to the North-eastern part of Kaduna river basin which borders the Chad basin. The Kubanni River takes its source from the Kampagi Hills in Shika near Zaria. The Kubanni River is one of the main tributaries of Galma River; it has its headwaters from Kampagi Hills and flows into the Galma River near Tudun Wada Zaria, passing through the South-eastern direction of Ahmadu Bello University. The Kubanni river flows Southwards in a total length of 21 km into river Galma (Latitude 11° 59.77"N to 11° 08" 29.77N and longitude 07° 34"0.59-0.84"E to 07° 41' 59.84"E) (Figure 1). The River is a seasonal stream flowing at full capacity during the raining season with little surface water along stretches of the river channel in the dry season. The kubanni dam is located along the river at Ahmadu Bello University Main campus.

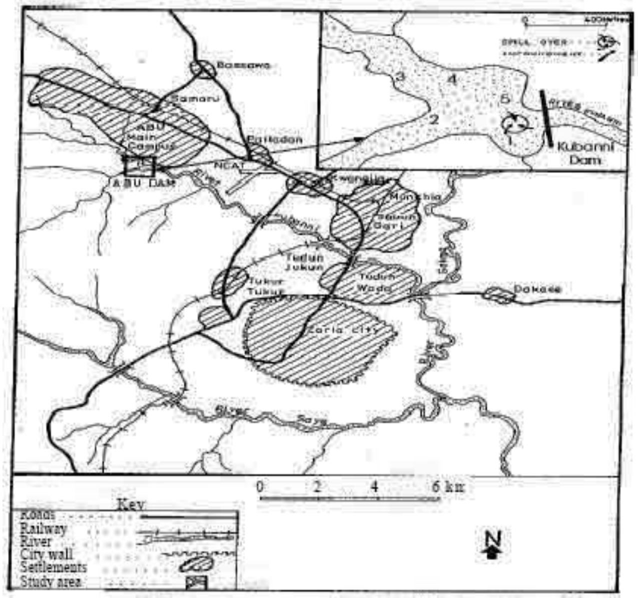

Fig 1: The Kubanni catchment area

The Kubanni earth dam (embankment) retains water of 7.5 m deep over an area of 57.5 Km^2. The Storage capacity of the dam is 2.6 x 10^6 m^3. The length and width of the crest are 800m and 6.0m respectively. The crest elevation of the dam is 646.34m and the normal top water level of the upstream reservoir is 644.81m above mean sea level. The crest elevation of the dam is 646.34m and the normal top water level of the upstream reservoir is 644.81m above mean sea level. The dam has a central spillway

3. Description of the model

The term seepage often is used to describe flow problems in which the dominant driving energy is gravity. The flow through a homogeneous embankment would be an unconfined flow problem in which seepage losses occur from a reservoir to a downstream exit point. Unconfined flow problems were often considered more difficult to analyse because of the determination of the location of phreatic surface which was integral to the analyses. The phreatic surface is the point at which the transition from positive to negative pore water pressures occurs. Transient flow problems such as the advance of a wetting front within an earth structure after rapid filling are typical examples of situations in which it is impossible to simulate field behaviour without correctly considering the physics of flow through unsaturated soils. This research work uses SEEP/W package of the GeoStudio (2018) R2 software to model and analyse the seepage situation of Kubanni dam. The software considered phreatic surface as an upper boundary and any flow that may have existed in the capillary zone above the phreatic line was incorporated into the numerical model so that almost any kind of seepage problem can be analysed. SEEP/W is formulated on the basis that the flow of water through both saturated and unsaturated soil follows Darcy's Law which is shown in equation 3.

$$q=ki\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

Where, q is the specific discharge (or Darcian velocity), k is the hydraulic conductivity and i is the gradient of total hydraulic head.

4. Steady state seepage analysis

The embankment was represented with a single homogeneous Clay material, with very poor drainage. The length and width of the crest are 800 m and 6.0 m respectively. The crest elevation of the dam is 646.34m and the normal top water level of the upstream reservoir is 644.81m above mean sea level. Figure 1 shows the cross-section configuration of the Kubanni dam. The slope of the upstream face is 1(V): 1.8 (H) and the slope of the downstream face is 1(V): 1.4(H). The height of the dam is 10.36m. The cross-section configuration of the dam is shown in Figure 2. A two-dimensional finite element mesh pattern model of the dam, which contains 271 nodes represented as dots and 232 elements, is created based on the dam structure is shown in Figure 3.

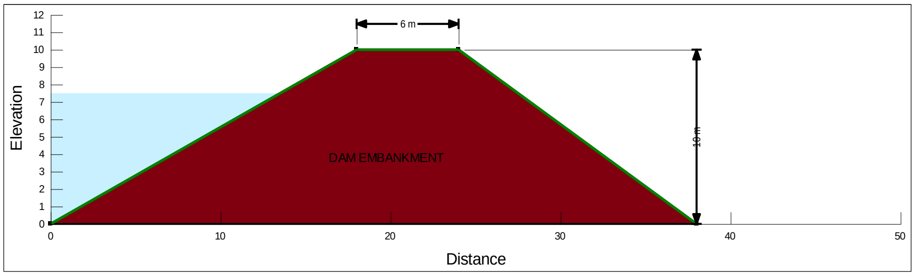

Fig 2: The cross-section configuration of the Kubanni dam

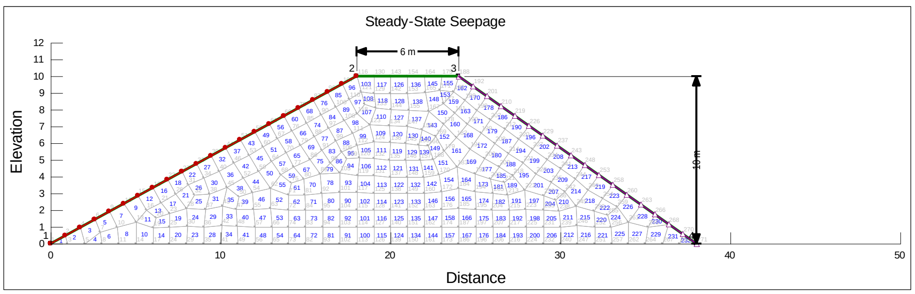

Fig 3: A two-dimensional finite element mesh pattern for the model of the dam

The sample material method was used in the analysis, by considering spatial variability of permeability using field data. The material selected based on the investigation of field conditions is found to have dominant saturated water content of 0.5. Figure 4 shows the graph of volumetric water content function parameters used in the simulation of the model and the dam materials.

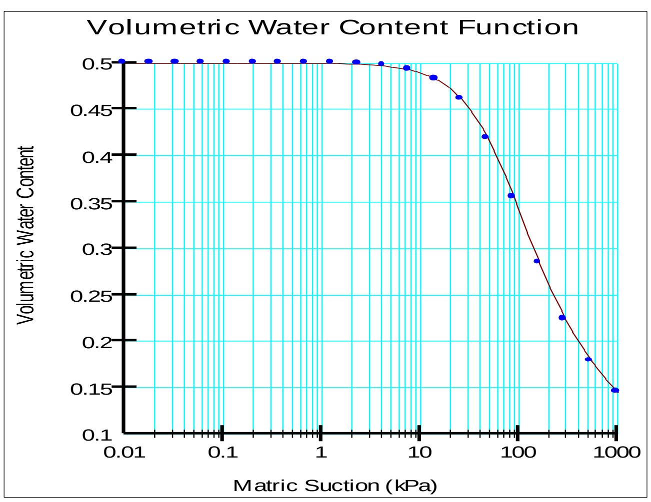

Fig 4: The graph of volumetric water content of the embankment material

The proposed equation of Van Genuchten (1980) was used as hydraulic conductivity function through the embankment material. The equation has four-parameter as a closed form solution for predicting the volumetric water content function as shown in equation 4.

$$\Theta_w = \Theta_r + \frac{\Theta_s - \Theta_r}{\left[1+\left(\frac{\Psi}{a}\right)^n\right]^m} \dots\dots\dots\dots\dots\dots\dots \quad (4)$$

Where: Θw is the volumetric water content, Θs is the saturated volumetric water content, Ψ is the negative pore-water pressure, and a, n, m are curve fitting parameters

The total seepage Water Rate (m³/sec) of different reservoir level from 1.0m to 7.5m was analysed using SEEP/W software package as a tool. The SEEP/W computes the hydraulic gradients and Darcian flow velocities at each of the integration points within each element in the nodal heads.

5. Discussion of Result

The flow vectors, which provide a direction and rate of seepage flow through the embankment along with the location of phreatic surface, or zero pressure isoline are shown in Figure 5. The relative size of the flow vectors corresponds to the magnitude of the flow velocity. The longest vectors indicate the areas of highest flow rate. Where the flow is extremely low, such as in the crest and upstream toe areas, the vectors become so small that they are not visible. There are vectors also above the zero-pressure line, which represent the flow in the capillary zone.

The vectors reveal the flow out of the domain occurring along the seepage face.

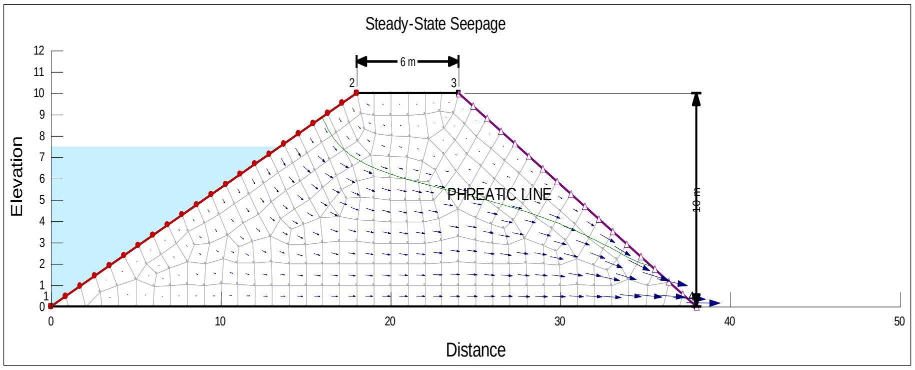

Fig 5: The flow vectors and phreatic line.

To conduct seepage analysis and determine seepage quantities, pressures and forces. The total head contours or equipotential lines are determined as shown in Figure 6. The energy potential along equipotential lines is constant. A seepage face is on the downstream slope The Total water Head contours are displayed in Figure 6, with the flow vectors. The total water head ranges from 0m to 7.5m, with the maximum on the upstream face of the embankment.

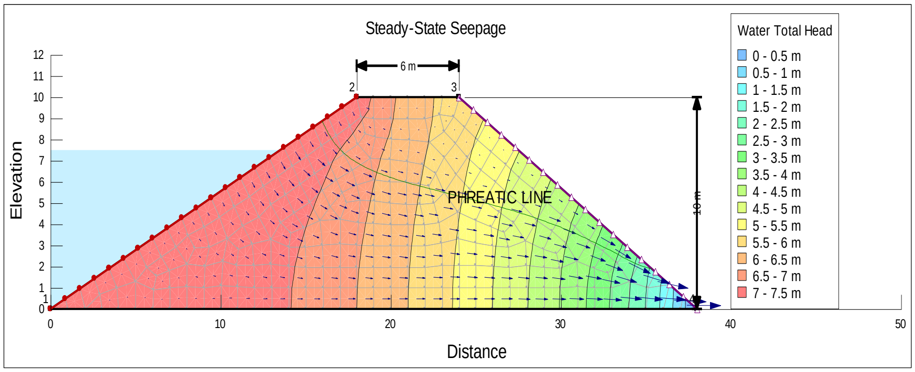

Fig 6: The Total water Head contours, phreatic line and the flow vectors

The water pressure contours of the embankment has a maximum value of 60 to 80 kPa. These values are distributed along the upstream toe of the embankment as shown in Figure 7.

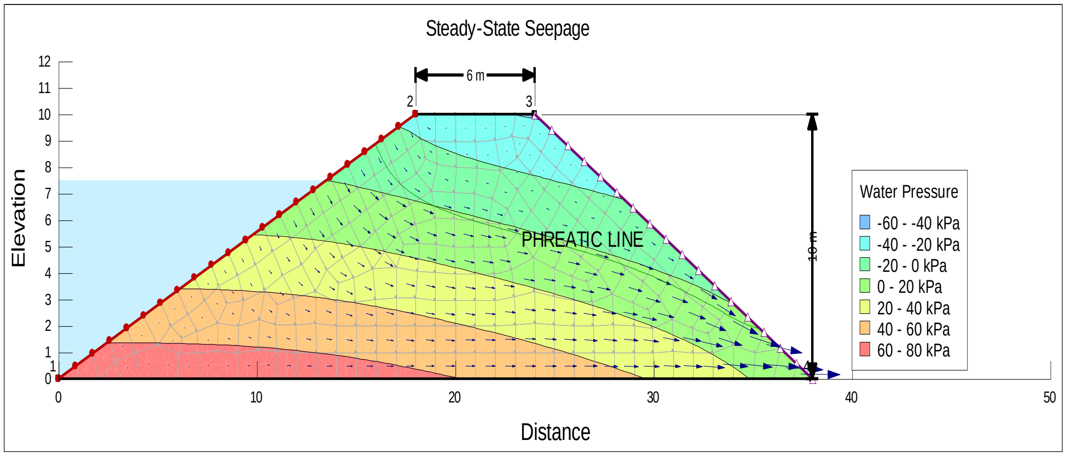

Fig 7: The Water Pressure Contours of the embankment

The graphs of the variation of water pressure along upstream and downstream faces are shown in Figure 8. The graph of upstream face shows a linear increase from -20kPa to 75 kPa, and that of downstream face shows a decrease from 0kPa at the top of the embankment to -42kPa at the distance of 18m on the x-axis or bottom face of the embankment

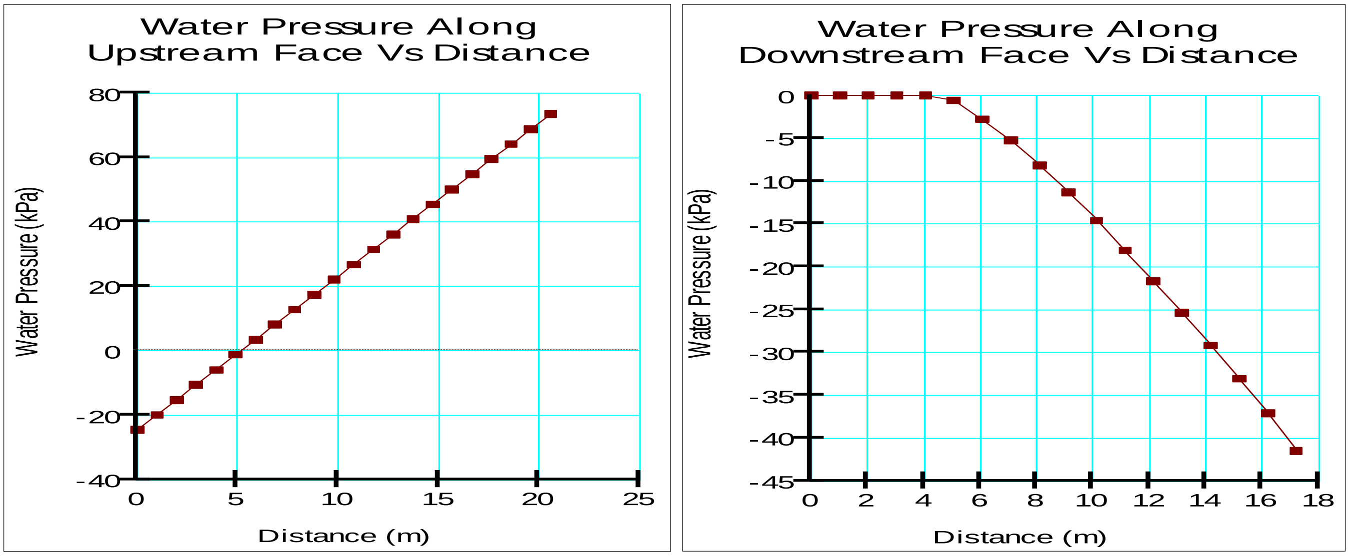

Fig 8: The graph of Water Pressure along the upstream and downstream faces of the embankment

The variation of water pressure head in metres is shown in Figure 9.

This indicates a maximum pressure head of 6 to 8m at the lowest part of the upstream face of the embankment.

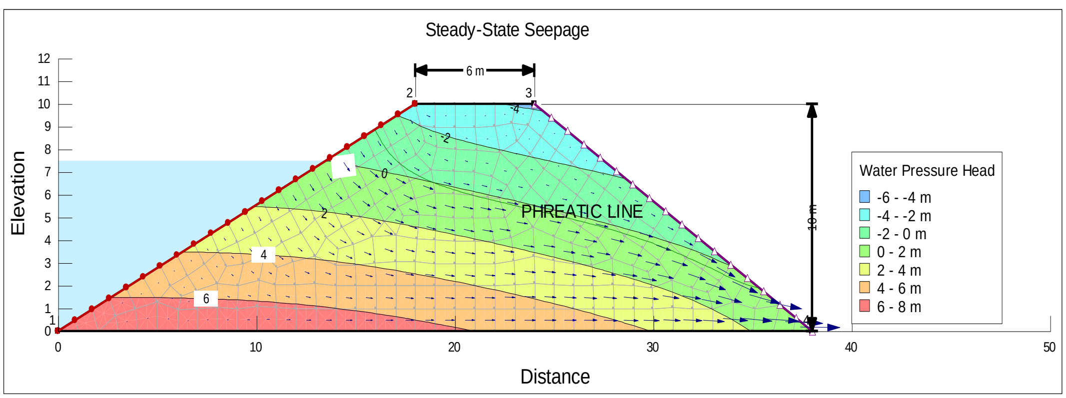

Fig 9: The Water Pressure Head Contours of the embankment in metres

The computation of flow quantities With SEEP/W is done by defining a flux section. Figure 10 shows the water flux contours of the cross-section of the embankment.

This indicates a maximum of (greater than or equal to) 4 x 10^{-7} $m^3/sec/m^2$ water flux at the lowest part of the downstream face of the embankment.

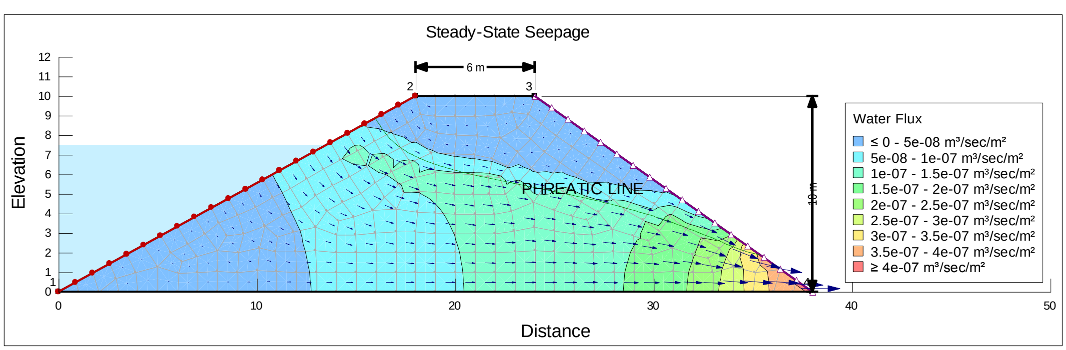

Fig 10: The Water Flux Contours of the embankment

The cumulative water fluxes across the entire upstream and downstream faces of the embankment are 6.745724e-07 and 2.4627461e-06m³/sec/m², respectively.

Figure 11 shows the graphs of Water Fluxes along the upstream and downstream faces of the embankment.

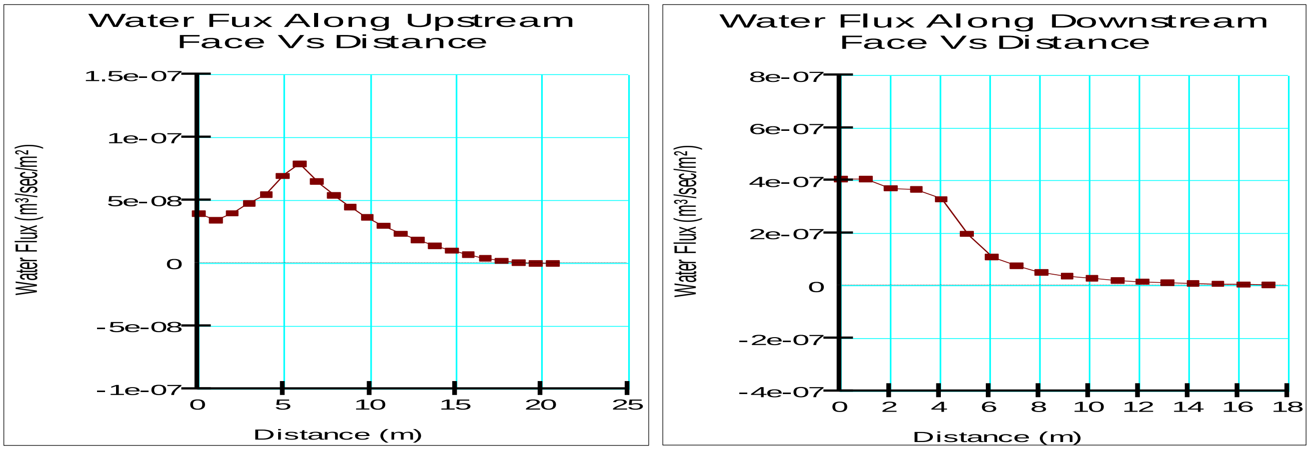

Fig 11: The graph of Water Fluxes along the upstream and downstream faces

The degree of saturation contours of the embankment is shown in Figure 12,

With maximum of greater than 0.98 over the largest portion of the embankment.

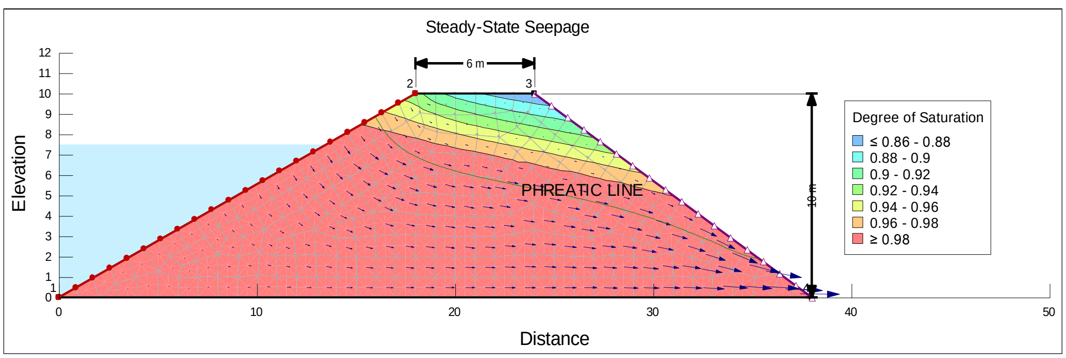

Fig 12: The Degree of saturation Contours of the embankment Material

Figure 13 shows the graphs of degree of saturation along the upstream and downstream faces of the embankment. The upstream face shows tha variation from 0.928 to 1.0 at the horizontal distance of 5m from upper part of the face. The downstream face shows the variation from 0.86 to 1.0.

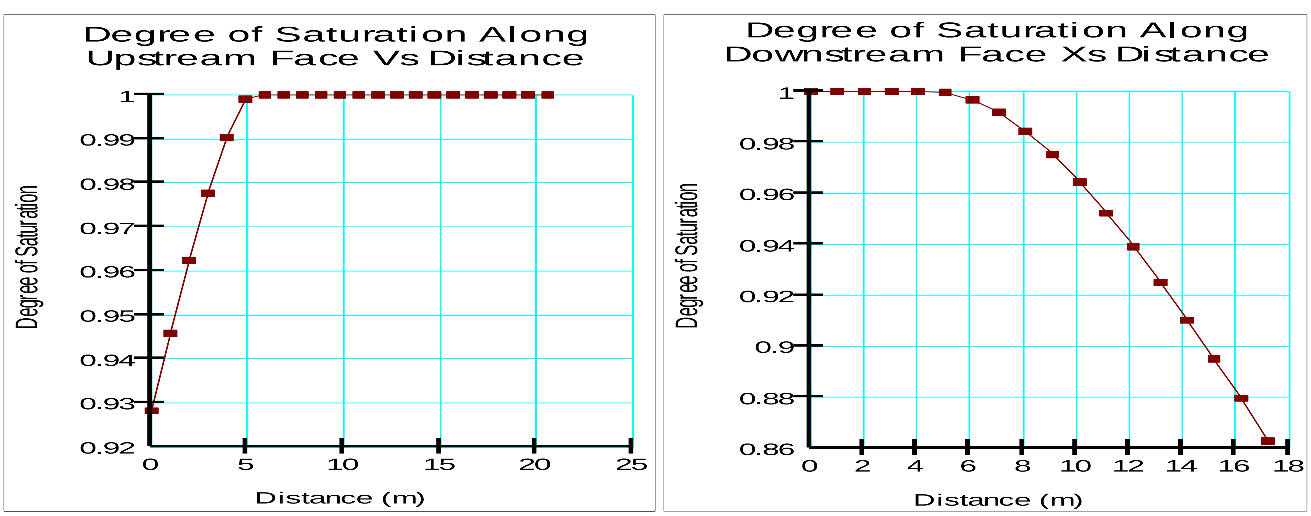

Fig 13: The Degree of Saturation along the upstream and downstream faces of the embankment

Figure 14 shows the graphs of total water flow rate along the upstream and downstream faces of the embankment. The upstream face shows tha maximum of 1e-07 m^3/sec/m2 at the horizontal distance of 5m from upper part of the face, the positive value is indicating suction of water in to the embankment. The downstream face shows the highest negative value of 2.46e-07m^3/sec/m^2, the negative sign indicates that the water is going out of the embankment.

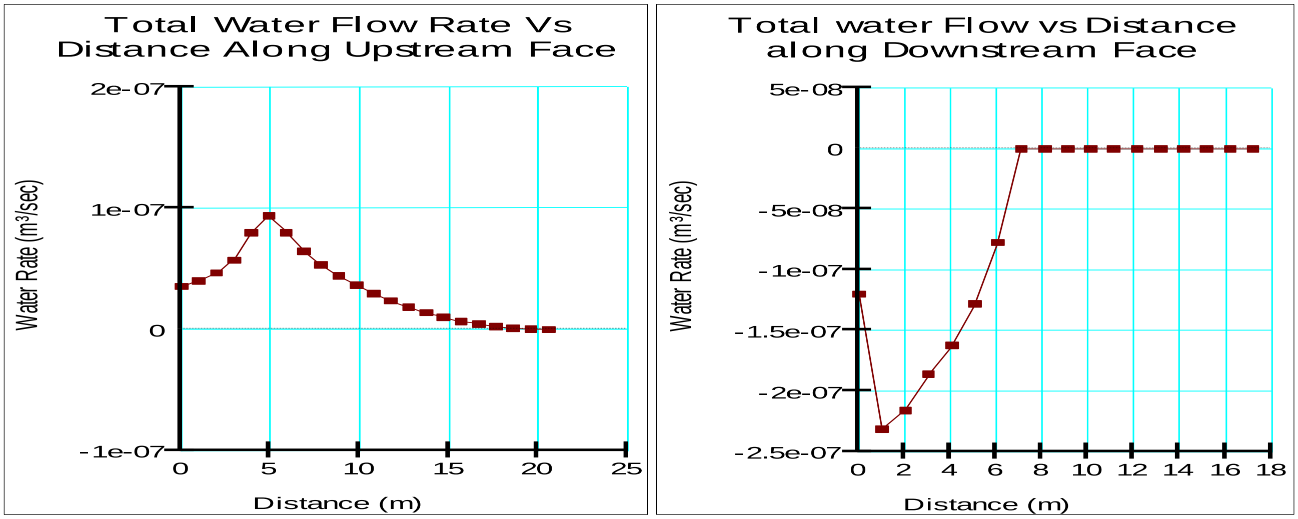

Fig 14: The Total Water Flow Rate along the upstream and downstream faces of the embankment

When the depth of water at the upstream side of the embankment is 7.5m high, the total seepage Water Rate at the downstream face is -7.44e-07m^3/sec/m^2. The negative sign indicates flow is occurring out of the domain. This is equal to -0.0642m^3/day/m^2. In one year period the total water loss due to seepage will be 23.43m^3/annum/m^2. While, the total seepage Water Rate at the downstream face is -6.40e-07m^3/sec/m^2 at the depth of water at the upstream side of the embankment changes to 7.0m high,. This is equal to 0.0553m^3/day/m^2. In one year period the total water loss due to seepage at this depth will be 20.18m^3/annum/m^2. Table 1 shows the result of seepage rate at different depth of water. The 1.0m depth is normally below the dead storage of the dam.

Table 1: The seepage rate at different depth of water

Depth of water at the Upstream Face (m)	Seepage Water Rate (m^3/sec/m^2)	Seepage Water Rate (m^3/day/m^2)
7.5	-7.4355e-07	-0.0642
7.0	-6.3968e-07	-0.0553
6.5	-5.4801e-07	-0.0473
6.0	-4.6354e-07	-0.0400
5.5	-3.8917e-07	-0.0336
5.0	-3.2152e-07	-0.0278
4.5	-2.6235e-07	-0.0227
4.0	-2.1217e-07	-0.0183
3.5	-1.6572e-07	-0.0143
3.0	-1.2442e-07	-0.0107
2.5	-9.1626e-08	-0.0079
2.0	-6.4246e-08	-0.0056
1.5	-4.2208e-08	-0.0036
1.0	-2.4126e-08	-0.0021

Figure 15 shows the relationship between the depth of water at the upstream face and the seepage water rate at the downstream face of the embankment in m^3/sec/m^2. The two variables can be related as shown in equation 5.

$$y = -3e^{-09}x^2 + 1e^{-07}x - 8e^{-07} \ldots\ldots\ldots \qquad (5)$$

Where y is the seepage water rate and x is the depth of water at the upstream face of the embankment.
Figure 16 shows the relationship between the depth of water at the upstream face and the seepage water rate at the downstream face of the embankment in m^3/day/m^2. The two variables can be related as shown in equation 6.

$$y = -0.0003x^2 + 0.0092x - 0.0725 \ldots\ldots \qquad (6)$$

Where y is the seepage water rate and x is the depth of water at the upstream face of the embankment.

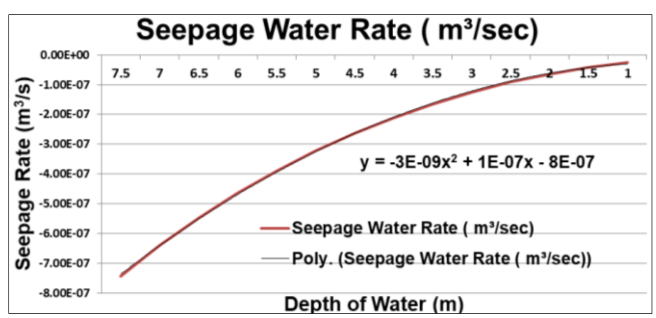

Fig 15: The graph of Seepage water rate variation with Depth in m^3/sec/m^2

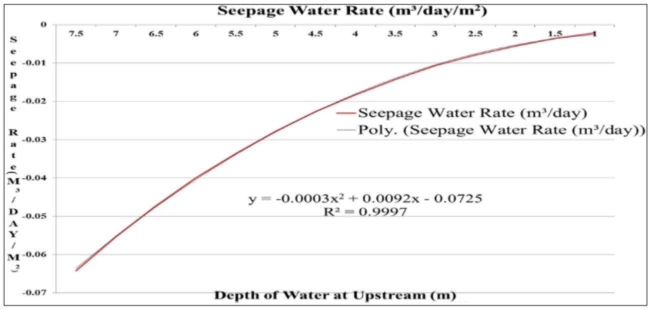

Fig 16: The graph of Seepage water rate variation with Depth in $m^3/day/m^2$

6. Conclusion

The performance analysis of an existing earthdam (Kubanni dam) was carried out using modelling and analysis of the steady state seepage condition under drawdown of an earth dam was carried out through the application of finite element numerical model software (SEEP/W).

Finally, this paper provides a general purpose simple and systematic model approach of the seepage analysis that requires only the depth of water at the upstream face of the embankment. The result obtained here can be used for stability analysis of the embankment.

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