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Review of Earth Dams Research Combining with Seepage and Stability

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Abstract. Water supply, energy production, flood control, and irrigation are all possible uses for embankment dams. Seepage is one of the primary reasons for the embankment dam failure. Numerical analysis and computer tools are commonly used to simulate a diversity of seepage flow conditions in earth dams. An embankment dam's numerical analysis is a procedure in which the challenge is represented in the real world and explained in abstract form. The major numerical techniques typically utilized in the field of computational mechanics are the finite difference (FD), finite element (FE), and boundary element (BE). The use of mathematical modeling to predict seepage in earth dams was presented in this work. MODFLOW, GOESTUDIO, ANSYS, PLAXIS, PDEase2D, SVFLUX, and other software used to analyze embankment dams were covered.

Keywords. Earth dam, numerical analysis, Seepage, slope stability, Software, drawdown.

INTRODUCTION

Water resources projects, specifical dams, possess extraordinary significance in the monetary advancement of any country. Most dams in Iraq are multi-purpose dams. Dams are among the main key foundations in the country because of their financial returns and the grand totals spent on their foundation. Also, critical results might happen if these dams neglect to play out their laid-out purposes or break down. Numerous dams worldwide had imploded during their underlying development and working years. Earthen dams are the most broadly utilized and are the least expensive. It is generally a trapezoidal section and has a wide foundation. A non-overflow with a different spillway is built in an earth dam. Homogeneous, zoned, and diaphragm earth dams are the three major types of earth dams [1].

Earth dams' failure often happens because of water drainage course through the permeable infill materials. Failure can take different forms like piping or internal erosion, foundation weakness, and defects besides slope instability failure. Earthen dams might turn out great for a long time. However, they require a reasonable plan and upkeep. They fail rapidly, assuming they are presented with an occasion ready to make them break down. Rapid drawdown is a hazardous condition under which the dependability of the upstream face can be basic. Hence, the incline slope stability of upstream faces is guaranteed during all conditions of the dam's presence [2]. One of the significant viewpoints in geotechnical design is slope stability. Slope stability involves colossal worry in the development of earthen dams whose failure might cause serious death toll and harm to property. , it is vital to design the dam to fulfill both security and financial thought [3]. Because they seep water, earth dams have historically been connected with seepage. Water has sought the lowest-cost passage through the earth dam and its foundation [4]. Dupuit (1863) used Darcy's Law to calculate the discharge rate passing for each vertical profile of the dam, assuming that the hydraulic gradient is equal to the free surface slope according to Eq. 1 [5].

$$q = k\left(\frac{h_1^2 - h_2^2}{2l}\right) \tag{1}$$

Casagrande (1937) used Eqs. 2 and 3 for a situation with zero downstream head, to compute the quantity of seepage through the body of a homogeneous earth dam built on a waterproof foundation, and advised the parabolic free surface to initiate at a position upstream, where (Δ) is equal to the base width of the upstream triangular part [6].

$$q = kl\sin^2\alpha \tag{2}$$

$$l = \sqrt{d^2 + h_1^2} - \sqrt{d^2 - h_1^2\cot^2\alpha} \tag{3}$$

Schaffernak (1917) proposed that the phreatic surface intersected the downstream slope at a distance (l) from the impervious base to establish an approximate method for calculating seepage through a homogeneous earth dam with zero downstream head, Eqs. 4 and 5 [7].

$$l = \frac{d}{\cos\alpha} - \sqrt{\frac{d^2}{\cos^2\alpha} - \frac{h_1^2}{\sin^2\alpha}} \tag{4}$$

In addition, to solve the governing equations of flow via earth dams, the finite element approach has been devised. For solving the flow issue under steady-state settings, Al-Damluji et al. (2004) compared the results obtained using finite element and boundary element approaches [8]. The investigation and calculation of seepage discharge in dams by Baghalian et al. (2012) were based on piezometric head data values of dam seepage discharge [9]. In an earth dam [10], Javad et al. (2012) developed a one-of-a-kind non-boundary fitted mesh that can handle unconfined seepage in areas with varying geometry and permeability. On anisotropic soil foundations, for seepage flow beneath hydraulic structures. Consider that Artificial Neural Networks (ANN) is a type of artificial intelligence technology with various capabilities that have been researched in the dam's body. The (ANN) has software approaches that are made up of one or more layers, each with many processing units (neurons).

PREVIOUS STUDIES

Previous Studies on Seepage in Earth Dams

The goal of seepage analysis is to ensure that dams are designed and maintained in a safe manner. If not addressed properly, excessive seepage might lead to dam safety issues. The following are the reasons why seepage analyses are performed:

- To figure out how much pressure is in a foundation or embankment.
- To calculate pore pressures within a foundation or embankment.
- Calculate the embankment's toe exit slopes and/or uplift pressures.
- To determine how much seepage flow can pass through a foundation or embankment.
- To compare the efficacy of different seepage control solutions.
- To calculate the amount of seepage flows captured by drainage features and their size and construction.
- To determine the effectiveness of dewatering systems or to assist in their design.

These aspects are taken into account when recommending corrective procedures for existing dams. Due to the advent of high-speed computers, many numerical analytic approaches for solving complicated engineering problems have evolved over the last six decades. Different mathematical models for handling the same problem are feasible depending on the modeling technique. The finite difference method (FDM), finite element method (FEM), finite volume method (FVM), boundary element method (BEM), and meshless method have become more popular among scientists and engineers among the numerous numerical approaches accessible. FEM is utilized to address exceedingly large and complex problems, and the solution approach must be both efficient and cost-effective. Engineers may always employ improved pre-and post-processing techniques to make FEM more efficient and dependable. MODFLOW, SEEP/W, PLAXIS, ANSYS, PDEase2D, SVFLUX, and other tools are used to analyze an embankment dam's seepage analysis [11].

Abdallah et al. (2008) [12]

This study employed both an experimental sandbox method and a computational Boundary Element Method method. The influence of chimney and horizontal filters on seepage properties also underwent research, with the comparison of experimental data and numerical findings for each filter type. The authors conclude that the free water surface was not affected by the chimney or horizontal filters at the same position. The height of the dam's outflow point without a filter was less than the length of the seepage slope for the chimney and horizontal filters. The seepage throughput from the chimney or horizontal filters was greater than the dam without a filter. Although the percent seepage discharge obtained by a chimney drain was greater than that attained by a horizontal drain, the difference was minor. To reduce the volume of material used in filter construction, it is preferable to utilize a horizontal filter rather than a chimney system.

Keyvanipour et al. (2012) [13]

The Bar Dam, a 35.5-meter-high embankment dam, was instrumented to track internal soil behavior, settlement, and stress. Two soil models were chosen for the stress-strain analysis: Mohr-Coulomb and Hardening. The PLAXIS 2D finite element software was used to assess the dam's stress, strain, and deformation during the initial impoundment. According to the author's conclusions, the instrumentation is the most fundamental tool for evaluating dam behavior and ensuring that planning and implementation parameters are correct. The hardening behavior and instrumentation results are less different from the results of the Mohr-Coulomb model. According to the software PLAXIS and two models, the study's findings, the method's efficiency, and the software used it to estimate embankment behavior throughout construction are all satisfactory (Mohr-Coulomb and Hardening). One of the most basic models of soil behavior is the Mohr-Coulomb model. The modeling flexibility of the hardening model is greater. According to the authors, the two models in this study showed similarly and near members. The results of the two models, Mohr-Coulomb and Hardening, were validated using the instrumentation data and the results of the two models. The results of common stress meters and computer analysis were compared.

Kamanbedast and Delvari (2012) [14]

In this study, the behavior of soil dams with various effective parameters was analyzed. Maroon dam, located 19 kilometers north of Bahaman on the Maroon River, has been chosen as the case study. The soil stability of the dam was investigated using ANSYS, and the results were compared to those obtained using the GEO STUDIO Software. Dam seepage was predicted using the Analysis technique. ANSYS has an 18% lower seepage rate than GEO STUDIO. Slope stability is also looked upon, as well as dam behavior. The results are nearly equal when it comes to slope stability. However, the safety factor numbers (for two different software) were significantly different. Bishop technique is used to compute the safety factor for upstream slopes 1, 2, 4, and 1.5 for GEO STUDIO. Finally, movement and max. and min. Strain and stress and a settlement around the crack zone are evaluated using the stress and strain analysis method. The vertical movement is expected to be 6 meters.

Anjali and Hangargekar (2017) [15]

The seepage and phreatic line of the Ujjani dam were simulated in this paper using finite element software called GEO-STUDIO sub-product SEEP/W. On the Bhima River in Maharashtra, an earth dam was built. Because the phreatic line and exit gradient met normal design standards, the earth dam was found to be safe against internal erosion and piping. The SEEP/W results are compared to the actual field that was seen. The computed seepage flow and the measured real field have a small maximum relative error (R^2 = 0.9759), indicating that SEP/W software may be utilized effectively for seepage investigation.

Arshad et al. (2019) [16]

Hub Dam, a non-homogeneous earth dam in Karachi city, was used to investigate the effect of core on seepage. The seepage through an earth dam was simulated using Geo-Slope software based on the finite element method for two different cases: The dam with core (i.e., core materials different from shell materials) and the dam without core (i.e., core materials the same as shell materials). Three water level scenarios were examined in the two cases: maximum, normal, and minimum pool levels. According to the first case results, the earth dam proved safe against internal erosion and piping in all scenarios.

In the second case, the earth dam was unsafe to internal erosion and piping under the same circumstances as the first. The earth dam without a core had a higher seepage flow and exit gradient than the dam with core (12.768 – 41.378%) and (85.896 – 91.809%). It indicates that a core was seen as a safety key in an earth dam controlling the phreatic surface. Compared to shell materials, the core had a very fine material with a high ability to resist seeping and lower each positive pore water pressure, seepage flux, and exit gradient Mesh of the non-homogeneous cross-section with core [16].

Al-Janabi et al. (2020) [17]

Researchers compared homogeneous physical, numerical, and mathematical models to analyze seepage behavior through the earth-fill dam. The SEEP/W program was used to assess the numerical model, while L. Casagrande solutions were used to examine the mathematical model. In both SEEP/W and L, the phreatic line is plotted. Casagrande solutions compared to the phreatic line of a physical model. The result revealed that the three models' flow rates had converged. The seepage amount through piping cannot be determined in the numerical and mathematical models when the phreatic line contacts the downstream face and the exit gradient is more than 1.0 (piping would be acquired). The drainage study evaluated seven dam designs (four homogeneous and three zonal dams) at standard and maximum water levels. If there are sufficient silty sand soils in the proposed dam location, leakage analysis has revealed the best design configuration for a homogeneous earth-filled dam with a medium drain length of 0.5 m. Otherwise, a zonal earth-fill dam with an outer core and a center core is planned (1H: 0.5 V) [17].

Seepage and Slope Stability of an Earth Dams

Noori and Ismaeel (2011) [18]

The free surface seepage line, the quantity of seepage through into the dam, the pore water pressure distribution, total head measurements, and the impact of anisotropy of the core materials of the Duhok zoned earth dam were all calculated using a finite element method and a computer program called SEEP2D. The accuracy of the program was checked utilizing prototype dam data, and the results revealed that it was adequate. The influence of the horizontal-to-vertical permeability ratio (Kx/Ky) on seepage was investigated, and the results showed that as this ratio increased, so did the amount of seepage. A slope stability computer software, STABIL2.3, was used to assess the stability of the Duhok zoned earth dam. A dam example with a known factor of safety (solved by hand calculations) is used to test the program. The verification findings showed that the program was accurate. The slope stability analysis revealed that as the Kx/Ky ratio increases, the factor of safety drops. Under the current operating conditions, the Duhok zoned earth dam is safe from piping and slope sloughing, according to the conclusions of this study. Furthermore, their research revealed that the dam's field piezometer readings were inaccurate.

Hasani et al. (2013) [19]

SEEP/W software was used to analyze seepage in the Ilam earth-fill dam. Considering four mesh sizes: coarse, medium, fine, and unstructured mesh, the effect of type and mesh size on total flow rate and total head through the dam cross-section is examined. According to the results, the average leakage flow rate for the Ilam dam was 0.836 liters per second for the whole length of the dam. The SLOPE/W software is used to assess slope stability in a variety of situations. Analyzes using Bishop, Janbu, and Morgenstern methods and the conventional method of slides are computed for each condition and slope, with the least safety factor in each of these ways treated as a slope stability safety factor.

Athani et al. (2015) [20]

The seepage and slope stability of an earth dam was investigated using the finite element program PLAXIS and the limit equilibrium approach. The dam was examined for the following issues:

The maximum level of the pool (i.e., full-height reservoir condition).

The pool's minimum depth.

Rapid depletion over a period of 5 to 10 days.

Slow depletion during a 50-day period

According to the findings, the safety factor for both the maximum and minimum pool levels was greater than 1.6. This is due to the fact that when the water level drops suddenly, the phreatic surface cannot shift quickly. The factor of safety values, on the other hand, was lower than the real values for other conditions [20].

Abbas et al. (2017) [21]

The effect of soil strength factors on the upstream slope stability of the ALWand homogenous earth dam. The soil strength parameters that were input in the finite element program were cohesion, unit weight, and angle of internal friction (GEO-STUDIO version 2007). SEEP/W and SIGMA/W, are used together or separately with SLOPE/W during the analysis to model the earth dam. The safety factor of the upstream slope was found to be proportional to cohesion and the angle of internal friction (phi) but inversely proportional to the soil's unit weight. The upstream earth dam face can be vulnerable to failure if the water level in the reservoir is rapidly depleted [21].

It is feasible to say that the researcher's reviewed study (Athani et al. [20]) in seepage and slope stability is a full investigation of all scenarios that could influence earth dams and that the results generated from the program finite element program PLAXIS and the limit equilibrium approach are good and reliable.

Rapid Drawdown

Khattab (2010) [22]

They evaluated the effect of rapid drawdown on the slope stability of the Mosul Dam, which was determined using Bishop method and a finite element computer program called GEO-SLOPE OFFICE. The program was used during a three-period rapid water level drawdown under saturated-unsaturated soil transient seepage (31, 21, and 8 days). The major findings demonstrated that over eight days of fast drawdown, the slope stability for the minimum safety factor was on the second day, which is considered the most crucial case [22].

Khassaf et al. (2013) [23]

The effect of rapid drawdown on the Mandali dam's slope stability was explored. The Morgenstern-Price approach was used to examine it using the SLIDE V.6.0 finite element computer program. The program was used to calculate the safety of the zoned earth dam and determine the probable slip surface during rapid drawdown conditions for maximum elevation with seismic forces impacts. The stability of the upstream slope was shown to be steady in this study, despite the fact that it had substantially dropped due to rapid drawdown conditions. Under rapid drawdown conditions and a seismic stress coefficient of 0.07g, the safety factor's minimal value is around 1.254 [23].

Fattah et al. (2017) [24]

The influence of reservoir water depletion on the stability of the upstream slope was studied using finite elements and limit equilibrium. SEEP/W and SLOPE/W, both part of the Geo-slope package, were used to model an earth dam (Al-Wand dam) as a case study. The program's input data included the rise of water behind and before the earth dam, the soil qualities that make up the earth dam, and boundary circumstances. The output data included pore water pressure, seepage flux, and exit gradient. Three-time periods were used to test the drawdown condition: 11 days (planned duration), three days, and one day. Pore water pressure and seepage flux dropped linearly with time throughout all drawdown episodes. Due to a lower exit gradient value, the safety factor against boiling and piping during drawdown conditions increased with time. During the three periods, the minimum safety factor against slipping upstream slope was 1.3, 1.231, and 1.154 [24].

Zedan et al. (2018) [25]

The KHASA-CHAI dam, which is located on the KHASA-CHAI River, was investigated for the effect of fast drawdown conditions on the upstream slope's stability. Subproduct software (SEEP/W and SLOPE/W) was utilized to simulate the earth dam using the finite element method in the geotechnical engineering application (GEO-STUDIO). During the two examples of quick decline analysis (sharp in 20 days and extended in 40 days), the reservoir's maximum water level was measured. The lowest safety factor against sliding was greater than (1.0) for both cases, indicating that the upstream slope was safe.

During both sharp and extended decline, the phreatic line decreased in roughly the same place. The volume of the active pore, the hydraulic conductivity of the dam drops, the drawdown rate, and the angle of the upstream slope were the four variables that influenced the phreatic line's delay. The water drainage and exit gradient at the toe of the earth dam decrease with time during drawdown conditions, making the earth dam safer against piping and boiling [25]. Due to the close proximity of the data produced and the consistency of the programs employed in terms of accuracy, it is somewhat difficult to distinguish between the studies reviewed regarding the lake's rapid drawdown.

CONCLUSIONS

For constructed dams, seepage and slope stability through earth-fill dams must be assessed to ensure the seepage control is adequate for the dam's safe and long-term operation. When designing and building modern dams, it's also critical to consider how to manage seepage through and below the dam efficiently.

- Hydraulic engineers used to rely mostly on physical modeling to refine and verify their hydraulic designs, which they would accept (at first) based on existing theoretical conceptions and practices. Simulation employing numerical modeling to reflect real-world circumstances is quickly coming up to or surpassing the ability of physical models to simulate physical occurrences, thanks to the introduction of powerful computers and developments in computing techniques. The pore water pressure declines linearly at all sites within the dam body during the rapid drawdown, indicating steady-state flow. During the water drawdown period, negative pore water pressure may influence some downstream locations in the dam, indicating that the water level drops below these places. Within a short period following the commencement of rapid drawdown of water in the reservoir, the safety factor against dam slope sliding reduces significantly, then increases.
- In many real-world circumstances, numerical modeling solutions are preferred to physical modeling due to time limits on building physical models, broad provision of personal computers/laptops, and affordable commercial software. The information offered in this paper will aid both designers and students in this area.
- Many case studies for each of the three standard numerical modeling approaches, namely FDM, FEM, and BEM, are found for seepage modeling. MODFLOW, SEEP/W, PLAXIS, ANSYS, PDEase2D, and SVFLUX are six commercial or open-source software packages that researchers and designers have successfully used to study various aspects of seepage flow in earth dams.
- The following elements are modeled: drain efficacy, dam stability, total seepage flow rate evaluation, settlement and internal soil stress, seepage prediction, and 2d/3d seepage flow rate estimation. Compared to physical models, its impressive how quickly numerical models can adapt to changes in design parameters. According to the review study, the GEOSTUDIO program is the best and fastest at producing accurate results related to investigating slope stability and seepage through earth dams.

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