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Numerical Analysis of Seepage in Embankment Dams

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ABSTRACT: *Embankment dams are structures used for water storage, energy production, flood control and irrigation. One of the main causes of the embankment dam failure is seepage. Numerical analysis using computer programs are widely used to model a variety of seepage flow conditions in embankment dams. Numerical analysis of an embankment dam is a process in which the problem is represented as it appears in the actual condition of real world and is interpreted in abstract form. Finite Difference (FDM), Finite Element (FEM), Boundary Element (BEM) methods are the important numerical techniques commonly used in the computational mechanics field. This paper presents the application of mathematical modeling of seepage in embankment dams. Various software used in the analysis of embankment dams like MODFLOW, SEEP/W, ANSYS, PLAXIS, PDEase2D, SVFLUX, etc., are discussed with reported case studies. Each software has its own advantages and limitations, which are discussed briefly in the paper.*
Keywords - *Embankment dam, Finite Element Method, Numerical Analysis, Seepage, Software*

1. Introduction

Dams are constructed for various purposes like flood control, navigation, water source, recreation, power generation etc. Earth dams have always been associated with seepage as they impound water in it. The water seeks paths of least resistance through the dam and its foundation. Seepage will become a problem only if it carries dam materials also along with it. Seepage must be controlled to prevent the erosion of embankment or its foundation. Different methods like analytical, electrical analogy and flownet (Ali, S., and Fardin, 2005; Abdullahi *et al.* 2000, and Casagranade, 1961) are used to study and monitor seepage in dams.

Embankment dams are more common than any other type of dams because of various reasons like the use of ordinary technology construction method utilizing cheap raw soil materials and subsurface materials, no need of a particular valley shape etc.,. The geometry of embankment dams depends on burrowed soil materials, subsurface conditions and type of construction. One of the important factors causing failure of embankment dam is seepage and hence seepage analysis of embankment dam is of greater importance.

Some seepage problems can be evaluated through the use of graphs and charts available from published literature. These simplified methods depend on saturated flow theory and highly idealized conditions may be appropriate for preliminary evaluations of seepage issues. Physical models that simulate the flow of water through porous media are sometimes used to evaluate seepage in embankment dams. The various models coming under these are: electrical analogy, sand models and viscous models. Because of the analogy between Ohm's law and Darcy's law and also because the Laplace Equation describes both the electrical potential distribution in a conducting medium and the hydraulic potential in a saturated porous medium, the electrical analogy methods are effective. Billstein et al. (1999) used experimental models to determine discharge, pore water pressure, seepage face and free surface profile. Physical models are no longer used routinely.

The flow net is a graphical procedure consisting of hydraulic potentials and flow direction in a 2D saturated, steady state seepage system [1]. Flow nets can be useful for estimating pore pressure, hydraulic gradient, and flow quantity when the system can be idealized into one or two uniform material zones and limited parameter variation is required.

Recently, Finite Element Method (FEM) is being used for the seepage analysis of embankment dams. Several authors, namely, Papagianakis and Fredlund (1984), Potts and Zdravkovic (1999), Darbandi *et al.*

(2007) and Rushton and Redshaw (1979) had performed seepage analysis through an embankment dam using finite element method. Also, Agbede (1989) presented a computer simulation of the groundwater flow through a porous medium in the Northern State of Nigeria (Kolawole Adisa Olonade, 2013).

The present paper is meant to disseminate information related with seepage analysis of embankment dams, numerical methods and software available, and, to report various case studies presented in literature. Students and practicing engineers can make informed choices on software to be procured for their embankment dam related seepage and stability analyses, and also on methods of formulation of the mathematical modeling of problems relating to the field situations.

2. Purpose of Seepage Analysis

Dams must be designed and maintained to safely control seepage. Excessive seepage leads to dam safety issues, if not treated carefully. Seepage analyses are carried out for the following reasons:

- To estimate the phreatic surface within an embankment,
- To estimate pore pressures within an embankment or foundation,
- To estimate exit gradients and/or uplift pressures at the toe of an embankment,
- To estimate the amount of seepage flow that may pass through an embankment or foundation,
- To evaluate the relative effectiveness of various seepage reduction measures,
- To estimate the amount of seepage flows intercepted by drainage features and to size and optimize the configuration of these types of drainage features,
- To evaluate the effectiveness of, or to aid in the design of, dewatering systems.

All these are factors taken into consideration while suggesting remedial measures in existing dams.

3. Theory of Seepage in Embankment Dams

Darcy's law can be used to describe water flow through soils in both saturated and unsaturated conditions (Richards, 1931) which can be stated as follows:

$$q = k * i \qquad (1)$$

where,

q = discharge per unit area,
i = total head gradient, and
k = co-efficient of permeability.

The governing partial differential equation for seepage through a heterogeneous, anisotropic, saturated-unsaturated soil can be derived by satisfying conservation of mass for a representative elemental volume. If the assumption is made that the total stress remains constant during a transient process, the differential equation can be written as follows for the three dimensional transient case:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right) = m\,\gamma\left(\frac{\partial h}{\partial t}\right) \qquad (2)$$

where,

k_x, k_y and k_z = co-efficient of permeability of soil in *x, y* and *z* direction, respectively, and
m = water storage (the slope of the soil-water characteristic curve).

For steady state seepage, only the co-efficient of permeability is required because the time dependent term disappears and the water storage term drops out. But to solve transient seepage problem associated with a saturated - unsaturated soil system, the two soil properties (i.e. co-efficient of permeability and water storage) are required (Thieu, Fredlund, *et al.*, 2001).

4. Finite Element Method (FEM)

Because of the prominence of the finite element method (FEM) as an analytical tool in seepage analysis of dams and in the various SOFTWARE discussed later, an introduction on FEM is given in the following paragraphs[2][3][4].

In order to analyze an engineering system, a mathematical model is developed to describe the system. While developing the mathematical model, some assumptions are made for simplification. Finally, the governing mathematical expression is developed to describe the behavior of the system. The mathematical expression usually consists of differential equations and given conditions. The best way to solve any physical problem governed by a differential equation is to obtain the analytical solution. There are many situations, however, where the analytical solution is difficult to obtain. The region under consideration may be so irregular that it is mathematically impossible to describe the boundary. The configuration may be composed off several different materials whose regions are mathematically difficult to describe. Problems involving anisotropic materials are usually difficult to solve analytically, as are equations having non-linear terms.

A numerical method can be used to obtain an approximate solution when an analytical solution cannot be developed. Especially, the finite element method has been one of the major numerical solution techniques. One of the major advantages of the finite element method is that a general purpose computer program can be developed easily to analyze various kinds of problems. In particular, any complex shape of problem domain with prescribed conditions can be handled with ease using the finite element method. A complicated domain can be sub-divided into a series of smaller regions in which the differential equations are approximately solved. By assembling the set of equations for each region, the behavior over the entire problem domain is determined. Each region is referred to as an element and the process of subdividing a domain into a finite number of elements is referred to as discretization. Elements are connected at specific points, called nodes, and the assembly process requires that the solution be continuous along common boundaries of adjacent elements.

5. Software Used in Seepage Analysis of Embankment Dams

Many numerical analysis methods have evolved in the last six decades for solution of complex engineering problems due to advent of high speed computers. Mathematical modeling of an engineering problem is a process by which the problem is represented as it appears in the real world and interpreted in an abstract form. Depending on the modeling approach, different mathematical models are possible for tackling the same problem (Snehal P. Abhyankar, Shekhar D. Bhole, 2011). Out of various available numerical techniques, 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. FEM is applied to very large and complex problems, and it is very important that the solution process remains efficient and economical. From Engineer's point of view, FEM can always be made more efficient and easier to use with sophisticated pre and post processing tools. [2] Various software used in the seepage analysis of an embankment dam are: MODFLOW, SEEP/W, PLAXIS, ANSYS, PDEase2D, SVFLUX etc.

5.1 Software: MODFLOW

MODFLOW is a three dimensional groundwater flow model, developed by USGS (United States Geological Survey), and based on the finite difference method (Harbangh *et al.*, 2000). It is used to simulate systems for water supply, mine dewatering, containment remediation *etc*. Various user-friendly computer packages like

GMS, have been developed by using the MODFLOW program. The 3D flow movement of the ground water of constant density through porous earth material can be described by the partial differential equation,

$$\frac{\partial}{\partial x}\left(k_x\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z\frac{\partial h}{\partial z}\right)-W = S\left(\frac{\partial h}{\partial t}\right) \quad (3)$$

where,

k_x, k_y, k_z = hydraulic conductivity along *x, y* and *z* co-ordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity,
h = potentiometer head,
W = volumetric flux per unit volume and represents source and /or sinks of water, and,
S = specific storage of the soil.

The equation, along with the flow specification and initial head conditions, constitutes a mathematical representation of a ground water flow system.

Kishan Kakarla (2005) in his open thesis[5], entitled “Numerical analysis of seepage in earth slopes” did a series of experiments in laboratory on a physical model and a series of tests on computer models. To study the effectiveness of the drains, the analysis was carried out for various parameters like angle of slope, soil properties, water level and trench spacing. Numerical analysis was carried out for both laboratory and field conditions under steady state and transient conditions. Transient behaviour of longitudinal drains was studied determined the duration of time needed for the drain to become completely functional. It is concluded that longitudinal drains are very effective in reducing seepage in slopes. The first and second drains in most cases collect more than 50% of the total drainage. Influence of slope angle, trench spacing, seepage-depth and soil-type in the reduction of seepage in slopes were studied using both steady and transient state methods. The limitation is that only in the case of saturated flow conditions, it can be applied. Also, the density of the groundwater must be constant. The principal direction of horizontal hydraulic conductivity or transmissivity should not vary within the system.

5.2 Software: SEEP/W

GEOSTUDIO software is one of geotechnical program that is based on the finite element and can do analysis such as, stress-strain, seepage, slope stability, dynamic analysis. SEEP/W (SEEPage for Windows) is a finite element software product that is coming under GEOSTUDIO, used to model the movement and pore-water pressure distribution within porous materials like soil and rock. It is formulated on the basis that flow of water through saturated soil follows Darcy’s Law. The SEEP/W model is constructed to solve 2-dimensional flow situations with multiple soil layers. Flow directions of groundwater can be analyzed. Under steady state conditions, the difference between input flux and output flux is zero at all times. For finite element calculations, the SEEP/W model is divided by nodes. The elevation of water level at each node is calculated. In the SEEP/W models, the following assumptions are made: (i) the aquifer is heterogeneous and isotropic, and (ii) the aquifer is partly confined and partly unconfined. Good quality output graphics allows a visual display of equipotential lines and flow paths, and contours can be plotted for different properties like pore pressures, seepage velocities, and gradients. Computations include flow quantities and uplift pressures at user-selected locations in the model.

5.2.1 Noori and Ismaeel (2011)

Dr. Bahzad M. A. Noori and Khaleel S. Ismaeel of University of Duhok, wrote, in *Al-Rafidain Engineering Journal* (2011), a paper[6] on “Evaluation of Seepage and Stability of Duhok Dam”. They used a finite element method through a computer program, SEEP2D, to determine the free surface seepage line, the quantity of seepage through the dam, the pore water pressure distribution, the total head measurements and the effect of anisotropy of the core materials of Duhok zoned earth dam. Cross Section of Duhok Dam is shown in (**Fig. 1**).

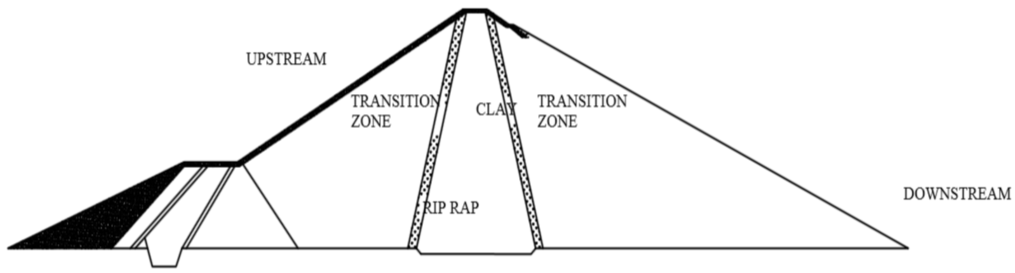

Figure 1: Cross Section of Duhok Dam
After, Noori and Ismaeel (2011)

The accuracy of the program was tested using the data of experimental dam and the results showed an acceptable accuracy of the program. The effect of the ratio of the permeability in the horizontal direction to that in the vertical direction (K_x/K_y) on seepage was tested and results indicated an increase in seepage quantity as this ratio increased. The stability of Duhok zoned earth dam was analyzed using a slope stability computer program, STABIL2.3. The program is verified through a dam example of known factor of safety (solved by hand calculations). The results of the verification indicated good accuracy of the program. The slope stability analysis results showed that the factor of safety decreases with the increase of K_x/K_y ratio. The analysis of the results of this study showed that Duhok zoned earth dam is safe against the danger of piping and slope sloughing under the present operating levels. Also, the study by them showed that the field piezometers readings of the dam were not accurate.

5.2.2 Hasani *et al.*, (2013)

H. Hasani of Payame Noor University (Iran), with J. Mamizadeh and H. Karimi (2013), in their *journal* paper[7] entitled "Stability of Slope and Seepage Analysis in Earth Fills Dams Using Numerical Models (Case Study: Ilam Dam, Iran)", reported seepage analysis in Ilam earth fill dam that was done using SEEP/W software. Cross Section of Ilam dam is shown in **Fig. 2**.

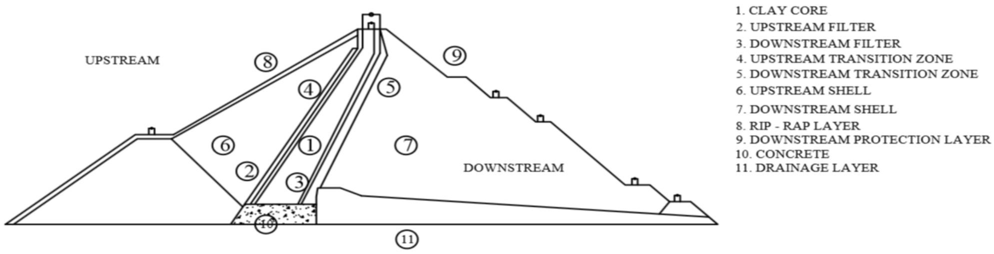

Figure 2: Cross Section of Ilam Dam
After: Hasani, Mamizadeh and Karimi (2013)

In order to evaluate the type and mesh size on the total flow rate and total head through the dam cross section, four mesh size such as coarse, medium, fine and unstructured mesh is considered. Result showed that average flow rate of leakage under the different mesh size for Ilam dam equal 0.836 liters per second for the entire length of the dam. SLOPE/W software is used to evaluate slope stability under different conditions. Analyzes for each state and each slope with Bishop, Janbu, and Morgenstern methods and ordinary method of slides, is calculated such that the minimum safety factor in each of these methods, be considered as a safety factor of slope stability.

5.2.3 Giglou and Zeraatparvar (2012)

Abolfazl Nazari Giglou of Islamic Azad University and Aziz Zeraatparvar of Azerbaijan University, Iran (2012) in their paper[8] entitled “Seepage Estimation Through Earth Dams” presented a simplified method to estimate the seepage rate through homogeneous earth dam with vertical drainage and by considering the saturated-unsaturated flow under steady-state conditions. The seepage rate through homogeneous earth includes saturated and unsaturated flow. Different homogeneous earth sections with heights of 5, 10, 20, 30, 40 and 50m were analyzed numerically with a two-dimensional finite element code. The cases investigated include the most frequent types of homogeneous earth designed to retain municipal or industrial wastewater. Solutions were proposed to solve numerically two difficulties related to the representation of saturated and unsaturated physical flow conditions. The difficulties faced were treating a downstream seepage face and treating the passage of water from the core into a draining layer. The authors presented simple expressions to predict the total (saturated and unsaturated) seepage flow rate through a homogeneous earth and precautions to be taken. A simplified method to estimate seepage through earth dams under steady-state conditions was also presented.

5.3 Software: PLAXIS

PLAXIS is the geotechnical finite element software, specifically developed for the 2D and 3D analysis of deformation, stability and groundwater flow. Geotechnical applications require advanced constitutive models for the simulation of the non linear, time dependent and anisotropic behavior of soils and/or rock. In addition, since soil is a multi phase material, special procedures are required to deal with hydrostatic and non hydrostatic pore pressures in the soil. PLAXIS software has been optimized to accurately simulate this highly non-linear behaviour. PLAXIS includes geometry creation tools and automated settings to allow geotechnical problems to be analyzed efficiently & accurately with the minimum of training. PLAXIS software is developed in Delft, Netherlands.

Masond Keyvanipour of Islamic Azad University, Iran with Mahdi Moharrampoue and Sina Faghih (2012) presented a paper[9] related with the study of Bar Dam, in the *International Conference on Environmental Science and Engineering*, entitled "An Evaluation and Comparison of Bar Embankment Behaviour with Instrumentation Data and Software PLAXIS". The Bar Dam, a 35.5 m high embankment dam was instrumented in order to monitor internal soil behaviour settlement and soil stresses. **Fig. 3** show the cross section of Bar dam. Two soil models including Mohr-Coulomb and Hardening models were selected for stress-strain analysis. PLAXIS 2D, finite element code was used to simulate the behaviour of dam during the first impounding and analyze for stress, strain and deformation.

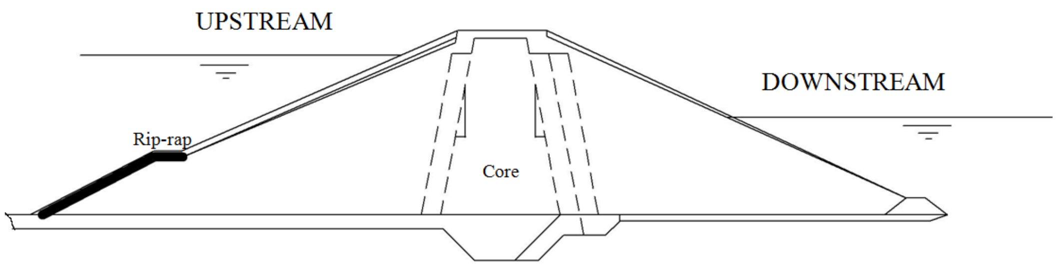

Figure 3: Cross section of Bar dam
After: Keyvanipour, Moharrampoue and Faghih (2012).

The author's conclusions are the following: Instrumentation is the most important means for investigation of dam's behaviour and ensuring that the design and execution parameters are accurate. The difference between Hardening behaviour model and instrumentation results is lesser than that of Mohr-Coulomb model.

As the software PLAXIS and two models (Mohr-Coulomb and Hardening) show, the results of the study, efficiencies of the method and the software used for modeling the embankment behaviour during constructions are acceptable. Mohr- Coulomb model is one of the simplest models of soil behaviour. Hardening model has more flexibility in modeling. As per the authors, in the modeling of this study, the two models demonstrated similar and close members. The validation of results carried out using the instrumentation data and the two models results i.e. Mohr- Coulomb and Hardening models. The results of general stress meters were compared with those of computer analysis.

5.4 Software: ANSYS

ANSYS is engineering simulation software (computer-aided engineering, or CAE). ANSYS is a general-purpose finite-element modeling package for numerically solving a wide variety of mechanical problems. These problems include static/ dynamic, structural analysis (both linear and nonlinear), heat transfer, and fluid problems, as well as acoustic and electromagnetic problems. Treatment of engineering problems basically contains three main parts: create a model, solve the problem, and analyze the results. ANSYS, like many other FE-programs, is also divided into three main parts (processors) which are called pre-processor, solution processor, postprocessor.

Kamanbedast and Delvari, Islamic Azad University, Iran, (2012), in their *World Applied Sciences Journal* paper[10] "Analysis of Earth Dam: Seepage and Stability, Using ANSYS and Geo-Studio Software" discussed the behavior of soil dam with different effective parameters. The case study was Maroon Dam which is located 19 kilometer North of Bahaman, on Maroon River. In the research, soil stability of dam was done using ANSYS and results were compared with GEO STUDIO Software result. Dam was studied using Analysis method, and seepage was predicated. (*See* **Fig. 4** for the Cross section of Maroon Dam, and **Fig. 5** for the flow network and seepage from dam.)

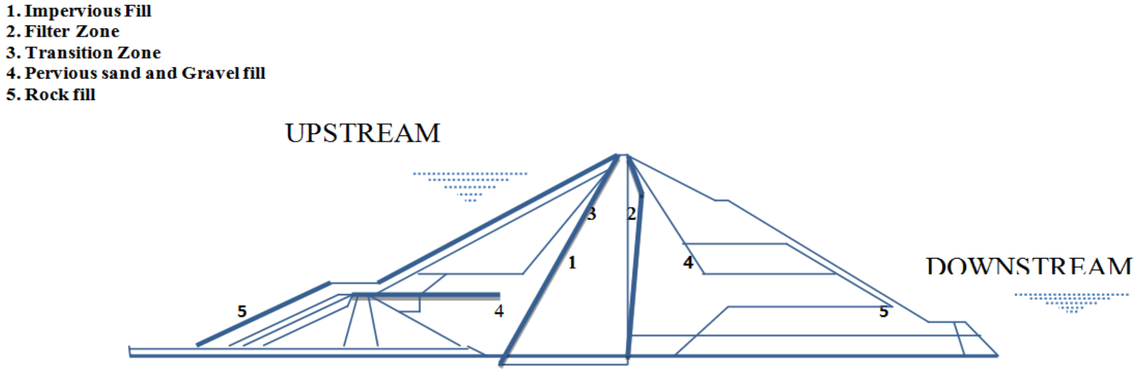

Figure 4: Cross Section of Maroon Dam
After: Kamanbedast and Delvari, 2012

The seepage rate in ANSYS was 18% percent lower than GEO STUDIO results. Besides, slope stability is studied and behavior of dam was simulated. The results are almost in similar range for slope stability result. But safety factor values (for two software) had distinctive difference.

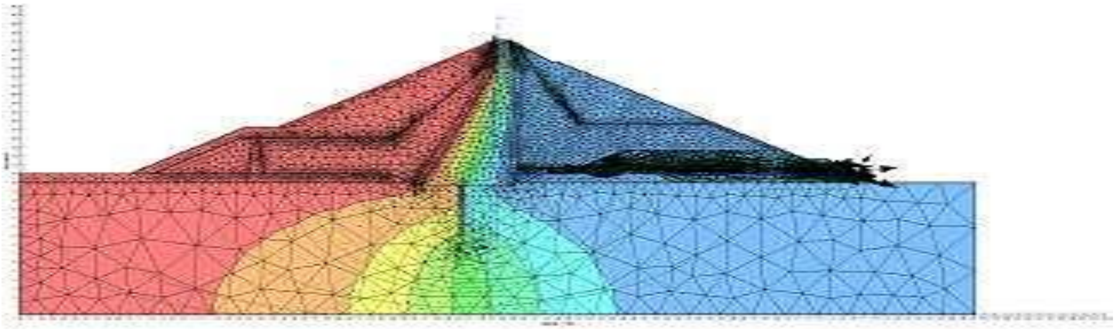

Figure 5: Flow network and seepage from dam
Source: Kamanbedast and Delvari, 2012.

The calculated safety factor, according to the Bishop method, for upstream slope 1, 2, 4 and for GEO STUDIO, value equal to 1.5 are determined. Finally, movement and maximum and minimum strain and stress are calculated with analysis method of stress and strain and settlement around crack zone is determined. The maximum vertical movement is estimated around 6 meters.

5.5 Software: PDEase2D

PDEase2D is extremely flexible and easy to learn software which solves problems in heat transfer, solid mechanics, reaction/diffusion, fluid mechanics, electromagnetic, groundwater flow, quantum mechanics, and other fields. PDEase2D combines the convenience of scientific notebooks with the flexibility of a highly automated finite element engine. PDEase2D's simple input language, automatic grid generation and refinement, on-line help, and 140 working on-line demonstrations dramatically reduce the time required to solve nonlinear static, dynamic, and eigenvalue problems with upto 32 simultaneous equations plus constraints. PDEase2D uses the same scientific notebook interface as another Macsyma Inc. product, Macsyma mathematics software. Macsyma software can be used to pre-process complicated equations for solution by PDEase2D and to post-process data generated by PDEase2D. The case study is included in the case study of SVFLUX software.

5.6 Software: SVFLUX

The software SVFlux (a proprietary product of Soil Vision Systems Ltd., Saskatoon, Sask, Canada) has been used to carry out seepage analysis on 2D and 3D models. It is a useful tool for Geotechnical Engineers. SVFlux can be coupled with a database package, Soil Vision (a proprietary product of Soil Vision Systems Ltd., Saskatoon, Sask, Canada) to perform analysis without an extensive laboratory programme. Soil properties can be obtained from a laboratory database of a variety of soils and geometry of 3D problem can be input as surfaces and layer using survey data.

The governing partial difference equation for seepage through a heterogeneous, anisotropic, saturated-unsaturated soil can be derived by satisfying conservation of mass for a representative elemental volume. If it is assumed that total stress remains constant during a transient process, the differential equation for 3D transient case:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial h}{\partial z}\right) = \left(m\, \gamma \frac{\partial h}{\partial t}\right) \qquad (4)$$

where,

k_x, k_y, k_z = co-efficient of permeability of soil in *x, y, z* directions, respectively,
m = water storage (the slope of the soil-water characteristic curve)

N. T. M. Thieu of VGI, Vietnam, and M. D. Fredlund, D. G. Fredlund, V. Q. Hung of University of Saskatchewan, Canada (2001) presented a paper[11] in the International Conference on Management of the Land and Water Resource entitled "Seepage modeling in saturated/unsaturated soil system". They have presented three example problems, the first associated with steady state seepage in 2D, the second associated with transient state seepage in 2D and the third associated with transient state seepage in 3D.

Steady state seepage in 2D is presented to illustrate the different forms of input the coefficient of permeability. When analyzing steady state seepage through an isotropic earth dam with a horizontal drain. Geometry, boundary condition and finite element mesh used in running PDEase2D for steady state seepage example.

Transient state seepage in 2D is presented to show different forms that can be used to input the coefficient of water storage when analyzing transient seepage through an isotropic earth dam with a horizontal drain. Base of dam is taken as datum. Initially, the dam, at steady state condition, with reservoir water level of 4m above datum and time assumed to be zero, water level in reservoir is instantaneously raised to level of 10m above datum. A steady state condition with water level of 4m is first performed to get distribution of initial pore water pressure head. The number of elements and nodes used in running the process varies with time from 181 to 1006, and from 428 to 2215, respectively.

In three dimensional steady state seepage, modeling of a simulated tailing pit was done. The geometry is highly irregular and soil properties range from fine silt material in the centre of basin to a coarse gravel on edges of the problem. SVFlux simplified the solution of such problem by allowing complex geometry to be input based on survey data. Reasonable boundary conditions are added to model as well as placing flux section throughout the problem to model flow of water.

Conclusions from case study are that, general partial differential equation solvers and SVFlux are useful tools for solving unsaturated soil problem because of the following reasons:

- Ensuring convergence when solving non-linear equation,
- Allowing material properties to be input in a variety of form,
- Allowing material properties to be non-linear in characteristics,
- Possible to use a variety of formats for the input of soil property functions.

MathCAD and Soil Vision software can be used in conjunction with SVFlux to compute acceptable mathematical functions for unsaturated soil properties. Database program, Soil Vision can be used for the selection of coefficient of permeability's and /or water seepage functions for the analysis when experi-mental data are not available.

5.7 Boundary Element Method

BEM is another method used to solve seepage problems in which only boundary is discretized. James and Philip, Brebbia, Paris *et al.* and Chang stated that the boundary must have one dimension less than the region, which affects a drastic reduction in unknowns to be solved. The basic equations of porous media flow are the continuity equation and the generalized Darcy's law. Substituting Darcy's law into continuity equation gets Laplace Equation.

$$\left(\frac{\partial^2 h}{\partial x^2}\right) + \left(\frac{\partial^2 h}{\partial y^2}\right) = 0 \quad (5)$$

where,

h	$= H+Y$,
H	= pressure head,
Y	= elevation head,
x, y	= x, y directions

and Laplace Equation (5) is the governing equation for steady state seepage through homogenous isotropic porous media.

Khalaf Allah S., Abdallah M. G., El-Masry A., and El-Alfy, K. S., all of Mansoura University, Egypt (2005), in their research paper[12] entitled " A study of seepage through earth dams with chimney or horizontal filters" studied the effect of both chimney and horizontal filters separately on seepage characteristics through earth dams. In the study both experimental method by sand box method and numerical method by Boundary Element Method were carried out. The effect of chimney and horizontal filters on seepage characteristics was also studied and comparison between the experimental data and corresponding numerical results for each type of filters was carried out.

The conclusions made by the authors are: Chimney and horizontal filters had the same effect on free water surface at the same position. The seepage face length for chimney and horizontal filters were less than the height of exit point for the dam without filter. Seepage discharge for either chimney or horizontal filters was greater than seepage discharge through the dam without filter. The relative seepage discharge for chimney drain was larger than that obtained by horizontal one, but the difference was very small. For the filter volume, it is preferred to use horizontal filter than chimney system to reduce the volume of used material in filter construction.

6. Conclusion

In the past, hydraulic engineers used to heavily depend on physical modeling to refine and test their hydraulic designs that they would (initially) adopt on the basis of existing theoretical concepts and practices. With advent of fast computer and advances in computing techniques, simulation using numerical modeling to represent real world situation is fast catching up with or overtaking the ability of physical models for simulating physical phenomena.

Three factors, namely, time constraints on building physical models, easy availability of personal computers/laptops, and availability of commercial software at reasonable cost, contribute to making numerical modeling solutions more advantageous over physical modeling in many real life situations. In this respect the information provided in this paper is useful to designers and students alike.

Use of three standard numerical modeling approaches namely, FDM, FEM and BEM are identified with one or more case studies for each of these methods for seepage modeling. Six commercial or public domain software, namely, MODFLOW, SEEP/W, PLAXIS, ANSYS, PDEase2D and SVFLUX are identified that have effectively been used by researchers / designers for modeling different aspects of seepage flow in earthen embankments and dams.

The specific features modeled are: effectiveness of drains, stability of dam, evaluation of total seepage flow rate, internal soil stress and settlement, prediction of seepage, and 2D and 3D seepage flow rate estimation. The ability of the numerical models to quickly adapt to changes in the design parameters is remarkable when compared to those of physical models.

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