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2D-Flow Analysis Through Zoned Earth Dam Using Finite Element Approach

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Abstract

This paper presents an application of finite element analysis using CivilFEM/ANSYS(11) software to predict two dimensional steady state water seepage through an earth dam of two soil zones resting on impervious base. Seepage characteristics (quantity and length of seepage surface) produced at downstream are investigated against permeability coefficient ratio changing of the two soil zones, and based on results of the solution it was found that seepage quantity and velocity downstream are very sensitive to any change of permeability ratio of the two soil zones forming the dam.

Keywords*:* finite element method, seepage, dam, soil

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الخلاصة

البحث المقدم يشمل على تطبيق نظرية العناصر المحددة من خلال برنامج CivilFEM/ANSYS(11) لتمثيل ظاهرة التسرب الثابت ثنائي البعد خلال سد ترابي يتكون من نطاقين للتربة ومستند على قاعدة غير نفاذة للماء. تم دراسة تغاير خواص التسرب (كمية التصريف وطول سطح التسرب أسفل منحدر السد) مقابل تغيير نسب النفاذية بين نطاقي التربة.

Introduction

Seepage analysis forms an important and basic part of geotechnical engineering. A large number of procedures have been used for solution of flow problems, Dupuit's, Schaffernak-VanIterson,Casagrande's and other solutions were introduced in literatures to determine the discharge and the free surface through 2D homogeneous earth dams of impervious bases, mentioned solutions makes use of Dupuit's assumptions for unconfined flow in (1863)[1,2]. The category of flow involving a free (phreatic) surface is called unconfined and the seepage through an earth dam under invariant upstream and downstream heads represents a steady unconfined condition [3]. Primary concern is the location of the surface seepage at downstream toe of the dam, seepage following the saturation line must be limited and if seepage surface interacts the face of the dam, erosion may produce and possible failure of dam[3]. Non-homogeneous earth dams or zoned earth dams (dams consisting of more than one zone of soil type) is difficult to be solve accurately using traditional solutions, in addition, many of the equations governing the flow problems are non-linear and most of the natural conditions are extremely complex, therefore analytical (closed-form) solution methods are not highly accurate for such problems and resource to the numerical methods

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(i.e. finite element) become necessary [4].

In the late 1970's, the finite element method in combined with the increase in digital computer power become a powerful tool in solving complex seepage problems [4, 5, 6]. ANSYS/SEEP-W/PLAXIS programs can be used for finite element analysis of dams [4]. to evaluate seepage, recently a software package named **CivilFEM(11)** which perform a full customization of the well-known finite element program **ANSYS(11)** has been introduced to allow seepage analysis in two and three dimensions in addition to the ability of generating finite element models of different geotechnical engineering problems (slope stability, piles, retaining walls…etc). The combination of both CivilFEM and ANSYS programs is through using same windows graphics user interface and sharing input data and output results [7]. This paper presents the solution of a (2D) seepage problem in an earth dam of (2) zones of soils (wet slope – no toe drain) resting on impervious base through using **CivilFEM / ANSYS (11)** software program tool.

Governing equations for saturated flow

Ground water flow in the direction of decreasing potential energy caused by differences in pressure and elevation. A common measure of this potential energy is the total head, Φ which is simply the sum of pressure head and elevation head. The volume rate of flow per unit area is directly proportional to the rate of change of head as given by the differential form of Darcy's Law [2,4,5]:

$$q = k_w . i \qquad \ldots (1)$$

where q is discharge per unit area and (i) is the total head gradient. The water coefficient of permeability k is a measure of the ability of soil to conduct water. For steady-state conditions, continuity requires that the amount of water flowing into a representative elemental volume be equal to the amount flowing out, continuity requires that the following equation holds [2]:

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} = 0 \quad \ldots (2)$$

Substituting the components of equation (1) into equation (2), produce:

$$\frac{\partial}{\partial x}\left[k_x \frac{\partial \Phi}{\partial x}\right] + \frac{\partial}{\partial y}\left[k_y \frac{\partial \Phi}{\partial y}\right] + \frac{\partial}{\partial z}\left[k_z \frac{\partial \Phi}{\partial z}\right] = 0 \quad \ldots (3)$$

Where:

k_x, k_y, k_z = coefficient of permeability in x, y, z directions, respectively.

$\Phi = p/\gamma_w + z$ = total fluid head

P = pressure

γ_w = unit weight of water

z = elevation head

Q = specified fluid flux

Equation (3) is known as Laplace's equation which governing equation for groundwater 2D flow through anisotropic, homogeneous aquifer under steady-state conditions.

CivilFEM data entry method

CivilFEM provids several TABS and interactive windows to input data in seepage problem solver. Geothechnical module has to be activated first then materials, geometry and boundry conditions can be defined and set [7].

1. **Material definition**:
   using Civil preprocessing material TAB, soil type can be set from material browser window and through modification TAB the permeability can be adjusted in x, y, z directions.
2. **Geometry definition:**
   ANSYS preprocessor modeling TAB is used to create the model of the dam and its base as lines.
3. **Boubdary conditions definition:**
   Civil preprocessor, Geotech.mod., and Seepage TABs are used to define areas bounded by geometry lines (defined in 2 above), initial saturation line, upstream and downstream heads.

Case study

A zoned earth dam resting on impervious base with assumed dimensions is shown in Fig(1). The dam is assumed to be constructed using two types of soils forming two zones (1) and (2). To study the effect of changing the coefficient of permeability of the soils forming the dam on the quantity of seepage downstream and on the length of seepage surface (wet slope) using finite element method, the coefficient of permeability (*k1*) of zone (1) assumed to be fixed at value of (0.0003 m/min) while (*k2*) of zone (2) was assumed to be varied according to *k1/k2* ratio that ranges between (1/4 to 4). Permeability in X and Y direction of the 2D flow was assumed to be equal (isotropic) in each zone.

Modeling the problem

The parameters that define each soil zone material (*kx*, *ky*, *kz*) and that define the geometry should be set first using (CivilFEM Seepage Geotech. Mod.), then the model to be created using ANSYS model creating option and based on Fig (1). It is essential then to establish the boundary conditions of the seepage problem, and saturation line (initial) is first defined. CivilFEM will iterate the location of initial defined points that form the saturation line to obtain the best approximation as a seepage model. The boundary condition of the saturation line of the start and end points was set as in table (1), the starting point stays fixed at the same location of upstream water level (Fixed condition) while the ending point slides from its initial x-y coordinate position along the downstream slop with a (seepage Exit condition).

Other boundary conditions to be assigned can be summarized in Fig (2) and as follow: (1) Upstream Head (=25m) is assigned using (~DLHEAD) command. (2) Seepage surface which under atmospheric pressure is set using (~DLSEEP) command. CivilFEM automatically consider other unassigned boundaries as an impervious boundary (base of dam). Free mesh is adopted to generate the meshing of the seepage boundaries, PLANE 42 element (structural 2D solids) is used in CivilFEM by default to solve 2D seepage problem, the element has four nodes with a single degree of freedom **(hydraulic head in each node).**

Application and results

Major features of **CivilFEM / ANSYS (11)** software in seepage analysis include [7]:

- Calculation of saturation line.
- Calculation of hydraulic heads (h).
- Pore water pressure.

- Head gradient.
- Velocity vector.
- Flux or Flow through each of the element faces.

CivilFEM solution results through (~NWTSOLVE) command option for the generated model problem is listed in table (2). Quantity of flow through seepage surface downstream (Q) in addition to its length (L) is calculated based on varied values of permeability *k1/k2* ratio of the two zones. V is the velocity of seepage through seepage surface (Q/L ratio per 1 unit length).

As a verification step, the results based on K1/K2=1 ratio value (homogeneous soil) obtained from the program solution are listed against traditional solutions (Dupuit's and Schaffernak's) as in Table (3). Results indicates excellent agreements.

Fig (3) and based on results in table (2) illustrate the sensitivity of changing permeability ratio of both 2 zones on the quantity of flow and the length of the seepage surface downstream. Results indicate that the discharge amount and seepage surface length are sensitive for any change in the permeability ratio *k1/k2* of the two zones, noticing the slope change of the curve in Fig(3) indicates that Q is high sensitive at (*k1/k2* □ 1 where zone 2 more permeable than zone 1). Increasing *k1/k2* ratio at a fixed value of (*k1*=0.0003 m/day) reduce Q value. Generally, seepage surface lengths (L) values are in reverse proportion with the Q values and increase against *k1/k2* ratio increase; Therefore, the ratio Q/L which is represent the velocity of discharge was investigated.

Fig (4) reflects the change of velocity (V) of discharge through the seepage surface. Decreasing permeability of zone 2 increase *k1/k2* ratio and decrease the velocity, and again high rate of change for V at *k1/k2* □ 1 is noticed.

Previous results confirm the face that zone 2 should always consist on soil material with low permeability (lower than zone 1) to reduce discharge through dam body and the velocity to gain stability.

Fig(5) illustrates a typical water flow pattern through the seepage zone of the dam generated using CivilFEM/ANSYS software. Water head, pore water pressure and Seepage Flow change along the seepage surface for typical K ratio (=1) is also shown in Fig (6) to Fig (8). The results reflect logical useful information for each element forming the two zones (i.e high head at the entrance of each zone and low at exit).

Conclusions:

Based on analysis performed, following conclusions are drawn :

1. CivilFEM/ANSYS(11) Seepage solver appeared to be very useful tool for seepage analysis of earth dams with different zones.
2. For the case study, construction of second zone Z(2) of dam at downstream side with lower permeability than zone one (less than 0.0003 m/min) is recommended and seems to reflect more stability in seepage control through the body of the dam (i.e. lower seepage quantity and velocity along seepage surface), seepage discharge and velocity at downstream are very sensitive to the change of permeability ratio between the two soil zones of the case study, this sensitivity decreased at *k* ratio more than 2, if higher values are

chosen this may reflect uneconomic dam design.

References:

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Table (1) : Start and end point for the initial saturation line

Location	X- Coordinate (m)	Y- Coordinate (m)
Upstream (start point A)	50	25
Downstream (End point B)	105	10

Table (2): Total flow, seepage length and velocity at different *k1/k2* values of dam zones

K1 /K2	Q (10^{-4} m^3/min)	L (m)	V (10^{-6} m /min)
1/4	45.17	21.197	213.0962
1/2	22.28	22.554	98.78514
1.00	13.351	24.79	53.85639
2.00	7.61448	28.227	26.97587
3.00	5.47838	30.532	17.94308
4.00	4.43481	32.732	13.54885

Table (3) Results verification at (*k1/k2* = 1)

SOLUTION	Q (10^{-4} m^3/min)
Schaffernak's*	11.37
Dupuit's*	12.90
CivilFEM	13.35

*Method details and Equations as in [1]

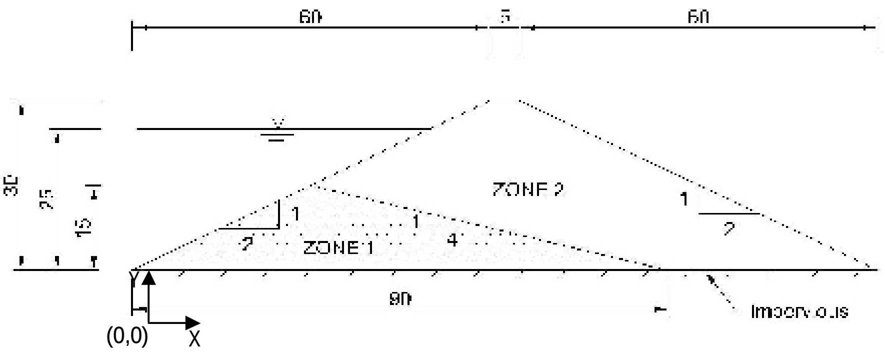
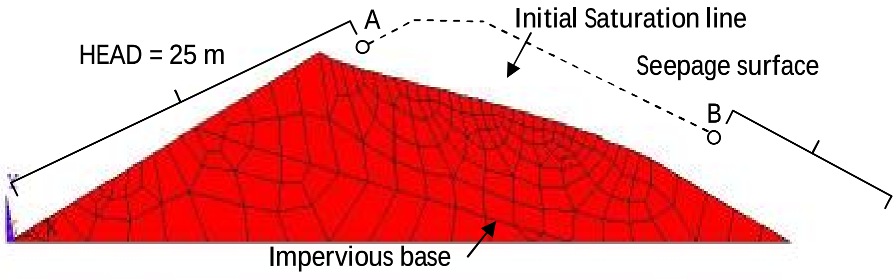


Figure (1) Case study earth dam (all dimensions in (m))



K1/K2 = 1/4

Figure (2) Mesh generation and boundary conditions

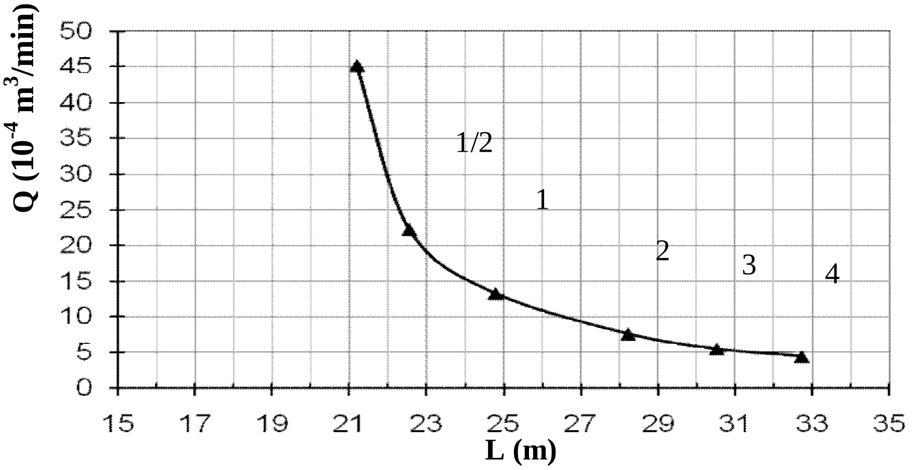


Figure (3) Variation of seepage quantity against length of seepage surface

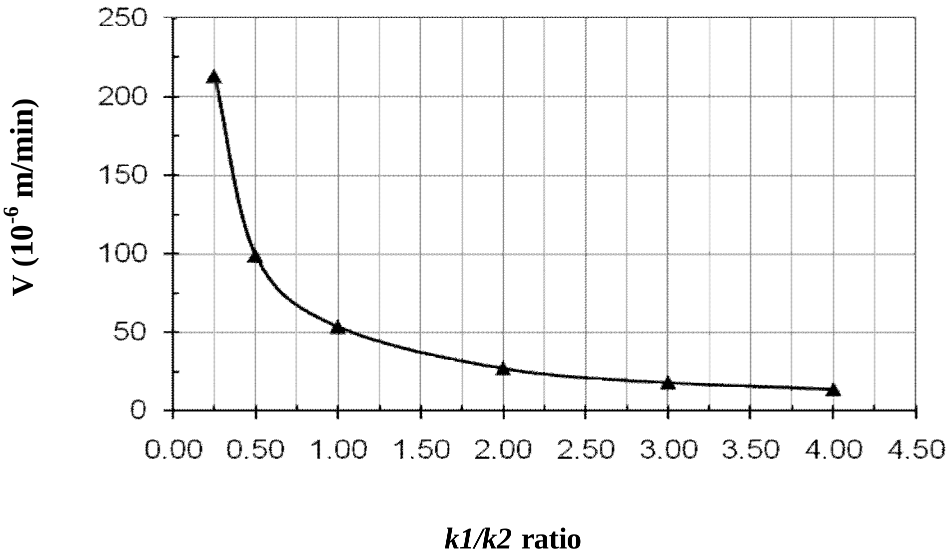


Figure (4) variation of flow velocity against *k1/k2* ratio

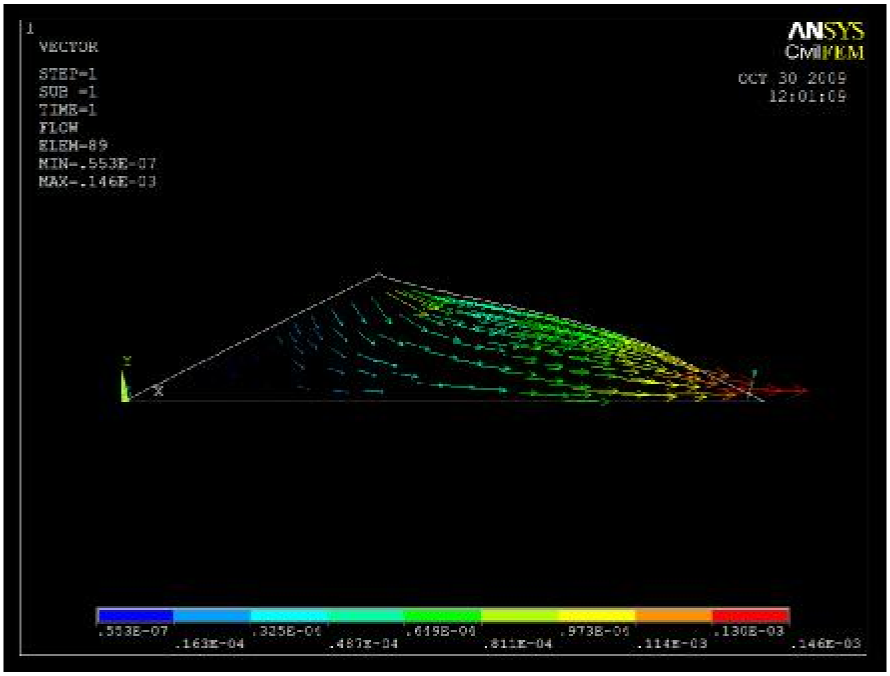


Figure (5) Flow pattern through dam body – CivilFEM output

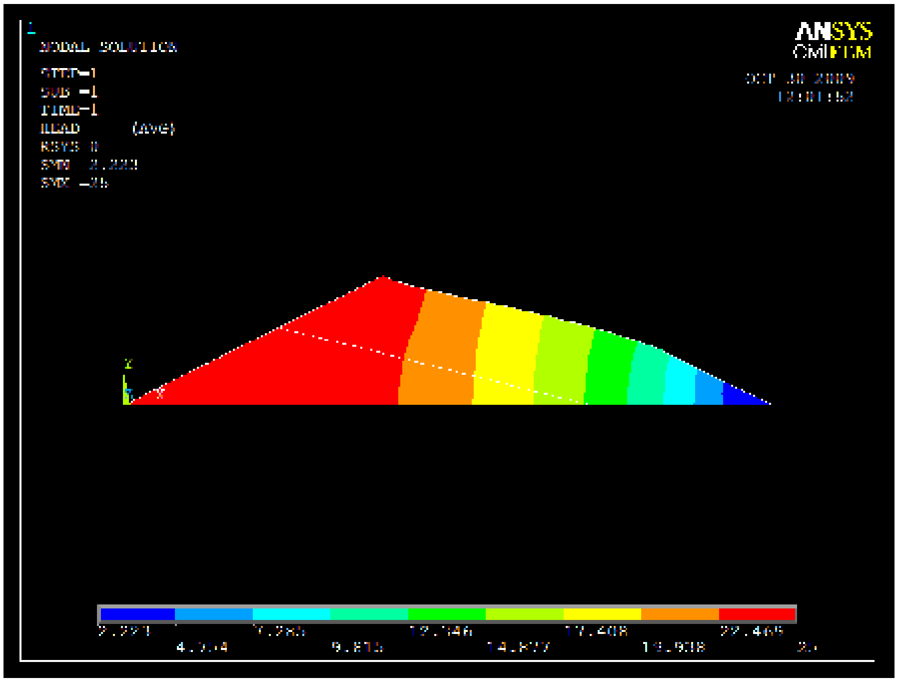


Figure (6) Water head variation through dam body – CivilFEM output

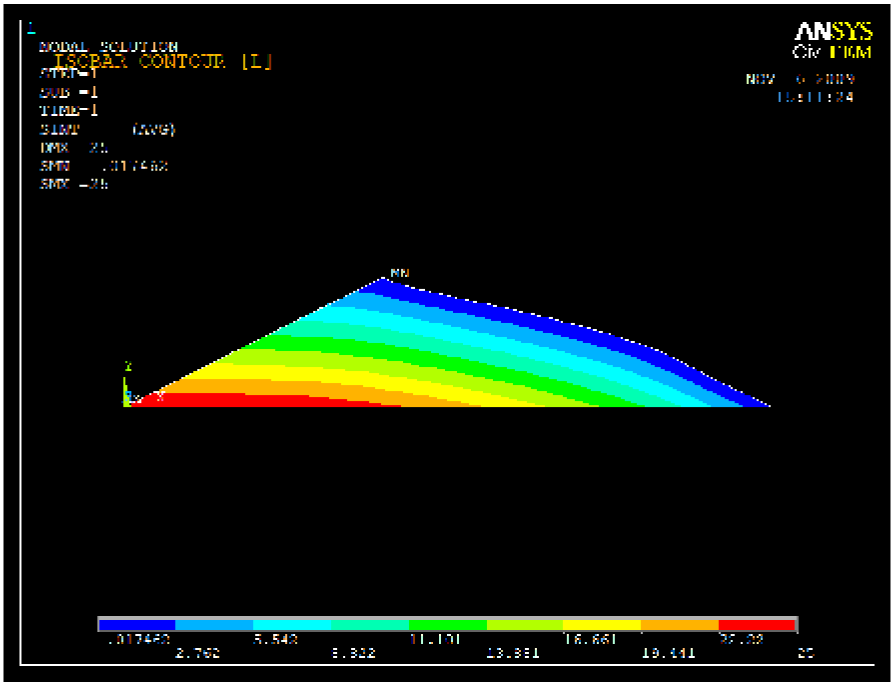


Figure (7) pore water pressure variation through dam body – CivilFEM output

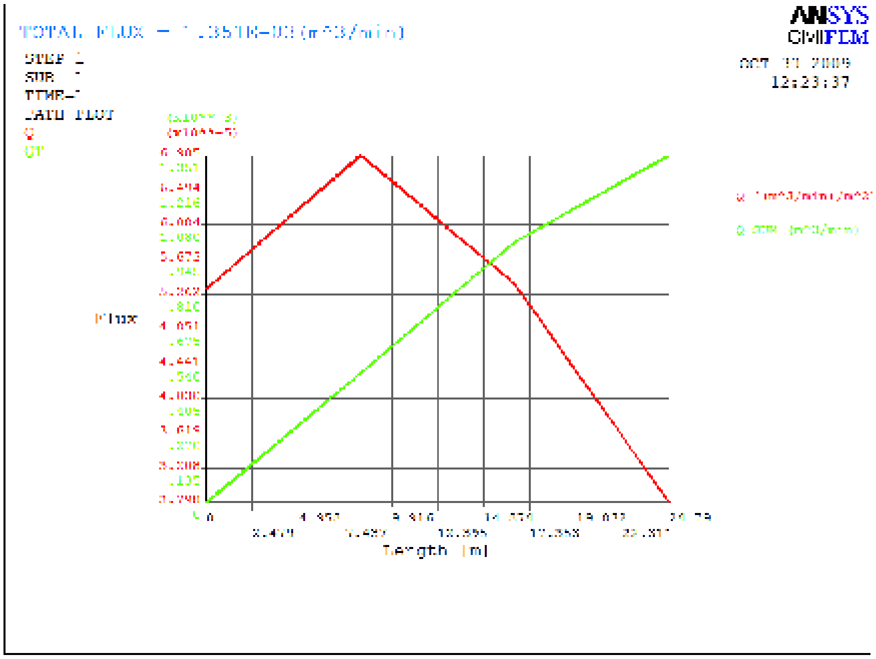


Figure (8) Total flow (Flux) change along seepage surface – CivilFEM output