2-D steady seepage flow model to simulate the contaminates transportation through homogeneous earth dam using Geo–Studio software

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Abstract. Geo-Studio program is used in this study with its sub-programs named SEEP/W and CTRAN/W 2012 to represent and analyse the phreatic line, the amount of seepage through the dam, the pressure head, the discharge, the total head and the amount of contaminants that transport through the body of the dam. The problem of transportation of contaminants through homogeneous earth dam due to seepage flow was studied and simulated using the computational fluid dynamic technique with the help of Geo–slope programs. The paper also studied the prediction of future contaminants’ levels in the specified dam. The study also discusses the effect of pool water level fluctuation from maximum to a minimum level on the seepage flow and the time of pollution transmission. From the Geo–studio software, it is deduced that when the water level is at the maximum height (20m), it needs 12 days, at normal height (15m) it needs 30 days, while at a minimum height (8 m) it needs 100 days to reach the drain zone.

Keywords: steady seepage flow; transportation of contaminates; Geo–Studio (SEEP/W); CTRAN/W.

1. Introduction
Seepage through homogeneous and zoned earth dams includes saturated and unsaturated flow. Unsaturated flow usually is ignored in the earth dam. Seepage analysis of earth dams is one of the major interesting points in geotechnical engineering.

The theory of flow through porous media is an analytical tool available for an engineer; it is normally used for calculating water seepage through earth dams and water pressure distribution. [1]

Water seepage through any earth dam is an essential phenomenon that should be taking into account in designing of earth dams. Excessive water seepage should be carefully studied during the design of an earth dam since it threatens dam stability. [2,3]
Giglou et al (2012) studied the physical and geometric factors of earth dam such as permeability, upstream and downstream slope of the dam on the analysis of saturated-unsaturated seepage problems. The seepage of water in dams has been numerically analyzed with a two-dimensional finite element simulation program with different heights of the dam of 5, 10, 20, 30, 40 and 50m. A simple expression to calculate the seepage for saturate and unsaturated flow rate is predicted. [5]

Salmasi et al. (2013) simulated more than seventy numerical models of finite elements by Seep/w software and compared the obtained data with the results previously published. The outcomes of this study indicated that the provision of the filter close to the upstream side caused higher seepage losses and it demands an increase in a filter length. The saturated zone of the dam was found to increase when the filter was located near the downstream toe which results a decrease in seepage losses and a reduction of the dry zone. In addition, the study compares two slopes of 1V:1.5H and 1V:2H and results show that further location of the filter from the upstream face required when the upstream slope is flatter.[6]

Irzooki (2016) used the computer program SEEP/W (which is a sub-program of Geo-Studio) for computing the quantity of seepage through a homogenous earth dam with a horizontal toe drain. The SEEP/W carried out with three different downstream slopes of the dam, three different upstream slopes, three variable horizontal toes drain lengths, three different free boards, three different top widths and three different heights of the dam. The quantity of seepage was determined for each definite case. The results showed that the seepage discharge increased with increasing upstream slope, downstream slope, upstream reservoir water depth and length of the horizontal toe drain. Also, the results showed that the seepage discharges decreased by increasing the upper width of the dam and the height of the freeboard.[7]

Jamel (2016) studied the quantity of seepage through a homogenous earth dam without filter resting on impervious base by using computer program SEEP/W (which is a sub-program of Geo-Studio). Using SEEP/W, the experiments carried out with three different downstream slopes of the dam, three different upstream slopes, three variable downstream head, three different upstream head, three different height of earth dam and three different top widths of an earth dam. The quantity of seepage had calculated for each run. To develop an empirical equation the dimensional analysis was used with the helping of the theoretical results in order to calculate the quantity of seepage. Also, the SEEP/W results had been verified with an artificial neural network (ANN), and compare it with the analytical methods. Results showed a comparison between the suggested equations with SEEP/W results in less than 2% error, with an artificial neural network less than 3% error, Casagrande’s solution has more than 15% error and Dupuit’s solution has more than 20% error.[8]

The movement of contaminant through porous media is generally obtained by solution of advection dispersion equation. Advection means that the contaminants transport at a velocity equal to the average velocity of the groundwater [9]

Many studies derived the advection-dispersion equation from mass and mass flux balance equations [9–13].

![Cross-section of homogenous earth-fill dam with blanket drain](Image)
Computer programs and mathematical models for the solution of one-dimensional convective-dispersive solute transport equation were first presented by Genuchten et al. (1982). The models solve the differential equations of diffusion, linear equilibrium adsorption, convection, and dispersion considering the impact of zero-order production and first-order decay.[14]

An experimental data of diffusion test was published by Barone et al. (1992) for calculating diffusion and absorption coefficients for different organic compounds in clayey soil. The chemical compounds tested in experiments were chloroform, acetone, toluene, and aniline, at concentrations of 200-300 mg/L. Batch experiments were also performed for the same compounds for comparison with the diffusion data.[15]

The research of SHENG et al. (1999) focuses on the advective transport of a soluble contaminant passes on homogeneous soil assuming non-linear sorption through the stationary porous media. Langmuir and Freundlich sorption isotherms were assumed for the non-linear first-order hyperbolic equations sorption isotherm. The shock fronts in Langmuir sorption was developed at the leading edge while the shock fronts in Freundlich sorption was developed at either the leading or trailing edges.[16]

A new lecture on simulation and laboratory experiment approach was presented by Likos and Lu in 2004 for illustrating the diffusion of a chemical compound in soil. Dyes were used to modeling the contamination of flowing soil-water system to provide visual learning presentation and avoiding complex traditional chemicals.[17]

An experimental and simulation study by Swami et al. (2013) was performed for the behavior of solute diffusion through stratified porous media. The numerical simulation was solved to simulate the experimental data of chloride and fluoride diffusion. The results showed that the maximum of breakthrough curves of non-reactive solute was higher than that of reactive solute.[18]

The purpose of this paper is to study and investigate the seepage flow and transportation of contaminants through a homogeneous earth dam. The results were presented using Geo-studio software.

1.1. Contaminates Transportation:

The advection may be defined as the movement of dissolved solute with the seepage of water through porous media. Moreover, both advection and hydrodynamic dispersion can be expressed as the physical properties that control solute flux. Since the solute is transported by the seepage lines through the porous media, the advection is governed by Darcy's law.

The hydrodynamic dispersion results from mechanical mixing and molecular diffusion, which is a process where ionic or molecular constituents move in the direction of their concentration gradient. On the other hands, the constituents move from regions of higher concentration to regions of lower concentration. The diffusion depends on the intensity of the gradient and is governed by Partial Differential Equation (PDE) which is described as advection diffusion time-dependent equation [19].

1.2. Geo – Studio Software

According to Geo-Slope International (Geo-Studio) SEEP/W is a finite element software product for simulating groundwater seepage. It is comprehensive formulation allows for one to consider analyses ranging from simple, saturated steady state problems to complicated, saturated / unsaturated time-dependent program. SEEP/W simulates the movement of liquid water or water vapor through saturated and unsaturated porous media. This might include simulations of steady or transient groundwater flow within natural flow systems subject to climatic boundary conditions.[20]

CTRAN/W is a numerical model that can be simulated and analyzed all types of problems about contaminant transport through a medium. The simulated program use the seepage-flow velocities from the flow of saturated and unsaturated zones for solving the model [21].

2. Homogeneous Embankment Dam:

A homogeneous embankment type earth dam which composed of a sandy soil with the horizontal drainage at the downstream is chosen. The height of the dam was (22.5) m and its length, L = 107.25m, while the upstream side slope was 2.5H: 1V and the downstream slope 2H: 1V. Table (1) illustrated the technical specifications of the earth dam.
Table 1. The technical specifications of the embankment.

| Type of Dam          | Homogeneous Earth dam |
|----------------------|------------------------|
| Dam                  | Height: 22.5; Length: 107.25 m |
| Freeboard           | 2.5 m                  |
| U/S Water level     | 20 m                   |
| Type of Material    | Sandy Soil             |
| Slope of the dam    | Upstream: 2.5:1; Downstream: 2:1 |
| Thickness of Filter | 1 m                    |
| Type of Dam         | Homogeneous Earth dam  |

3. Theoretical Analysis

3.1. Geo – Studio:
Seepage water (SEEP / W) and the transportation of contaminants through the soil (CTRAN/W) were studied as follows.

3.1.1. Seepage Flow: The first state studies flow net (stream lines and equipotential lines) through earth dam. SEEP/W depending on the fundamentals that the water flow thru both, saturated as well as unsaturated soil supports Darcy’s Law, which states that:

$$V = k \, i$$

(1)

Where:
- \( v \) = the Darcian velocity.
- \( k \) = hydraulic conductivity, and
- \( i \) = hydraulic gradient.

Darcy's Law was originally derived for saturated soil, but later researches had shown that it is applicable to water flow thru unsaturated soil. However, it must be noted that the hydraulic conductivity is not constant any longer under unsaturated flow conditions. This is the main difference where the mentioned conductivity differs with water content changes. However, it varies indirectly with pore water pressure changes.

It must also be noted that the real averaged velocity for the movement of water thru the soil is a linear one. This corresponds to the “Darcian velocity divided by the porosity of the soil. In unsaturated soil, it is equal to Darcian velocity divided by the volumetric water content of the soil”. Therefore, SEEP/W calculates and demonstrates the Darcian velocity only.

3.1.2. Solute Transfer: The second state studies the transportation of contaminant through an earth dam through sub-program (CTRAN/W).

The contaminant is transported by groundwater through: (i) retardation, caused by sorption; (ii) dispersion, caused by molecular diffusion and mechanical mixing; and (iii) advection, caused by the groundwater flow [22].

Advection refers to the transport of dissolved solute with groundwater flowing in porous media at the seepage velocity that follows Darcy’s law.

Dispersion occurs due to two procedures; mechanical mixing and molecular diffusion.

Fick’s law can be used for expressing molecular diffusion as:

$$F = -D \frac{dc}{dx}$$

(2)
Where:
- \( F \) = mass flux per unit area per unit time,
- \( D_f \) = diffusion coefficient,
- \( C \) = contaminant concentration,
- \( \frac{dc}{dx} \) = concentration gradient”.

Molecular diffusion \( D^* \) represented by:
\[
D^* = \omega D_f
\]
(3)

Where \( \omega \) is the empirical coefficient with the value of less than 1, which considers the influence of the porous media’s solid phase on the diffusion. The range of \( \omega \) is from 0.5 to 0.01.

The coefficient of hydrodynamic dispersion is given by:
\[
D_L = \alpha_L V + D^*
\]
(4)

Where:
- \( D_L \) = longitudinal mechanical mixing component of dispersion
- \( \alpha_L \) = longitudinal dispersivity = 0.1 L, where L is the length of the flow path.

Advection-dispersion transport:
In saturated zone, dispersion as well as advection is prevalent. The relation that controls this process is:
\[
\frac{\partial^2 C}{\partial x^2} - \frac{\partial C}{\partial x} = \frac{\partial C}{\partial t}
\]
(5)

Sorption refers to the molecular and ionic trade between liquid and solid phases. This includes desorption as well as adsorption. For calculating the retardation coefficient, the distribution coefficients for the contaminant can be used as well as the characteristics of the porous medium such that:
\[
R = \left[ 1 + K_d \times \frac{C_s}{C_e} \right]
\]
(6)

The distribution coefficient \((K_d)\) was calculated by taking the ratio of adsorption concentration in soil \((C_s)\) and equilibrium concentration in solution \((C_e)\). Thus, the distribution coefficient \((K_d)\) was calculated using the equation:
\[
K_d = \frac{C_s}{C_e}
\]
(7)

For calculating the groundwater contaminant’s velocity, the following correlation can be utilized:
\[
V_c = \frac{V}{R}
\]
(8)

Where \( V_c \) is the velocity of the contaminant movement in groundwater, \( V \) is the groundwater velocity, and \( R \) is the retardation factor” High adsorption coefficient is represented by a high value of retardation factor, which substantially impedes the passage of groundwater contaminants.

Boundary Conditions:
The boundary conditions are satisfied by the following points:
- At inlet
  \( H = 20 \text{m}, \text{ and } C = 100 \text{ (g/m}^3) \)
- At outlet
  \( H=1 \text{m}, \text{ Mass rate of dispersive contaminant (} \dot{m} \text{) } = 0 \text{ (g/day)}. \)

3.1.3. Partial differential water flow equations: The governing equations used in transient flow formulation are from "Seepage Modeling with SEEP/W" (Geo-Slope)
\[
\frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + Q = \frac{\partial e}{\partial t}
\]
(9)
Where:

\[ H = \text{total head}, \]
\[ k_x = \text{hydraulic conductivity in the x-direction}, \]
\[ k_y = \text{hydraulic conductivity in the y-direction}, \]
\[ Q = \text{applied boundary flux (per unit volume)}, \]
\[ \Theta = \text{volumetric water content}, \] and
\[ t = \text{time (t)}. \]

The equation states that the change in volumetric water content is same as the difference between the flow of incoming and outgoing of an elemental volume at a point in time (flux). Basically, the volumetric water content’s rate of change is equal to the summation of rate of flow changes in 2 dimensions and the externally applied flux. The flux stays same at all times under steady-state conditions. Thus, this eliminates the equation’s right side thus reducing it to:

\[ \frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + Q = 0 \]  

(10)

Moreover, variations in soil properties and stress states result in changes in the volumetric water content. SEEP/W is devised for constant total stress conditions. To elaborate, this signifies that no loading or unloading of the mass of soil takes place. Changes in pore water pressure can be associated to changes in volumetric water content through the following correlation:

\[ \partial \Theta = m_w \times \partial u_w \]  

(11)

Where:

\[ u_w = \text{the pore-water pressure}, \]
\[ m_w = \text{slope of the storage curve}, \]
\[ H = \text{total hydraulic head}, \] is given by:

\[ H = \frac{u_w}{\gamma_w} + y \]  

(12)

Where:

\[ \gamma_w = \text{the unit weight of water}, \]
\[ y = \text{the elevation (L)}. \]

Rearranging Equation (12) gives:

\[ u_w = \gamma_w (H - y) \]  

(13)

Substituting equation (13) into (11) gives the following equation:

\[ \partial \Theta = m_w \gamma_w \partial (H - y) \]  

(14)

Substituting into equation (9) results in:

\[ \frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + Q = m_w \gamma_w \frac{\partial (H - y)}{\partial t} \]  

(15)

The \( y \) derivative respecting time disappears since the elevation is constant. This results in the below-mentioned governing differential equation:

\[ \frac{\partial}{\partial x} \left( k_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_y \frac{\partial H}{\partial y} \right) + Q = m_w \gamma_w \frac{\partial H}{\partial t} \]  

(16)

3.1.4. Contaminant transport equations for CTRAN / W software differential water flow equations: The governing equation for contaminant transport was taken from "Contaminant Modeling with CTRAN/W" (Geo-Slope). By taking into consideration the mass flux, \( q \), in an elemental volume of
porous material, the equation for solute transport can be derived. This is also demonstrated in Figure 2. Across the element, the absolute net mass flux is given as:

\[
\text{Net mass flux} = \frac{dq}{dx}
\]  \hspace{1cm} (17)

Figure 2. Mass balance in a 1D element.

For mass conservation, “the rate of change of the total mass \(M\) in the element must be equal to the net mass flux”. As a correlation, this is given as:

\[
\frac{\partial M}{\partial t} \, dx = -q \frac{dx}{dx} \, dx
\]  \hspace{1cm} (18)

The concentration \(C\) may be defined as the mass \(M\) of dissolved solute per unit volume of water (solution) such that:

\[
C = \frac{M}{V_w} \text{ or } M = CV_w
\]  \hspace{1cm} (19)

The volumetric water content \(\Theta\) is defined by the volume of water in unit volume of the element. The resulting mass, \(M\), in unit volume is:

\[
M = C\Theta
\]  \hspace{1cm} (20)

Substitution for \(M\) in Equation (19) followed by dividing by (dx) results in:

\[
\Theta \frac{\partial C}{\partial t} = -q \frac{dx}{dx}
\]  \hspace{1cm} (21)

The mass flux through the element arises from both advection and dispersion processes. In equation form, these two mechanisms are:

\[
\text{Advection} = v \Theta C = U
\]
\[
\text{And, dispersion} = -\Theta D \frac{\partial C}{\partial x}
\]

where:

\(v\) = average linear velocity,
\(\Theta\) = volumetric water content,
\(C\) = concentration,
\(D\) = hydrodynamic dispersion coefficient, and
\(U\) = Darcy velocity (specific discharge)

In the dispersion term, the negative sign shows the mass flow direction is from high concentration to a low concentration. Thus, the fundamental transport equation can be derived by the substitution of the previous two terms into Equation (22):

\[
\Theta \frac{\partial C}{\partial t} = -\frac{\partial}{\partial x} \left[ -\Theta D \frac{\partial C}{\partial x} + UC \right] = \Theta D \frac{\partial^2 C}{\partial x^2} - U \frac{\partial C}{\partial x}
\]  \hspace{1cm} (22)

Dividing this equation by \(\Theta\) results in:

\[
\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - v \frac{\partial C}{\partial x}
\]  \hspace{1cm} (23)

Diffusion coefficient \(D^*\), average linear velocity and dispersivity are all related to the hydrodynamic dispersion coefficient, \(D\) by:
Equation (22) represents advection – dispersion equation, the fundamental transport equation of a non-reactive substance. To elaborate, this means that adsorption does not result in any loss of mass. In terms of the movement of reactive substances, the mass transfer is influenced by the soil particles adsorption of the solute. Mass amount adsorbed can be described by referring to the soil particles of bulk mass density. Therefore, the adsorbed mass, \( M_s \), is:

\[
M_s = S \rho_d
\]  \hspace{1cm} (25)

Where

\[
\text{“Ms = the amount of mass attached to a unit mass of soil particles”,}
\]
\[
S = \text{the adsorption, and}
\]
\[
\rho_d = \text{the bulk density.}
\]

The adsorbed mass’s rate of change can be given by:

\[
\frac{\partial M_s}{\partial t} = \rho_d \frac{\partial S}{\partial t}
\]  \hspace{1cm} (26)

where “the adsorption \( S \) is a function of concentration \( C \)”. Usually, experimental results are plotted as \( S \) versus \( C \) and the gradient of this plot is \( (\partial S / \partial C) \). Such a gradient is often known the distribution coefficient \( K_d \), where the relationship is linear. This leads to the rearrangement of previous equation as:

\[
\frac{\partial M_s}{\partial t} = \rho_d \frac{\partial S}{\partial C} \frac{\partial C}{\partial t}
\]  \hspace{1cm} (27)

Equation 22, the transport equation, can then be altered for including adsorption. This results in:

\[
\Theta \frac{\partial C}{\partial t} + \rho_d \frac{\partial S}{\partial C} \frac{\partial C}{\partial t} = \Theta D \frac{\partial^2 C}{\partial x^2} - U \frac{\partial C}{\partial x}
\]  \hspace{1cm} (28)

Or,

\[
\left[ \Theta + \rho_d \frac{\partial S}{\partial C} \right] \frac{\partial C}{\partial t} = \Theta D \frac{\partial^2 C}{\partial x^2} - U \frac{\partial C}{\partial x}
\]  \hspace{1cm} (29)

4. Results:

A schematic diagram of homogeneous earth dam and the finite element mesh which used for the analysis by using Geo - Studio software is illustrated in Figures 3 and 4. The mesh type (Quads and Triangles) includes elements for the whole body of the dam, and the global element size is 2 m. The numbers of elements for all boundaries are 328 elements and the numbers of nodes are 374 nodes.
In homogeneous earth dam, the phreatic line starts from the water surface level and drops throughout the dam until it passes through the horizontal drainage filter and exit at the dam toe, throughout the filter. The object of the horizontal drainage filter is to pull the phreatic line down into the filter such that it does not intersect with the downstream side of the dam. The location of seepage line at steady state seepage flow through earth dam at (20m, 15m and 8m) upstream water level using Geo–Studio software is indicated in Figure 5.A, B, C respectively. A dotted blue line represents the phreatic line in the dam. The colored area represents a drop in pressure head from (20 m) to (1 m) as shown in Figure 5.A.
Figure 5 A, B, C. Location of seepage line and equipotential lines

Unsteady state (time dependent) contaminates transportation through the dam is indicated in Figure 6.A, B, C. The colored area represents the transmission of contaminates from the upstream or the source of the contaminants down through the earth dam. It is shown that the contaminant needs 12 days, 30 days, and 100 days until reach the drain zone at the upstream water level of 20m, 15m and 8m, respectively as shown in Figure 6.A, B, C.
Table 2. and Figure 7 illustrate the effect of water level on the time rate of change of contaminates transportation and discharge through the earth dam till reaching the drain zone.

**Table 2:** Effect of reservoir water level on the time rate of contaminates transportation and discharge through the dam

| Head (m) | Time (day) | Discharge (m$^3$/day) |
|----------|------------|------------------------|
| 8        | 100        | 1.25                   |
| 15       | 30         | 5.85                   |
| 20       | 12         | 12.95                  |

The contaminates reach the state of stability or close to the concentration of the reservoir after (54) days (75) days and (225) days at 20m, 15m and 8m height of water level respectively as shown in Figure 8.A, B, C.
5. Conclusions:
The following conclusions can be drawn from this research:

1. Flow through porous media and transportation of the contaminants are well simulated by a two-dimensional finite element seepage flow model based on the basic equations of steady seepage flow of homogeneous earth dam and definite conditions by using the Geo–Studio (SEEP/W sub program). The program is applied on Homogeneous earth dam to specify the location of the free surface seepage line, the quantity of seepage through the dam, and the total head measurements.

2. The phreatic line starts from the water surface level and drops throughout the dam until it passes through the horizontal drainage filter and exit at the dam toe, throughout the filter. The object of the horizontal drainage filter is to pull the phreatic line down into the filter such that it does not intersect with the downstream side of the dam and then mitigate the damage of dam side.

Figure 8 A, B, C. The Contaminants’ Transportation for t=6 hrs.
3. The transportation of the contaminant is simulated by a two-dimensional finite element model based on the equations of unsteady contaminant transportation through porous media (advective – dispersion equation) with definite conditions by using the Geo – Studio (CTRAN/W sub program). Geo- studio software indicates that the contaminant needs (12) days until reach the drain zone while they reach the state of stability or close to the concentration of the reservoir after (54) days at 20m height of water level. Also, the contaminants needs (30) days until reach the drain zone while they reach the state of stability or close to the concentration of the reservoir after (75) days at 15m head of water level. Moreover, the contaminants required (100) days to reach the drain and (225) days to reach the concentration as in the reservoir at 8m height of water level in the reservoir.

4. There is an inverse relation between the effect of water level on the rate of change of contaminates transport; while the discharge through the earth dam varies as the change in water level.

Acknowledgments:
The authors would like to thank Mustansiriyah University (www.uomustansiriyah.edu.iq) and college of engineering Baghdad-Iraq for its support in the present work and the Hydraulic and hydrology Laboratory staff in the College of Engineering for their support and helps through the period of the experiments.

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