



ANALYZE THE UNCERTAINTY EFFECT OF SATURATED AND RESIDUAL WATER CONTENT OF SOIL WITHIN HOMOGENEOUS EARTHEN DAM ON SEEPAGE VALUES

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ABSTRACT

Background: Earth dams are one of the most important engineering facilities and an essential part of the infrastructure supporting the economy in various fields in Syria and other countries. **Objectives:** We focus in this research to determine the effect of the uncertainty in both saturation and residual water content of the unsaturated soil on the seepage through a homogeneous earth dam for steady state conditions as it will be considered as random variables, which provides the best simulation reflecting the actual situation of any similar engineering facility. **Methods:** A mathematical model for the dam was created using the Seep/W program based on the flow relationship that includes both the saturated and the unsaturated state, taking into account the uncertainty and unreliability of the studied parameters, after a code has been written for the governing equations of the unsaturated flow that allows the generation of random values from their statistical characteristics and last been added to the Seep/W program through the Add-in function. The Monte Carlo simulation method (MCSM) was adopted to solve the seepage issue for a very large number of models (5000 models for the total cases studied in this research), each parameter was analyzed independently and a deterministic model was built for comparison. **Results:** The results show the minimal effect of the variance of the saturation content on the seepage for the studied soils in this research, and the possibility of neglecting the effect of its residual water content. **Conclusions:** so saturated and residual water content for the unsaturated zone in homogeneous earth dams can be treated as deterministic parameters for steady state seepage.

Keywords *Unsaturated soil - earthen dams - residual water content-saturated -water content.*

1. INTRODUCTION

Inputs for many engineering issues, such as initial conditions, boundary conditions, and different parameters are random in fact, and their statistical characteristics are known from observations in previous researches based on field or laboratory measurements, and these random variables may cause a different behavior of systems than expected, so it was necessary studying the randomness of some of the unsaturated soil parameters within earth dams, and its impact on the seepage through it. which may make it vulnerable to the risk of collapse due to many factors such as construction materials, weather factors, etc. [1, 2].

Uncertainty in the soil parameters (as residual and saturated water content, hydraulic conductivity ,etc.) may be caused by uncertainty in the dimensions and proportion of pores, components of the soil grains and the dimensions of these grains, the ratio of fine grains, the presence of clay and organic matter, the irregularity of the grain forms and changes in some properties due to stacking during the construction of the dam or because of the change of porous pressure during Humidification and drying also), so it was necessary to study randomly some of the unsaturated soil parameters within the earthen dams to define their extent effect on seepage.

Previously research had been neglected and canceled the unsaturated region when studying earthen dams but Aigner et al. (2004) explained the importance of studying it on the stability of the downstream face. AIGNER model (6) clearly demonstrated the impact of unrefined soils by various factors applied to the physical model such as the storage level on the upstream face of the dam and the occurrence slipping on the downstream soil above the seepage line in the unsaturated or partially saturated zone clearly shown in Figure (1) [3].



Figure 1: Physical model of an earthen dam that slid on the downstream face due to its water content [3].

considering the soil water content in the unsaturated zone above seepage Line is very important but highly complex, the researchers use modeling ways to clarify these issues Like other complex engineering issues and the adoption of random probability analysis parameters to simulate systems without simplifying.

Groundwater flow problems (steady and unsteady states) have been extensively conducted for many years Warren and Price (1961), Yeh et al. (1985), Zhang (1999) the researchers applied analytical methods for stochastic analyses [4-6]. Seepage analysis in earth dams was conducted also and the FEM and MCS methods were used together for this object Ahmed (2009) and Fenton et Griffiths (1996) their modeled hydraulic conductivity as a spatially varying random field following a lognormal distribution with known mean and variance [7, 8]. Le et al. (2012) made a same study but the porosity considered as a random variable and its impact on seepage rates [9].

Many models describe the unsaturated soil flow and investigate the soil-water characteristic curve SWCC as Gardner (1956) and van Genuchten (1980) and many researchers studied the unsaturated soil parameter specially van genuchten parameter as random variables [10, 11]. Li et al. (2009) have considered the randomness of the hydraulic conductivity and van Genuchten fitting parameters, α and n . in their stochastic seepage or groundwater flow models. the random fields of The parameters were independently generated using Karhunen-Loeve expansion technique. The study was focused on the efficiency of the probabilistic collocation method and resulted that this method can accurately estimate the seepage rate statistics with a smaller effort when compared with MCS [12].

Calamak (2016) analyzed stochastically the two-dimensional transient flows through a porous medium in earth dams and consider the randomness of hydraulic conductivity and van Genuchten fitting parameters, α and n . his results were hydraulic conductivity should be considered random, whereas van Genuchten parameters can be treated in a deterministic manner in transient seepage analysis [13].

Saturated and residual water Water content (θ_s, θ_r) of unsaturated soil in earth dams weren't studied as random variables in any study so we focus on the effect of their randomness on seepage flow rate in this study.

2. MATERIALS AND METHODS

2.1 Mathematical basis and hydraulic model for steady state

Darcy law can be applied to the model of water seepage through the saturated and unsaturated soils of earthen dams

$$q = K \cdot I \tag{1}$$

Where q : is the discharge, K : is the hydraulic conductivity of the soil, and I : is the hydraulic gradient. The Richard differential equation of flow through saturated and unsaturated soils is the governing of the two-dimensional seepage, as in a cross section of the earthen dam, based on the assumption that the flow follows Darcy law [14].

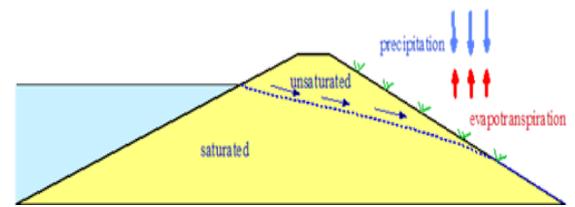


Figure 2: A simplified diagram of an earthen dam shows the distribution of saturated and unsaturated zones

$$\frac{\partial \theta}{\partial t} = \left[\frac{\partial}{\partial x} \left(K_x \frac{\partial H}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial H}{\partial y} \right) \right] + \dot{Q} \tag{2}$$

for steady state $\frac{\partial \theta}{\partial t} = 0$

Where K_x and K_y are the hydraulic conductivities in the x- and y-direction, H is the total head, Flow across the boundary condition, θ = volumetric water content, t =time.

2.2 Seep/W software

The program adopts the method of FEM finite element method to solve Richard equation Described in the previous section for seepage through saturated and unsaturated zones and the solution is executed iteratively. Seep/W is characterized by the ability to add new functions to define different parameters and conditions through the Add-In function feature. Where it is possible to add a code and generate Dynamic link libraries to model the research issue in order to assess the uncertainty in some soil properties [15, 16].

2.3 Unsaturated soil model

Several experimental and mathematical equations have been proposed to describe The relationship between water content and soil suction pressure by the water retention curve within specific areas of moisture, as (Brooks and Corey 1964) and others.

Van Genuchten also proposed the following relationship to define a water retention curve or the soil-water characteristic curve SWCC, which is the used model in this research [11]:

$$\theta_\psi = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha \cdot \psi)^n]^m} \tag{3}$$

Where: θ_ψ is water content of soil (m^3/m^3) Corresponding to the head of the water ψ (m), θ_s : saturated water content, θ_r : residual water content, α, n, m : Van Genuchten Experimental parameters for the soil-water characteristic curve SWCC.

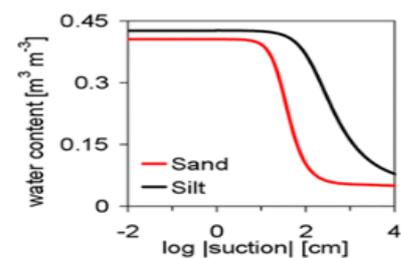


Figure 3: Illustration of the soil water curves of sandy and silty soil.

Seepage flow directly depends on the hydraulic conductivity of the soil, which significantly differs in saturated and unsaturated zones. Unsaturated hydraulic conductivity is determined by the suction and water content of the soil. (van genuchten,1980) will be used

$$Ku = Ks \cdot \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^l \cdot \left\{ 1 - \left[1 - \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)^{\frac{1}{1-n}} \right]^n \right\}^2 \tag{4}$$

Where: Ku : unsaturated hydraulic conductivity coefficient, Ks : saturated hydraulic conductivity coefficient, θ : water content of the soil, θ_s : saturated water content, θ_r : residual water content, n : is related to the slope at the inflection point of the SWCC and depends on the pore-size distribution (Sillers et al. 2001) [11, 17].

2.4 Generation Random variables

The soil uncertainty model is built by considering residual and saturated water content as random inputs. The parameters θ_s and θ_r follow lognormal distribution for most types of soils (Carsel and Parrish 1988). in the study of (Ning Lu et al.,2012) in Korea, they are stated to be independent for all studied soils also in van Genuchten (1980) they are stated to be independent, so the Box and Muller 1958 method were used. For the probability density functions (PDFs) of the parameters studied in the research (hydraulic conductivity coefficient, saturation content), defined by the arithmetic mean and the coefficient of variance for each of them, they follow the log-normal distribution of many types of soils according to previous studies that are internationally accredited [18, 19].

$$\sigma_{\ln x}^2 = \ln \left(1 + \frac{\sigma_x^2}{\mu_x^2} \right) \tag{7} \quad / \quad \mu_{\ln x} = \ln(\mu_x) - \frac{1}{2} \sigma_{\ln x}^2 \tag{8}$$

Lognormally distributed random values for a parameter (x) are obtained by using the following relationship:

$$x = \exp(\mu_{\ln x} + \sigma_{\ln x} r') \tag{9} \quad : \quad r' = (-2 \ln u_1)^{1/2} \sin 2\pi u_2 \tag{10}$$

Where: r' is the standard normally distributed random number obtained from the Box-Muller transformation (Box and Muller 1958), u_1 and u_2 are independent random variables with uniform PDF within the interval (0,1). (x) can be replaced by any other parameter that we want to generate random value as residual and saturated water content that studied in this research.

2.5 Monte Carlo Simulation (MCS)

Monte Carlo simulation is generally used to determine the output characteristics of complex systems with nonlinear behavior, without using any assumptions or simplifications, Reflecting the actual reality and this is the main advantage of this approach, in addition, this technique is relatively simple, practical and the most used approach in the random analysis of water movement in soils and its models [20]. MCS requires a detailed definition of the studied issues as engineering properties, initial and boundary conditions, soil properties as in this study (hydraulic conductivity coefficient, volumetric water content). Simulations of the same problem are performed and solved repeatedly with identical geometry and boundary conditions but with different random variables generated from their known statistical properties (PDF defined with a mean and variance). Solving each simulation gives an output (seepage rate), a set of outputs can be obtained when performing a large number of simulations, then the results can be analyzed statistically to understand the behavior of the system as in many research, by using the software like Minitab, Excel this method was adopted for each of θ_r , θ_s .

2.6 Engineering specifications of the studied dam

The research issue will be applied to a homogeneous earth dam consisting of sandy clay soil (SC), based on an impermeable foundation as in Figure (4). the engineering properties of the dam will be determined using the design specifications of the dams (United States Bureau of Reclamation (USBR) (1987) [21]. Dam height 25 m, the inclination of the front face is 1: 3, and the tilt of the back face 1: 2, dam base width 133 m, peak width 8 m. The seepage will be assessed within the dam's body only to show the effect of the random unsaturated soil parameters studied in this research.

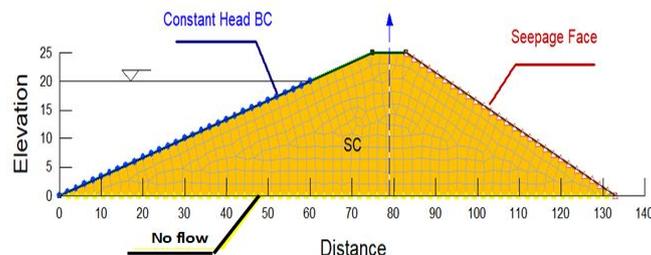


Figure 4: Cross-section showing engineering specifications and boundary conditions.

The model was done using the Seep/W program and subjected to steady state conditions The upstream side was considered as an initial condition with a constant head representing the height of the water in the reservoir (20 m), while the downstream as a seepage face and no discharge occurs through the base of the dam (impermeable foundation) thus

limit the effect on the seepage Through the embankment in the unsaturated region, and the seepage values were studied through a flow section in figure(4).

3. RESULTS

3.1 Deterministic Model

Initially, the issue of the deterministic model based on taking the mean values of both saturated and residual water content as fixed and average values as it is followed and common in most of the dams seepage studies, the result will be used for comparison later with random models results, the table shows (2) Values of Van Genuchten's parameters and the hydraulic conductivity coefficient of sandy clay soils [18].

Table 1: The table presents the hydrodynamic parameters of the unsaturated state of the sandy clay soils.

Soil type	parameter						Reference
	Hydraulic conductivity k(m/d)	Saturated content θ_s	Residual content θ_r	α (cm ⁻¹)	m	n	
Sandy clay	0.0288	0.38	0.1	0.027	0.187	1.23	Carsel and Parrish (1988)

Figure (5) shows the results of the modeling of the inevitable model in the Seep/W software. It shows the distribution of pressure head within the homogeneous dam body and the seepage line of the steady state flow condition is set by considering the parameters of the study as fixed values, where the value of the seepage rate across the flow section is 0.0765 m³/day.

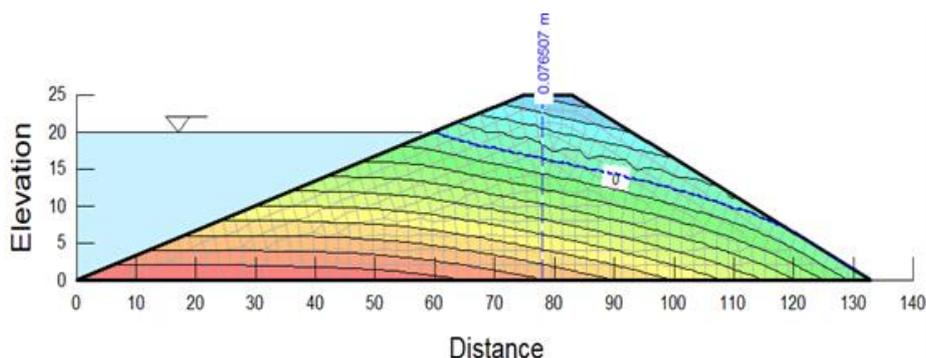


Figure 5: Results of modeling the inevitable model of the homogeneous earth dam for the stable flow condition.

3.2 Sensitivity Analysis of random parameters

This part of the paper provides sensitivity analyzes of steady state seepage across homogeneous earth dams. One sensitivity analyzes will be performed at a time to investigate the individual effects of residual and saturated water content as random variables according to the Van Genuchten model, that is, the sensitivity of the resulting flow values will be monitored according to the studied parameter change. To determine the number of models that will be built to implement the Monte Carlo technique in each study case, 1000 models were built by the Seep/W software, the parameters were entered as random variables together, and the seepage value was calculated via the flow section (we obtained 1000 flux value as outputs), the Variation of flux values were calculated until reaching a stable model, as it was found that this occurs after approximately 500 simulation models according to Figure (6). Steady state seepage analyses are conducted with SEEP/W for N models (1000 in this section). During the solution of the models, random variables are created individually for each simulation model using the #C code added to SEEP/W (for equations 3,4), producing (1000) flux value collected in one final Microsoft Excel file. Collection flux values are done using a code written in the Visual Basic language that is added to the Visual Basic for Application, so that we can open Excel files, import flow values and paste them into a final Excel file so that they can be processed and dealt with either within Excel or other statistical programs (i.e. Minitab)

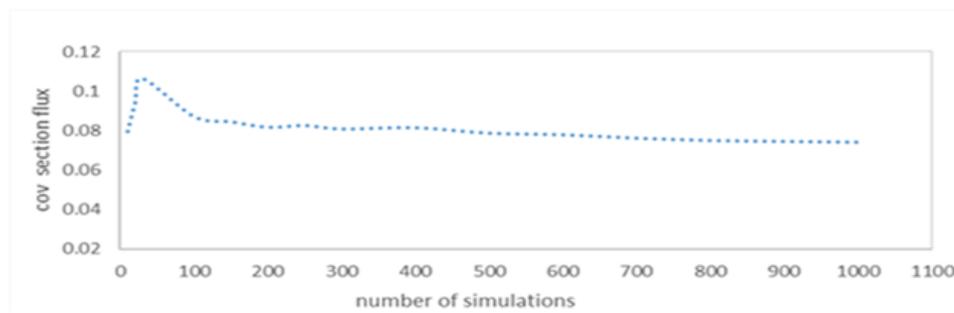


Figure 6: Change coefficient of flux variation in relation with the simulation models number.

In each set of simulation procedures for determining sensitivity, all parameters will be kept constant at their mean values, except one parameter that will be considered as a random variable whose coefficient of variation values vary from half (cov) to twice. According to Table (2), For example, in the first three cases, θ_s was considered as a random variable, while parameters hydraulic conductivity K , Residual content θ_r , α , and n are fixed at Their mean values 0.0288, 0.1, 0.027 cm^{-1} and 1.23, respectively, whereas θ_s is made random with the mean 0.38 and COV values 0.07, 0.14, and 0.28. Likewise, in the last three cases, Residual water content was considered as a random variable and the rest of the parameters are constants. In each case, a two-dimensional steady state seepage analysis is conducted stochastically with 500 MCS.

Table 2: Cases studied to clarify the leakage sensitivity of the parameters used.

Case description	parameter				
	Hydraulic conductivity $k(\text{m/d})$	Saturated content θ_s		Residual content θ_r	
	mean	mean	cov	mean	cov
1 Rnd θ_s - (Cov θ_s =0.07)	0.0288	0.38	0.07	0.1	--
2 Rnd θ_s - (Cov θ_s =0.14)	0.0288	0.38	0.14	0.1	--
3 Rnd θ_s - (Cov θ_s =0.28)	0.0288	0.38	0.28	0.1	--
4 Rnd θ_r - (Cov θ_r =0.065)	0.0288	0.38	--	0.1	0.065
5 Rnd θ_r - (Cov θ_r =0.013)	0.0288	0.38	--	0.1	0.13
6 Rnd θ_r - (Cov θ_r =0.26)	0.0288	0.38	--	0.1	0.26

3000 (6×500) simulation models of the six cases were performed. For the case where the Saturated water content was changing, the flow values for the first three cases (1500 values) were combined in one excel file and the box plot was drawn to display the results in Figure 7, and the seepage rate -Calculated by the deterministic model- was represented by the continuous blue line. Similarly, the residual water content variation for the last three states (1500 values) was combined in another Excel file and the box plot was drawn to clearly display the results for θ_r in Figure 8, Table (3) shows descriptive statistics in these cases calculated with Minitab after importing them from Excel.

Table 3: Descriptive statistics values are calculated for cases of variation of the saturated water content only.

Variable(Q) Statistics	N	Mean (Q)	COV (Q)	Minimum (Q)	Maximum (Q)	Skew	Kurt	Differ% b/w Q& Mean
$\text{cov}\theta_s=0.07$	500	0.07717	0.0	0.077125	0.077251	0.58	0.07	0.876
$\text{cov}\theta_s=0.14$	500	0.07715	0.0	0.077102	0.077244	1.08	1.77	0.838
$\text{cov}\theta_s=0.28$	500	0.07712	0.0	0.077097	0.077174	0.93	0.41	0.808
$\text{cov}\theta_r=0.065$	500	0.077282	0.0	0.077275	0.077296	1.54	2.57	1.022
$\text{cov}\theta_r=0.13$	500	0.077284	0.0	0.077270	0.077305	0.68	0.09	1.025
$\text{cov}\theta_r=0.26$	500	0.077287	0.0	0.077261	0.077317	0.20	-0.59	1.030

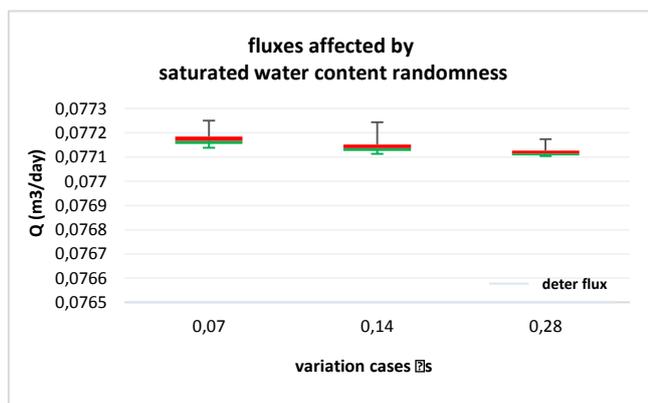


Figure 7: Box plots of stochastic seepage for steady state (variation of θ_s cases)

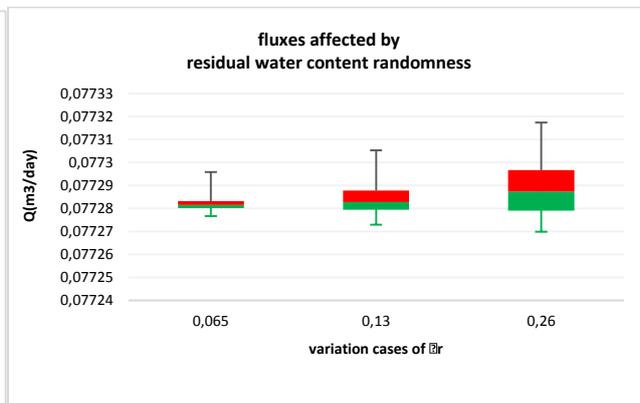


Figure 8: Box plots of stochastic seepage for steady state (variation of θ_r cases)

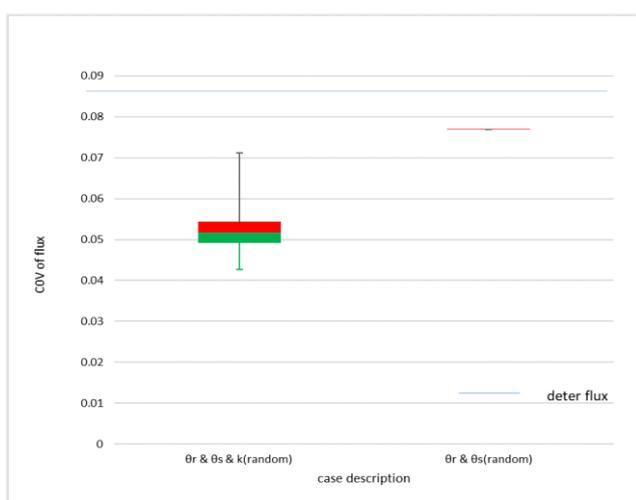


Figure 10: Box plots of stochastic seepage for steady state (variation of I&II cases).

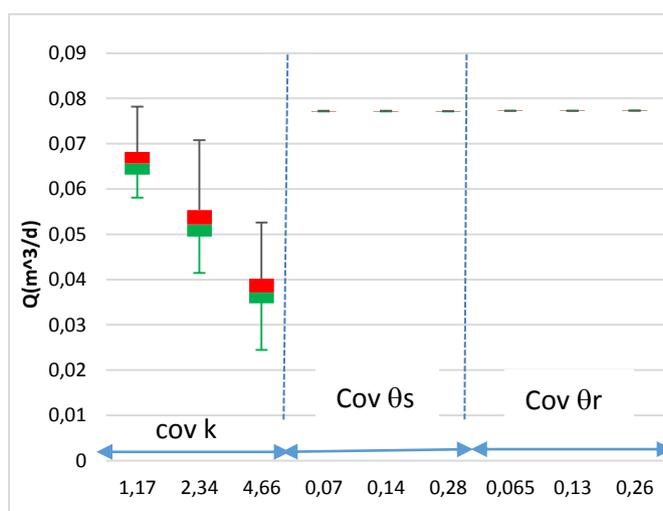


Figure 9 : Box plots of stochastic seepage for steady state (variation of θ_r, θ_s, k cases)

3.3 Statistical study for the seepage of random models

In this part of the research, two cases were studied and each case contained 1000 models that were constructed with the Seep/W program. In case I two parameters were considered as random variables (θ_s & θ_r) only, While In case II all parameters were considered as random variables (θ_s & θ_r & K) to assess the effect of the parameters randomness of the inputs on the seepage rate (as outputs) and on the statistical distribution that the outputs follow. Table (4) shows the results (descriptive statistics) of studied cases (I&II) measured as mentioned previously using the Minitab program.

Table 4: Descriptive statistics of Seepage values through the dam's embankment studied for 1000 random samples using Minitab.

Variable	Case number	Descriptive Statistics									
		N	Mean	StDev	COV%	Minimum	Median	Maximum	Skewnes s	Kurtosis	MSSD
Flux(Q) m ³ /d	I	1000	0.076875	3E-6	0.004	0.076872	0.076874	0.076901	0.04	0.25	0.00
	II	1000	0.05199	0.003857	7.42	0.040055	0.051822	0.071155	0.33	0.41	0.000015

To find the optimal distribution function for seepage data, a probability plot is used and the judgment is determined whether the distribution follow-up fits the data based on the following conditions: the points drawn will form an almost straight line; • Draw points will approach the fitted distribution line; • Anderson-Darling statistic will be small and the approval value (P-value) will be greater than the chosen a value level (we will adopt a = 0.05). After drawing the different distributions of the seepage rates data using Minitab, some of which were shown in Figure (12), as the function of the natural distribution and the natural logarithm, the gamma distribution, the Whipple distribution, the distribution of

maximum and minimum values, we applied statistical tests that provide an evaluation of the quality of data representation such as Anderson Darling using Minitab The results are presented in **Table (5)**:

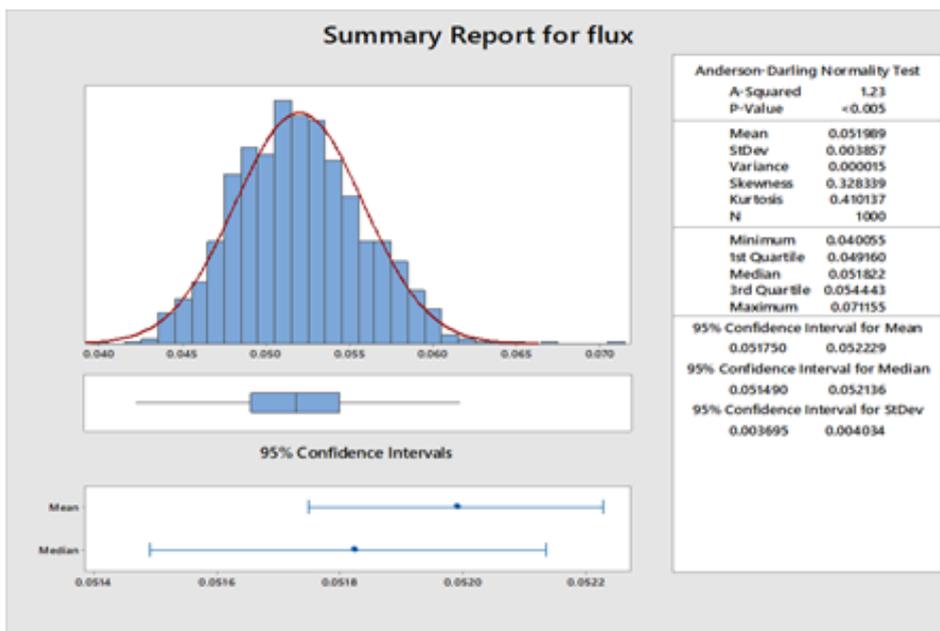


Figure 11: The histogram and normal distribution curve of flux data for 1000 random models(caseII).

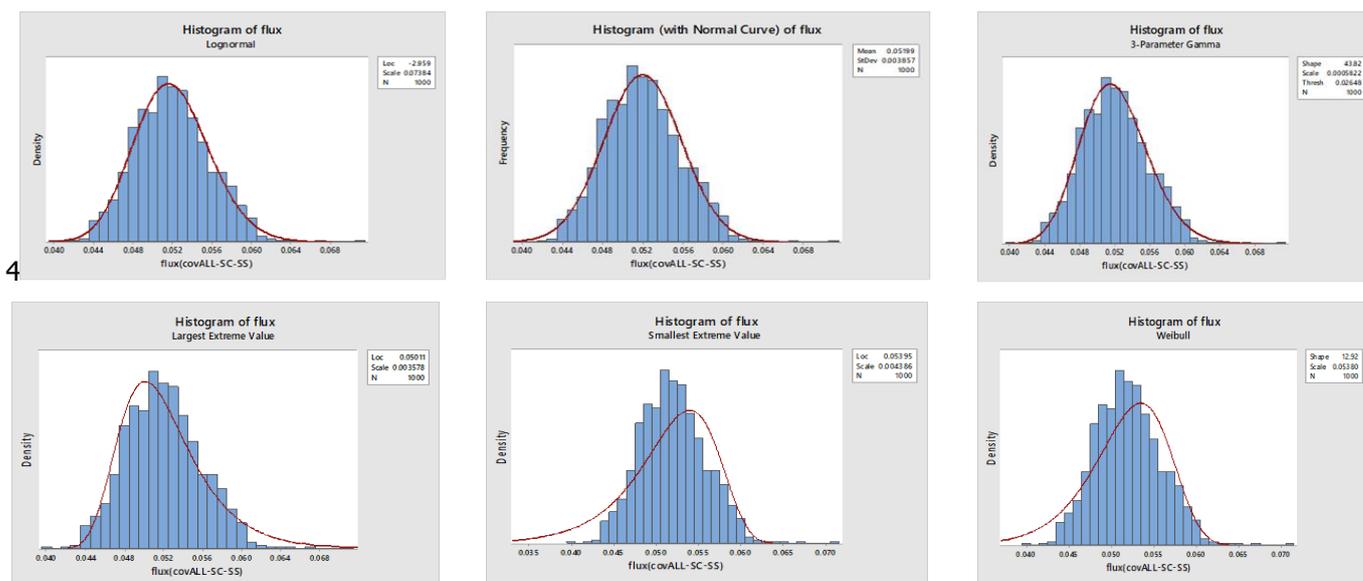


Figure 12: Some probability distributions of seepage data using Minitab.

Table 5: Descriptive statistics of Seepage values random samples using Minitab.

p-value	AD-statistic	Distribution Type
*	0.30108	lognormal-3p
0.341	0.36893	lognormal
>0.005	1.2251	normal
>0.01	4.2341	Largest Extreme Value
*	0.28873	Gamma (3P)
>0.005	1.658	Weibull-3p

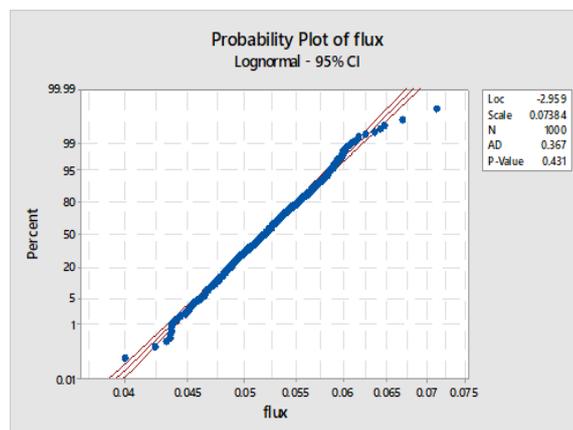


Figure 13: Some probability distributions of seepage data using Minitab.

From table (5), we conclude that if only the Anderson Darling test is relied upon, the normal logarithm distribution curve can be accepted as a distribution curve with random seepage rate values generated from random values for all parameters, as shown in Figure (13).

4. DISCUSSION

From the results of sensitivity analysis in cases (1-6) (table2), it was clear that for the cases (1-3) which the saturated water content was varying. We note that With the increasing of variance coefficient of the residual water content from (0.07-0.14-0.28), the mean values of seepage rate were (0.07717-0.07715-0.07712) respectively and their variance coefficient (cov%=0) is equal to zero as shown in table(3) (first three rows) and in Figure (7). for the cases (3-6) which the residual water content was varying, We note that With the increasing of variance coefficient of the residual water content from (0.065-0.13-0.26), the mean values of seepage rate were (0.077282-0.077284-0.077287) respectively and their variance coefficient (cov%) is equal to zero also as shown in Figure (8) in addition to the values (last three rows) in Table (3). In these cases, the mean, minimum, and maximum flux values were very close to each other and close to deterministic model flux $0.0765\text{m}^3/\text{day}$.

We found that considering the saturated water content as a random variable caused an increase in the rate of seepage through the dam to $0.07715\text{ m}^3/\text{day}$ with a difference between the mean flux values for sensitivity analysis cases and deterministic flux of 0.8%, while for considering the residual water content as a random variable caused an increase in the rate of seepage through the dam to $0.07728\text{ m}^3/\text{day}$ with a difference of 1% as shown in Table (3). When collecting seepage values for all cases of variation of the hydraulic conductivity as in Calamak (2016), residual and saturated water content, it is possible to deduce the possibility of neglecting the effect of the variation of the remaining water content and the saturation content that does not exceed 1% compared to the effect of variation of the hydraulic conductivity parameter that may reach 50% as shown in figure(9). With the possibility of considering the seepage rate as a fixed result of random inputs of the water content for the steady state flow through homogeneous earth dams. For Statistical study for the seepage of random models, That's clear in case I the randomness of $(\theta_s \& \theta_r)$ together was negligible that cov% is 0.004% very small and (Minimum& Median& Maximum) values were equal in table(4) . So we will continue the statistical analysis for case II which its cov% were bigger and boxplot in figure(10) clears the different between the two cases and when the saturated and residual water content were random only the flow rates were equal $0.076875\text{m}^3/\text{d}$. Figure (11) shows the iterative gradient of the seepage flux values through the homogeneous earth dam studied for the steady-state flow condition, where it is clear that the average seepage rate values range between (0.05175-0.052229 m^3/d) at a 95% confidence degree, and the median range between (0.05149) -0.052136 m^3/d at 95% confidence. The standard deviation of the leakage rate values ranges between (0.00369-0.004) at a 95% confidence level.

5. CONCLUSION

it is clear that individual changes of saturated water content and residual water content caused negligible effects on the seepage rate in the steady state flow through homogeneous earth dams, so it can be considered as a fixed value. Hydraulic conductivity must be treated as random inputs because of the importance effect on steady state flux values. The flow values of the steady state seepage can be considered to follow the lognormal distribution according to Anderson Darling test. There is a need to study the uncertainty effect of the saturated and residual water content (as a random parameters) on the transient seepage through earth dam in a subsequent study.

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