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Numerical Analysis of Seepage of Concrete-Coated Water Transmission Channels Considering Saturated – Unsaturated Conditions

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Abstract

Seepage of water transmission channels means waste of water, and is considered an undesirable phenomenon. A proper channel coating design can prevent this phenomenon. For this purpose, it is necessary to analyze the seepage of these channels and based on the results of this analysis, the best channel design is achieved. Since the soil around the channel is unsaturated, there is no possibility to analyze it with conventional methods, and using methods such as semi-empirical equations for estimating seepage gives approximate results. Although increasing the accuracy of field experiments, acceptable and accurate estimation of the seepage at various time intervals can be given, it should be noted that these methods are time consuming and costly. However, using numerical methods, a high volumes of data can be processed in a short time with minimum cost. Therefore, present study discusses numerical analysis of seepage phenomenon considering saturated-unsaturated conditions and assesses the ability of seep/w software model in estimating water seepage of concrete channel of Xiang River basin in China. Comparing these results with experimental results show that the results of numerical analysis is quantitatively consistent with physical models, and our model has a high capacity in estimating the seepage of water transmission concrete channels in the study area.

Keywords: Concrete Channel, Numerical Modeling, Seepage, Unsaturated Analysis.

1. Introduction

Water shortages in countries with arid and semiarid climates like Iran caused the issue of optimal management of water resources to be raised in order to reduce water loss. One of the causes of water losses is seepage of water transmission channels (such as irrigation channels and drainage). In total, one of the main challenges involved in designing water transmission channels is selecting the appropriate and optimized coating in terms of material properties and geometric characteristics, so that the proper amount of seepage can be achieved with minimal cost. A proper design requires analysis and accurate estimations. Estimation methods can be generally divided into four categories: mathematical analysis, numerical modeling, physical modeling, and semi-experimental techniques. The problem of seepage of channels is one of water seepage problems in soil, and its differential equations is the same differential equation for water seepage in soil, which is as follows for two-dimensional conditions:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial x}\left(k_y \frac{\partial h}{\partial y}\right)=q+\frac{\partial \theta_v}{\partial t}$$

where, θ_v is volumetric soil water content, q is the flow rate, k is permeability coefficient, and h is the hydraulic head. However, it should be noted that in arid and semi-arid regions where the channel is placed in the surface, soil conditions is unsaturated and does not follow the behavior rules of saturated conditions. It means permeability coefficient is not constant and varies with the degree of saturation. Thus, mathematical analyses can not solve the problem exactly. According to several studies, including Salemi and Sepaskhah[3] or Rostamian and Abedi

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Koopaei[7], semi-empirical analyses have large error, and are not appropriate except for initial estimates. Physical modeling is also costly and time consuming. Therefore, the numerical method is the most appropriate method to analyze and estimate the channel seepage before its construction. However, the accuracy of the numerical model should be evaluated.

Alavi[1], reported the transmission efficiency of Zayandehroud river network 95%,and loss of degree 1 and 2 channels 0.072 and 0.15 m3/m2 per day. He believed the min part of losses was due to seepage (92.5%) and only 7.5% was due evaporation. Abbasi[2], reported transmission losses in the West and East of Qazvin network 26% and 10%, respectively, and distribution losses 46% and 39%, respectively, and total loss rate of the network was 60% and 44%. Salemi and Sepaskhah[3] studied modifying empirical equations of channel seepage in the area of Roudasht, Isfahan. Comparing obtained equations with empirical equations, the equations were modified for the area under study. Soltani and Maroufi[4], reported the amount of water loss in transmission and distribution soil channels in irrigation network at Shavoor, Khuzestan 40% and 31.9% respectively. Bahramlou et al.[5] examined seepage of irrigation channels with concrete coating in cold climate and concluded that the total loss of water in irrigation channels with concrete coating is between 0.92 and 2.75 and on average 1.74 m3/m2 per day. Bahramlou[6] investigated the seepage of irrigation channels with rock covering in cold regions and concluded that in cold climate of the region and current technology, losses in local stone and mortar coating is one third of loss in concrete coating. Rostamian and Abedi Koopaei[7], according to the results of estimated seepage rate of soil channels in Zayandehroud network and using numerical analysis by SEEP software, examined ability of this software to estimate the seepage of soil channels. These results suggest that empirical equations worked too weak in estimating the seepage of area under study, and should be calibrated for local conditions.

Hatz[8], provided a list of the most important factors affecting the seepage of irrigation channels. These factors can be considered in three general categories: 1. soil characteristics, 2. Hydraulic characteristics such as depth of water in the channel, moist surrounding of channel, and groundwater level, and 3. Characteristics of water in channels. Phipps[9] measured channel seepage in 15 concrete channel in tank method, and conclude that for channels with less than 3.5 meter width, seepage losses is higher, and for channels with 0.9 to 11.6 m width, average seepage loss is 0.37cubic meter per day. Iqbal et al.[10] reported seepage volume in irrigation channels of 11 basins in Canada with the same age as 1.5 percent. Katibeh[11] analyzed seepage of coated channels with finite element numerical method and concluded that the permeability of channel coat, if the soil permeability is in the range of 0.001to 0.02, has a greater influence on the seepage flow rate of the channel. Newton and Perlay[12] determined that water loss for a soil channel with length of 8.2 kilometers is 25 percent and losses in the period of 210 days were 11.9 million cubic meters and concluded that by controlling loss, 30 to 45 percent of water consumption will be reduced. He concluded that water losses in the channel has a direct relationship with discharge. Chahr[13] used a detailed analytical method to assess seepage rate of a trapezoidal channel. He reported that method was effective for determining the amount of seepage or artificial recharge of groundwater for polygon channels. Using data from the ADCP, Kinsley et al.[14], estimated seepage of irrigation channels and provided a relationship based on flow rate and geometric characteristics of the channel to estimate the channel seepage. Ligiang et al.[15] tested channels with different coatings in Xiang River Basin in North West China to evaluate the seepage parameter, and concluded that the channel coating is not the only factor affecting the channel seepage, but material and the permeability of the soil below the channel bed can also affect the channel seepage.

Most reputable studies on seepage of channels are based on physical modeling techniques, and weaknesses of software or lack of data from the soil profile have prevented the development of numerical methods. Accordingly, this study is based on numerical methods, where the ability of the software SEEP/W in the estimation of seepage of water transmission channels is investigated depending on the channel coating and different layers of soil below the channel bed. The advantages of using software in calculations include processing high volumes of data in a short time and with minimal cost.

2. Numerical Modeling

For numerical modeling, SEEP/w software of Geostudio 2007 subset is used that has the ability to solve differential equations governing the problem (Equation 1) for saturated and unsaturated materials. In order to build a numerical model and evaluate the accuracy of its performance, Liqiang et al. physical model is selected and simulated. In the physical model, the seepage is measured of a concrete channel on layered soil, as shown in Figure (1).

3. Geometry of the Numerical Model

Based on information provided by Liqiang et al., channel geometry and its surrounding is considered as shown in figure (2).

4. Boundary Conditions

Boundary conditions of the problem, as shown in Figure (2), is identified with numbers and include:

1) zero head, 2) zero horizontal gradient (impermeable boundary) 3) zero head (surface water level) 4) head of water in the channel equal to 0.4 m

5. Material Properties

The materials in physical model consists of concrete and 5 layers of soil materials (Figure 3). To perform the analysis, considering the saturated – unsaturated conditions,

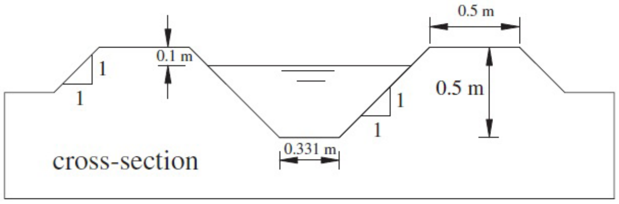


Figure 1. General profile for a cross-section of the selected physical model.

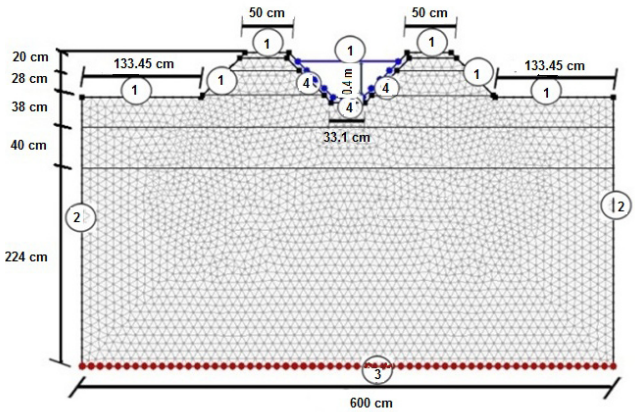


Figure 2. Geometry, mesh and boundary conditions for the numerical model.

material properties include permeability coefficient and volumetric water content that do not have fixed values, and are proportional to the amount of suction. This study, uses Van Genuchten equation to estimate the permeability coefficient for soil materials:

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{[1+(a|\psi|)^n]^{1-1/n}}$$

In this context, $\theta(\psi)$ is water property curve, $|\psi|$ is suction pressure, θs is amount of saturated water, θr is remaining amount of water, α is reversed suction air inlet (α > 0), n is brittle (n > 1). An example of the made function for horizontal permeability of materials according to the recent equation is shown in figure 4. Values of equation (2) for each of the materials are given in table 1.

6. Place and Time Partition

Partitioning of place is meshing in the place of the problem area which is conducted using three nodes using triangular elements with an average size of 0.05 m (Figure 2). Given the importance of the area adjacent to the channel, mesh density near the trapezoidal section is considered higher. For partitioning of time, time steps are considered logarithmic and automatically according to the acceptable error. After numerous analyses, the time

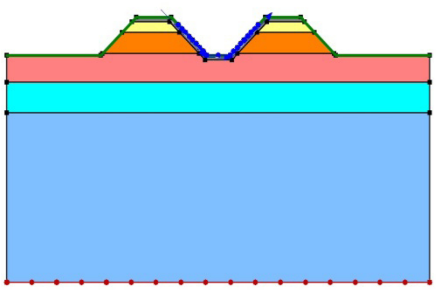


Figure 3. Definition of different soil (materials) layers.

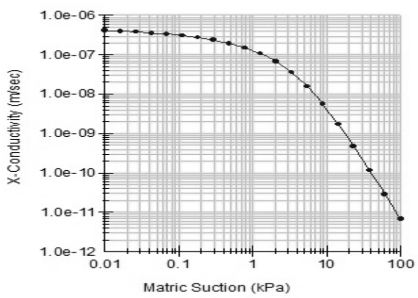


Figure 4. Permeability to suction curve.

Table 1. Classification of soil profiles in discrete regions based on soil texture and hydraulic properties

Layer Number	Soil depth	Soil bulk density	a	θ_r	θ_c	∝	N	K
	(cm)	(g·cm-3)	(kPa)	(cm3·cm-3)	(cm3·cm-3)			(cm·min-1)
concrete	6	–	4.905	0.067	0.45	0.02	1.41	0.0098
1	20	1.67	1.603	0.022	0.252	0.0612	1.632	0.00341
2	28	1.71	3.528	0.0257	0.3039	0.0278	1.422	0.01195
3	38	1.56	2.303	0.04	0.3616	0.0426	2.373	0.13089
4	40	1.64	5.638	0.0292	0.3108	0.0174	1.414	0.00246
5	224	1.56	11.54	0.0387	0.3522	0.0085	1.570	0.02798

step between minimum of 0.01 and maximum of 10^{8}8 is selected for the model.

7. Seepage Analysis

Given the characteristics of the numerical model, the channel seepage analysis is performed. In this regard, depending on the groundwater level based on the level of the floor area (according to section 2.2), the software considers suction of points above this level. Then, based on the head applied on the channel, seepage analysis is performed at different time steps. The results of the analysis as same- pressure curves, zero-pressure curve, and seepage level during 1000 and 6000 min after channel intake are shown in figures (5) and (6). As can be seen, the saturation field increases over time, and is limited to the fifth layer with low permeability, and tends to expand in width. It is obvious that if the fifth layer has a permeability as the third and fourth layers, the seepage will increase sharply. However, this layer has currently limited permeability area of water.

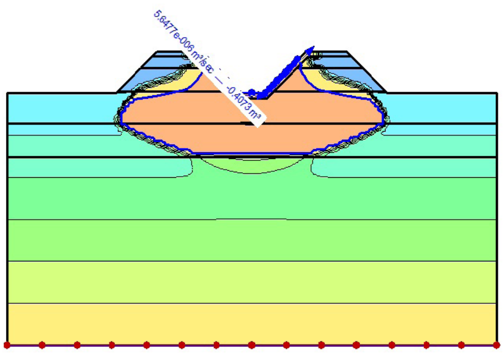


Figure 5. The same-pressure curves, zero-pressure curve, and the cumulative permeability of channel for 1000 minutes.

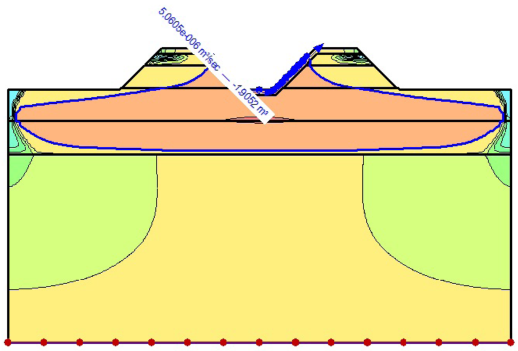
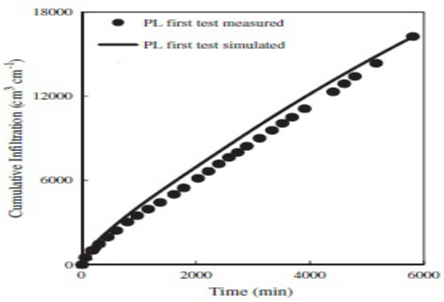


Figure 6. The same-pressure curves, zero-pressure curve, and the cumulative permeability of channel for 6000 minutes.

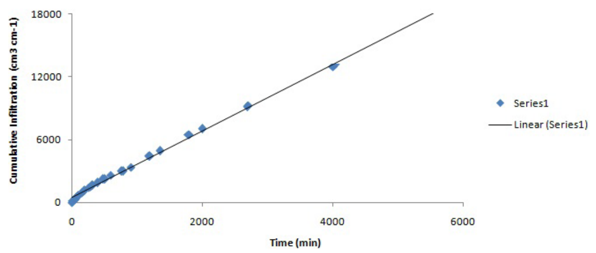
Also, using results of seepage analysis which is a transient and time-varying analysis, the amount of seepage of the channel at different times can be calculated. The results are summarized in Figure (7 b). Comparing the results obtained from our numerical model with the physical model indicates the high accuracy of our numerical model. Primary slight curvature of diagram is related to rapid penetration of saturated areas in the third and fourth layers, and the constant slope in the following sections is related to the limited scope of seepage, and reaching saturation in the third and fourth layers (Figures 5 and 6).

8. Conclusion

The present study creates a numerical model of transient seepage of water transmission channel coating into the soil for seepage analysis to unsaturated soil, that is one of the main issues in designing a proper coating for these channels. To assess the ability of the numerical model to replace other conventional semi-empirical or physical



(a)



(b)

Figure 7. Seepage rate change with time; a) Results of the physical model and b) Results of the numerical model.

methods of seepage estimation of the channels, a physical model is simulated.

Our numerical analysis is qualitatively consistent with the principles and theories of permeability in saturated soil, and quantitatively consistent with the results of the physical model. This proves capabilities of numerical models and their high accuracy in seepage analysis. Thus, using this model, seepage of channels can be analyzed and estimated with the lowest cost and time, and high accuracy at the same time, and with designing an appropriate coating, water loss due to seepage phenomenon can be prevented.

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