Journal of Environment and Sustainable Mining Vol.2 No.1 (2024) 30-39

University of Sistan and Baluchestan

Journal of Environment and Sustainable Mining

Available online at http://https://jesm.usb.ac.ir//

JESM

Determining the Depth of the Virtual Impervious Boundary as Bedrock to Determine the Amount of Water Seepage

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ARTICLE INFO

Article history:
Received: 2023-12-10
Received in revised form: 2024-01-24
Accepted: 2024-02-21
Published online: 2024-02-21

Keywords:
Seepage;Flow Net;
Bedrock Depth;Slope Stability;
Karun IV Dam

ABSTRACT

Landslides are one of the severe natural catastrophic that occur continuously around the world. Water is usually known as one of the main drivers of landslide failure. Due to the difference between the bottom of the trench of the Karun IV power plant and the water level in the surrounding rivers, it is exposed to water seepage and slope instability. The studied structure consists of Limestone, Marly Limestone and Marl with permeability of 1 to 36 Lugeons. Seep/w software has been used to analyze the amount and force of water seepage. One of the key parameters for seepage analysis is the position and depth of the bottom rock, which is defined as the impermeable boundary of the model. Since there is no index impervious layer in the site, in this research a virtual impervious layer on the bottom of the model is considered as bedrock to analyze the water seepage. To find the depth of the impervious layer of the bottom, seepage analysis was performed with different depths of the virtual layer for a cross-section as a sample, and the results were analyzed. Using statistical analysis, the depth of the virtual impervious layer of the bottom which increasing its amount has no effect on the volume of seeped water, was 150 m. Also, after determining the depth of the virtual impermeable layer, analysis and seepage calculations were performed for all trenches based on the depth of the virtual impermeable layer of the bottom.

1 .Introduction

The seepage and infiltration of underground water into trenches and open excavations and their stability is one of the important geotechnical issues. The presence of underground water in the rock mass is a critical factor in evaluating the slope stability. The water pressure exerts force on the discontinuities of the rock mass and reduces the effective stress, and as a result, the shear strength decreases. In addition, water always

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plays a role as an intermediary in the process of breaking slopes, dams, highways, roads and engineering projects.

The role and effect of water on slope stability is very complex. Among the effects of water, the decrease of soil suction, pore pressure increase, raising the water level, increasing the unit weight of the soil, and also shear strength reduction can be mentioned [1, 2]. Consequently, the interactions of water and land slope should be studied and understood in a broader sense. So, analyzing the slopes stability, without considering the water and the results of its presence, will not be realistic. Hoek & Bray have discussed some effects of the presence of water on construction operations such as reducing shear strength and creating pore pressure [3]. Also, Cedegren has pointed to some parameters such as horizontal seepage forces that increase the overturning force and the possibility of falling, and the increase of the forces on the sliding surface [4]. In general, the stability of a slope can vary greatly depending on the water conditions. A slope may remain stable under dry or well-drained conditions, but may undergo several types of sliding movement when the water table is high. In studying slope stability, special attention should always be paid to both water volume and water pressure. The water pressure depends on the water flow path and the geometric position of that point and is independent of the permeability, and to determine it, the hydraulic potential head and hydraulic gradient must be determined.

In recent decades, extensive research has been conducted on the failure mechanism of landslides caused by water seepage from rainfall or water level fluctuations [5-9]. Many empirical and semi-empirical relationships have been developed to quantitatively estimate the relationship between precipitation and landslide failure. However, most of the empirical research aimed at a specific type of slope or a specific region with very limited parameter range. Many researchers have conducted probing on the effect of seepage on the stability of the slope. Using the finite element method, Louhenapessy has investigated the effect of seepage from a river on the stability of a slope [10]. Liu has also developed a complex model with the finite element and the limit equilibrium method for water seepage and stability analysis, when rainfall causes water seepage on the sloping surface [11]. The results of his model show that the penetration of rainfall and the change of the underground water level can strongly affect the stability of the slope. Wang et al have also done a similar research on the effect of the rise of the water table due to rainfall and its effect on the stability of the sloping slops [12]. Ma et al. used an elastoplastic model for soil under a combined stress state to analyze slope stability with saturated and unsaturated seepage flow [13]. The results show that in the saturated state, water seepage (flow rule) significantly affects the slope stability. In a 3D model, Pan et al. investigated the effect of permeability coefficient, homogeneity and heterogeneity of the soil on the stability of the sloping slops under water seepage [14]. The consequence of all the conducted researches is that if for any reason water table rises on the sloping surface, it will affect the stability of the slope and may lead to the collapse of the slops. Therefore, it is necessary to carefully analyze the water seepage force and volume in the slopes and take its results into account in the slope stability analysis.

2. Trench of Karun IV power plant

The Karun 4 dam project is one of the hydroelectric projects on the Karun River, which is located in ChaharMahal & Bakhtiari province in the center of Iran. The Karun River is formed by the joining of two rivers, Bazfot and Armand, upstream of the axis of Karun 4 Dam. The Monj River with 80 km long and northwest orientation, 150 meters downstream of the Karun 4 dam, joins the Karun River. Karun 4 project consists of reservoir dam and surface power plant. In order to generate electricity, a power plant has been planned on the left side of the dam and on the bank of the Monj River with a usable electricity generation capacity of 1000 megawatts. Due to the suitable topographical conditions, Karun Dam 4 power plant will be built on the surface and on the right bank of the Monj River and the left bank of the Karun River. For this purpose, trenches will be dug for the construction of the power plant. Considering that the current bed of the Monj River is placed inside the trench, a channel will be built to transfer the Monj River path, which will change its path. The position of the trench according to the location of the dam, Karun and Monj Rivers and the Monj transmission channel is shown in Figure 1.

Due to the difference between the bottom of the trench and the bed of Monj and Karun Rivers, the considered trench for the construction of the power plant is exposed to water seepage and the instability of the slops. Water seepage into the pit of the power plant, in addition to causing problems with the presence of water during the excavation operation and Increase construction costs, will also cause instability of the trench slops.

In order to evaluate the effects of water seepage from rivers near the trench, it is necessary to investigate the amount of water seepage quantitatively and qualitatively. The volume and pressure of the water seepage to the trench slops may also affect the stability of the trench slops. For this purpose, to determine the hydraulic potential head of the water flow and the height of the water table, boreholes were drilled around the location of the trench and the height of the water table was recorded in them. The results of the measurements showed that there is a direct relationship between the fluctuation of underground water and water level of the Karun River. In this way, in the months of March to June, when the river is at its maximum discharge, the underground water level reaches its highest level.

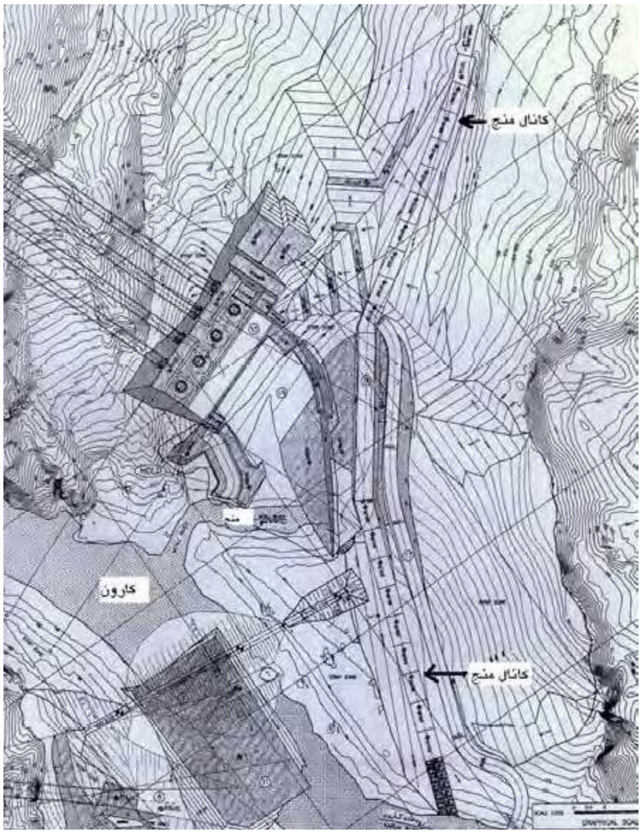

Figure 1: Position of the trench in relation to Monj and Karun rivers [15]

Also, the results show that the underground water level is higher than the water level in the Karun River. In addition to measuring the water level in the boreholes, the water leaks on the left and right banks of the dam site other constructed structures which are at higher levels than the water level of the river, and an artesian borehole near the confluence of two rivers, Monj and Karun, is a confirmation that the underground water level is higher than the water level of the Karun river. The reason for the high underground water level compared to the water level in the Karun River can be considered to be the proximity of the Monj

River to the power plant area and higher water level in it than the Karun’s River. The fact that the underground water level in the nearby observation boreholes is lower than the water level in the Monj River is also a proof of this. Therefore, before the construction of the transfer channel of the Monj River, the underground water level will be affected by the Monj River and after that, it will be affected by the water level of the Karun River.

Observing the water level in the boreholes in the power plant area revealed that the underground water level above the bottom of the trench will be the cause of water flow and seepage during the construction of the trench in the power plant [15]. Therefore, during trench excavation, there will be seepage and flow of water into the trench pit from Monj and Karun rivers. In order to determine the amount of seepage volume and force and its effects on the slope stability, it is necessary to model the flow of water into the trench. For this purpose, seep/w software has been used to model the water seepage.

3. Water seepage calculations and analysis

Two-dimensional flow net calculations have been used to determine the amount of seeped water into the trench and obtain the seepage pressure. For this purpose, precise vertical sections that show the geometric boundaries of the structure, water entry and exit surfaces and boundary condition have been drawn, and then seepage analysis has been done on these sections. A total of 5 sections; 2 sections across the trench and perpendicular to the Karun River and 3 sections along the length of the trench and perpendicular to the Monj River are considered to determine the amount and effect of seepage into the trench. The position of these sections is shown in Figure 2.

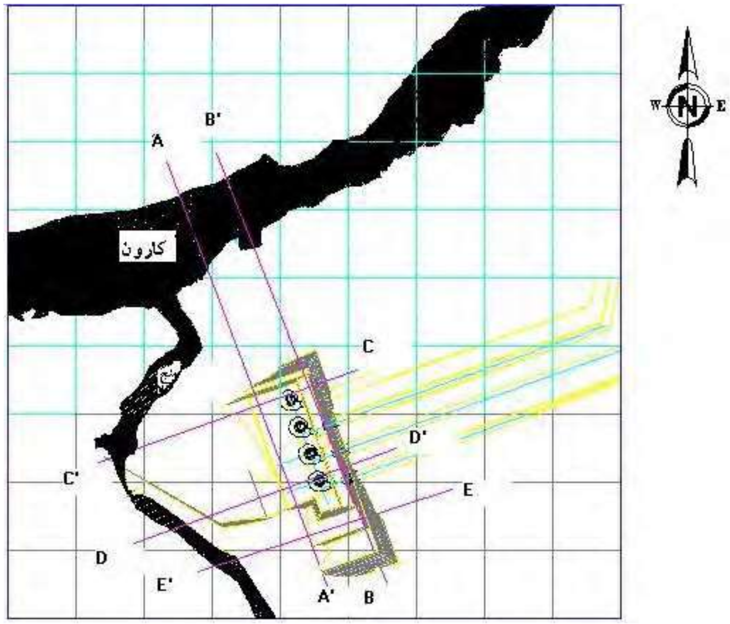

Figure 2: Location of power plant trench and five sections of seepage analysis

The water level in the river is the main source of water flow into the trench pit. Due to the fact that at the power plant construction site, the underground water level is higher than the lower levels of the trench, when excavating the trench at height lower than the groundwater level, the slope of the trench will hit the water level and there will be water seepage from the slope. This water level (groundwater) is an equipotential level for water flow. For this reason, to determine the amount of water entering the trench, the underground water level and the water level in the nearby rivers were defined as equipotential levels so that the flow network between these two levels can be drawn.

To determine the water height in nearby rivers, the most critical state was considered. That is, the water level was calculated in the months of the year when the water level in the river reaches its highest level. Table 1 shows the amount of water flow in different months of the year for the Monj and Karun Rivers.

Table 1: Maximum water discharge in different months of the year in Karun and Monj rivers [15]

month	Maximum discharge of the Karun River (m^3/s)	Maximum discharge of the Monj River (m^3/s)
April	1057.35	76.8
May	759.36	19.5
June	396.65	12.5
July	258.04	10.5
August	170.54	9.5
September	125.69	8.4
October	103.38	8.4
November	229.79	10.2
December	492.24	18.2
January	311.24	15.6
February	375.23	22.7
March	865.56	44.5

From Table 1, it is clear that the highest water flow is related to the month of April and the water height should be obtained using the water flow in this month. But the water level in these two rivers may increase during floods. To apply these boundary conditions, safety facto for flood situations were considered and the water height in two rivers was calculated based on the obtained flow rate. Table 2 shows the water flow before and after applying the safety factor in the Karun and Monj Rivers.

Table 2: The flow rate of Monj and Karun rivers after applying the safety factor

River	Maximum discharge of the river (m^3/s)	Safety Factor	Maximum discharge after applying the safety factor (m^3/s)
Karun	1057.35	1.4	1500
Monj	76.8	1.4	110

To find the height of the water at each section, according to the cross section of the river and the daily measurement of the water height in the nearby rivers throughout the year, the relationship between the amounts of water flow and the height or depth of the water in the rivers is determined. Table 3 also shows the values of water level height according to different flow at different times.

In the rivers path, the bottom of the both rivers are covered with alluvium up to several meters. Due to the fact that the permeability of these alluviums is usually high, water actually flows from the body of these alluviums. Therefore, it can be assumed with acceptable accuracy that these alluviums are also saturated with water and the bottom of these alluvial masses was assumed as the river bed. In the models built in the software, the level of water seepage from the river bottom is assumed to be the bottom of these alluviums.

Table 3: The amount of water height at different times based on the amount of river water flow

Cross section	Discharge of the river (m^3/s)	water level in the river (m)
AA'	1100	847.83
	1745	849.25
BB'	1100	847.83
	1745	849.25
CC'	110	855.06
DD'	110	868.5
EE'	110	870.56

To determine the permeability coefficient of the rock structure, the in-situ Lugeon test have been carried out. According to the Lugeon tests performed in the boreholes, the permeability coefficient values of different layers in each borehole were calculated and the average permeability coefficient value of the layers was determined. Table 4 shows the layers permeability.

Seepage flow calculations and analysis have been done using Darcy's two-dimensional law and flow net. Using flow net, it is possible to determine the seepage water flow rate and water seepage pressure. The model built to analyze the amount of water seepage should represent the exact geological and geotechnical conditions, this model should be able to consider the ground water conditions as an important component in the design of sloping slopes. It is also very important to ensure that accurate boundary conditions assumption is considered to build such a model.

Table 4: Permeability coefficients of different layers [15]

Layer	Permeability (Lugeon)	Permeability (mm/s)
Limestone	36	5.6
Marly limestone	3	0.258
Marl	< 1	0.005

To analyze water seepage using the flow net, detailed information on layering, permeability of layers, shape and geometric location of bed rock, position of depth of underground water table and surface water and geometric characteristics of the structure after construction are needed. The depth of the flow net in the model or in other words the position of the impervious layer at the bottom of the model is one of the key parameters of seepage analysis. The distance of water inlet levels (water level in Monj and Karun rivers) from bedrock has a direct effect on the amount and pressure of water seepage. The greater the depth of bed rock, the calculated volume of seepage water and the seepage pressure will increase. In order to consider the effect of seepage on slope stability, the depth of the bedrock must be determined in the seepage analysis in each of selected sections. However, in the trench construction of the power plant, there is no bedrock or impervious layer that can be considered as bedrock.

Despite conducting many studies on various aspects of flow hydrology in porous environments such as rock and soil, few specific studies have been conducted on the effect of conditions, physical topography and depth of flow. Few studies have investigated the relationship between soil moisture and topography at different conditions [16-20]. In the previous studies, the boundary of the model in the bottom was clearly defined for seepage calculations. While in this case there is no index impervious boundary in the bottom. Beiranvand and Jamal used a model whose boundaries were clearly defined to calculate seepage [17, 20]. Mostafa has pointed out the importance of model geometry and model boundaries in flow calculations [18]. Also, Murtdha have investigated the effect of sheet piles depth on the seepage water pressure using ANSIS program [19]. Tromp-van Meerveld has investigated the effect of topography and soil depth on the amount of water seepage [21]. In all the previous studies, the boundaries of the model have been known, and none of the researchers have mentioned that if the lateral boundaries or the impervious boundary of the bottom is not known, at what depth this boundary should be assumed in the modeling. The innovation of this research compared to similar researches is the assumption of a virtual boundary for seepage modeling and analysis.

The results show that there is a significant relationship between the thickness of the permeable layer and water flow. Meerveld et al. have studied the relationships between depth topography, soil moisture, and water flow rate inside 20 boreholes drilled in a sloping slops to investigate how moisture and water flow change at different depths [21]. The Meerved results show the importance of measuring soil depth to understand the relationship between soil moisture and flow in rainy seasons.

To analyze water seepage, Seep/w software is used. This software calculates the amount and pressure of seepage using finite element numerical method. The basic information required by the software is the geometrical shape of the cross-section, layering of geological units, boundaries of water entry and exit, the permeability of different layers, the boundary conditions of the problem (impermeable boundaries, source of water flow). According to the conducted studies, the depth of bedrock has a direct effect on the seepage flow rate, and since there is no impervious layer in the construction of the Karun 4 dam power plant, which can be considered as the impervious boundary of the bed, the depth of the cross-section whose increase does not have much effect on the amount of seepage should be assumed as the end boundary of the flow or the impervious boundary.

If there is an impermeable layer in the bottom such as bedrock, the flow of water can be limited to this impermeable layer. But if there is no impervious layer, impervious floor must be defined for the modelling. Considering that with the increase in depth, the porosity of the layers will be lower than the surface due to the in-situ stresses, so it can be expected that the ability to flow through the layers will decrease with the increase in depth. On the other hand, with the increase in depth, the water flow path will be longer and therefore the water in the longer path needs a higher hydraulic potential head to flow. Assuming that the hydraulic potential head difference in the model is constant (the difference in water height in the river and the canal bottom), it can be concluded that there is a threshold depth value that, by increasing it, the flow rate will not change much. Considering that there is no impervious layer index in the studied case, the aim of this research is to determine the depth at which the increase of the depth of the model does not have much effect on the seepage flow rate. So, the assumption of such a virtual boundary will not be far from the reality.

In order to determine the position of the virtual impervious layer, the volume of the seepage flow at different depths of the impervious boundary of the bottom was determined using Seep/w seepage analysis software. The value from which the effect of increasing the depth on the water seepage became insignificant was considered as the virtual impervious boundary of the bottom for the seepage analysis. AA section was considered as an example; the depth of the bottom boundary was considered from the river bottom and the seepage analysis was performed by the software with different depths of the bottom impervious boundary. Figure 3 shows the cross-section of AA with the bottom impervious boundary at a depth of 120 meters compared to the bottom of the Karun River. Table 5 shows the flow rate of seepage from the Karun River to the trench of the power plant in section AA with different depths of the virtual impervious boundary.

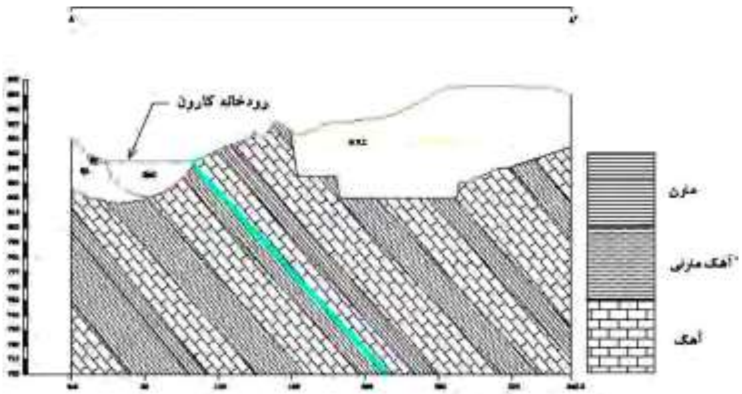

Figure 3: Cross section AA' with a depth of 120 meters of the impervious boundary of the bottom from the water level in the Karun River

Table 5: The flow rate of water seepage from the Karun River to the trench of the power plant at section AA' at different depths of the virtual impervious boundary of the bottom

Bottom depth (m)	Seepage discharge (m^3/s)	Bottom depth (m)	Seepage discharge (m^3/s)
20	5.739×10^{-3}	110	8.634×10^{-3}
30	6.08×10^{-3}	120	8.74×10^{-3}
40	6.64×10^{-3}	130	8.88×10^{-3}
50	7.105×10^{-3}	140	9.032×10^{-3}
60	7.516×10^{-3}	150	9.11×10^{-3}
70	7.81×10^{-3}	160	9.15×10^{-3}
80	8.08×10^{-3}	180	9.18×10^{-3}
90	8.3×10^{-3}	200	9.2×10^{-3}
100	8.46×10^{-3}	220	9.21×10^{-3}

4. Determining the depth of the virtual impervious layer of the bottom

For Determination of the depth of the bottom impervious boundary, SPSS statistical software was used to analyze the data in Table 5. In SPSS software depth as a variable and seepage flow rate as a function were considered. The statistical results are shown in Figure 4. As the results of Table 1 and Figure 4 show, increasing the depth of the impervious boundary of the floor causes an increase in the seepage flow rate to the power plant trench, but at high depths, the acceleration of the increase of the seepage flow rate decreases, so the depth at which the increase of the seepage flow rate becomes insignificant can be assumed as a virtual impermeable layer.

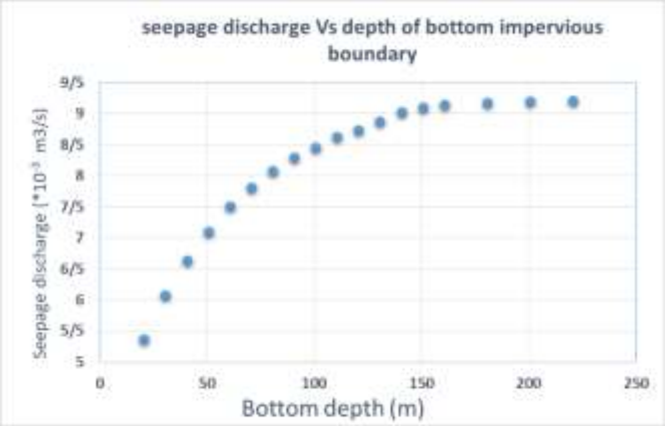

Figure 4: Seepage discharge according to the depth of bottom impervious boundary

As Figure 4 shows, the increase in flow becomes insignificant at depths of more than 150 meters. Therefore, to determine the analysis of water seepage from the Karun and Monj Rivers to the power plant trench in the 5 sections shown in Figure 2, the bottom depth of the section in the seepage analysis software can be defined as 150 meters compared to the water level in the Karun River, or a virtual impermeable layer at a depth of 150 meters can assumed. In the following, the analysis of seepage and slope stability can be completed based on this assumption.

5. Conclusions

According to the observations of the underground water table in the area of the power plant trench and the water level in Karun and Monj Rivers being higher than the bottom of the trench, water seepage into the power plant trench is inevitable. To determine the amount of water seepage and its effects on the stability of the slopes, seepage analysis should be done. To determine the depth of the virtual impervious boundary of the floor and the seepage flow rate, the statistical analysis of the seepage flow rates at different depths of the bottom impervious boundary have been used. The results show that increasing the depth of the bottom from 150 meters will not change much in the seepage flow, and therefore the depth of the virtual impermeable layer of the bottom from the water level in the Karun River was assumed to be 150 meters. In the next steps, the analysis and determination of water flow rate and seepage forces to the trench wall and slope stability analysis in 5 sections should be done based on the assumption of 150 meters depth of the impervious layer.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflicts of interest/Competing interests

No potential conflict of interest was reported by the authors.

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