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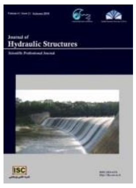

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Assessment of the Optimum Depth of Sealing Cutoff Walls in the Clay Core of Peygham-Chay Dam

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Abstract

Seepage is one of the most substantial factors in the embankment dams design. The Cutoff wall method is the ideal construction solution for controlling flow through the foundation of earth dams. In this study, the cutoff wall method is investigated at the site of the Peygham-Chay dam (Study area). According to the dam site, in terms of its materials as well as their different permeability, water influx is a potential hazard at the site. For this purpose, SEEP/W program as the finite element approach was employed to estimate the seepage and design of the optimum depth of the sealing element. The results of numerical analyzes imply that the sealing component is not needed because of the low permeability in the primary 260 m at the left abutment of the dam. Also, the optimum depth of the cutoff wall is evaluated as 15 m at the rest of the dam axis.

Keywords: Cutoff wall, Dam site, Peygham-Chay dam, sealing methods, Water seepage

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1. Introduction

Earth dams are noteworthy structures that provide both renewable energy and facilities for agriculture. Seeing that a dam system is significant and holds a considerable amount of water, its security efficiency is critical for environmental and economic considerations [1, 2]. Water seepage is one of the trivial problems in many of these dam systems, where impounded water finds ways of minimum stability across the dam, its foundation, and abutments. The geological and hydrogeological condition has an enormous effect on the seepage rate [3-7]. Wall stability is decreased due to water seepage, and an unforeseen flood of water may lead to human fatalities, tremendous damage, and property defeat [8-10]. Many destructive failures in geotechnical and dam engineering, based on Budhu's research, stem from the instability of soil masses due to water seepage [11]. Some details, including the strength and soundness of structural materials; vulnerable and permeable zones; geological inhomogeneities; and source, path, and amount of seepage would definitely help to determine efficiently and economically on the use of seepage management measures for a specific

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kind of structure [12], e.g., the hydraulic and technical analysis of the spillway of the dam was studied using data from Karkheh Dam in Iran. The key features for hydraulic considerations were discharge capacity, flood routings and chance of damage to cavitation [13].

Dams are the colossal artificial barriers widely used to hoard water. For this purpose, they are commonly constructed by placing and densifying different compounds of soil, sand, clay, and rock. Permeability can be minimized according to soil compaction as well as modification of soil structure [14]. Seepage in earth dams has two components based on their location: seepage through the body of the dam and the base of the dams. The most common technique for managing the seepage through the earth dam structure is the use of clay core, filters, and drains [15-18]. Peter (1982) described two solutions to seepage management via the earth dam and its foundation. The first solution decreases the quantity of filtration that can be obtained by supplying passive anti-seepage protecting elements such as sheet piles (steel or wood), cutoff wall, slurry trench, clay shield, impermeable shield upstream, grout curtain, concrete wall, diaphragm wall, etc. The second creates a protected outlet for running water, which also reaches the earth dam or foundation. It can be done by utilizing strong defensive anti-seepage components, such as filters, drains, sand drains, stone columns, ditches, and relief wells [19, 20]. The function of anti-seepage elements in the foundation of dams is to elongate the path of water to which the damaging drainage stress, hydraulic gradient, and overall depletion [21]. In addition, cutoff walls are built under the surface of the earth to manage the horizontal movement of groundwater and pollutants. That alluvium foundation materials should be included in cutoff wall building of earth dam foundations. A strong filling material such as drilling mud, durable concrete or plastic concrete can replenish the void [15].

For some cases, grouting was used before cutoff wall construction (pre-grouting), but there are some successful cutoff wall construction projects that did not require pre-grouting. For most cases pre-grouting was done to limit the construction risks during construction and/or concrete installation. The grout is typically injected into two or more lines making a grout curtain on both sides of the planned location along the dam's cutoff wall [22]. As a case in point, grouting strategy was used in the Karkhed dam to strengthen and reduce the body's high permeability [23]. Cutoff walls are most typically vertical and preferably penetrate down to a very low-permeable stratum, a clay or impervious bedrock that provides a well-sealed base for managing groundwater movement inside the bridge span [24, 25]. Because of cutoff walls affected by the dam settlement, horizontal and vertical displacement during the first impounding, and especially, conditions such as earthquake, it is necessary to be designed in a way that the deformations due these conditions be the least possible and prevent cracking in the wall. Some of the best alternatives is the use of plastic concrete for cutoff walls, since it has enough strength and durability to endure static and seismic pressures and experience seismic deformations along with the underlying earth [15, 26].

Mansuri and Salmasi [27] studied this feasibility of employing a horizontal drain and cutoff wall to limit the seepage from the presumed heterogeneous earth dam. They observed that the optimal location of the cutoff wall is in the center of the dam foundation for the mitigation of seepage rate and piping. Seepage from earth dam and its foundation is diminishing by increasing cutoff wall depth. Aghajani et al. [28] Findings study shows that, if the cutoff wall is not attached to a less impermeable layer of foundation, the impact of the differences in the cutoff wall location on the quantities of seepage are negligible. Universally there is some water seepage in all earth dams. If water seepage is considered as a potential problem, applying a sealing method at the level of design stage will diminish any risks to a lower limit [29, 30]. Hence, for the design of earth dams, it is necessary to evaluate the compatibility of soil materials, to estimate water seepage as well as determining the optimum sealing method [31-40]. To consider the optimal sealing method, estimating the water leakage flow is undoubtedly essential and imperative. Diverse numerical approaches including the Finite Element

Method (FEM), the Discrete Fracture Method (DFM), the Discrete Element Method (DEM), and the Finite Volume Method (FVM) may also be employed for accurate measurement of the water seepage in the dam base. The approaches are combined in estimation, as they need exhaustive information of the area and field of the dam [41-46].

In this study, firstly, the numerical finite element model using SEEP/W software was used for the estimation of water flow via the dam foundation. Then, depend on the amount of seepage rate, the optimum cutoff walls were designed to sealing the dam site.

2. Study of seepage through earth-fill dams

2.1. Analytical method

Dam failures in the 1700s and 1800s sparked study into more scientific methods of dam design and construction. Henri Darcy, 1856 published the first study that quantitatively quantified fluid flow through a porous media; he based his formula (now known as Darcy's law) on the flow of water through vertical filters in laboratory setups [47]. Henri Darcy demonstrated a basic equation between discharge velocity and hydraulic gradient depending on the tests, which he presented as follows:

$$v_d = k.i = Q/A \quad (1)$$

$$Q = k.A.i \quad (2)$$

where Q represents the rate of seepage (m3/s), vd represents the discharge velocity (m/s), I represents the hydraulic gradient (m/m), k represents the coefficient of permeability (m/s), and A represents the cross-sectional area normal to the flow direction (m2). Forchheimer established in the 1880s that the Laplace deferential equation governs the distribution of water pressure and velocity inside a seepage medium. Forchhiemer in Germany and Richardson in England independently devised a powerful graphical approach to derive approximate solutions to the Laplace equation [48] in the early 1900s. After the release of a complete study by researchers [49], this technology became commonly employed for earth dams. Since then, the graphical or electrical analog model solution of the Laplace equation has been a typical approach for seepage analysis [50]. The graphical method, on the other hand, necessitates a lengthy plotting approach, is time demanding, and is dependent on personal abilities [50]. When employing the L. Casagrande solution (Figure 1), the rate of seepage is:

$$q = k.a.sin^2 \beta \quad (3)$$

where q represents the Darcy flux or flow rate (m2/s), k represents the hydraulic conductivity or permeability (m/s), a represents the length of the seepage surface (m), and is the angle of the downstream slope.

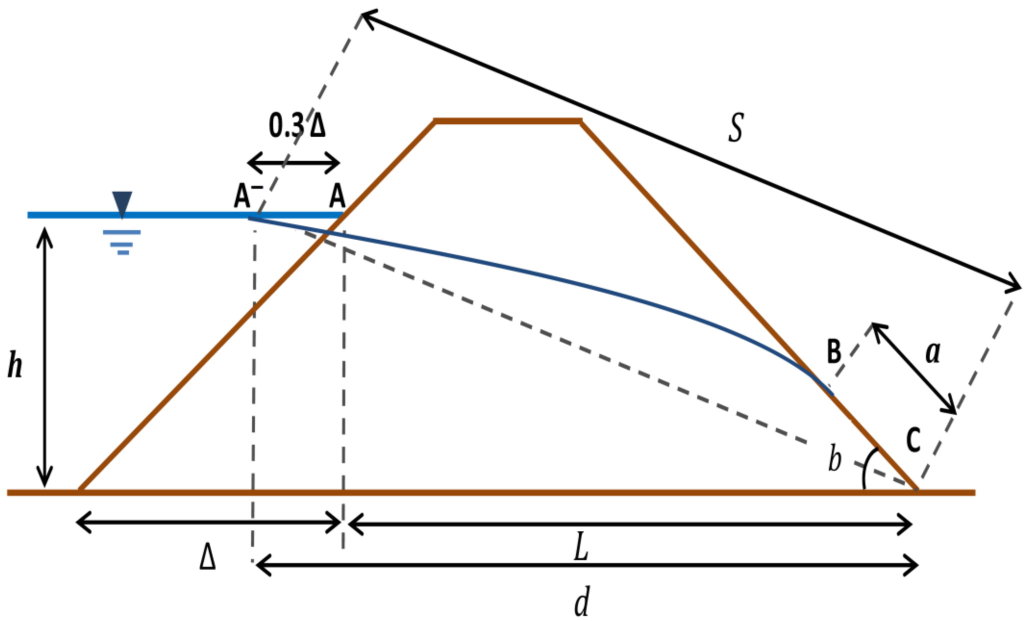

Figure 1: L. Casagrande's solution for flow through an earth dam [51]

The length of the seepage surface (a) using upstream head (h) is calculated as:

$$a = S - \sqrt{S - \frac{h^2}{sin^2\,\beta}} \tag{4}$$

where S is the length of the curve BC (m), and h is the upstream head (m).
where S denotes the curve's length in meters (m) and h denotes the upstream head (m).
We can, however, approximate S as the length of the straight line $\bar{A}$C with around a 4–5% error. Thus,

$$S = \sqrt{d^2 + h^2} \tag{5}$$

$$d = L + 0.3\Delta \tag{6}$$

2.2. Numerical method (SEEP/W)

Although the analysis of hydrological and geological conditions in sites is required for the study of seepage through earth-fill dams, many studies have been undertaken using physical models (e.g., [52-54]), because physical models provide a general picture of seepage behavior via earth-fill dams, including the phreatic line and flow rate. Furthermore, physical model tests can be an important tool for examining seepage behavior prior to the building of earth-fill dams, as well as for verifying the basic design of dams by disclosing potential flaws and exploring solutions.

However, because physical modeling has numerous restrictions and constraints, numerous studies (e.g., [55–57]) have employed numerical modeling, which is based on mathematical solutions, to tackle the most difficult engineering problems, including seepage studies. Numerical modeling is a quick and low-cost method, and the results may be quickly communicated with the parties involved. Numerical modeling differs greatly from both laboratory-scale physical and full-scaled field modeling [58] since it is solely mathematical. Physical modeling is usually advised in cases when numerical modeling is deemed inadequately validated, such as complex hydraulic circumstances, non-standard or irregular site-specific conditions, or project performance improvement employing non-standard designs. The seepage through earth-fill dams was explored using three methods in this work, namely physical, mathematical, and numerical models, and the results were compared. The SEEP/W program was then used to perform a seepage analysis for seven possible layouts of an earth-fill dam.

SEEP/W program analyzes groundwater flow and pore water pressure problems in porous media such as soil and rock using the finite element approach. Different flow modes, both saturated and unsaturated, can be verified with this program. SEEP/W uses a saturated-unsaturated formulation to detect water loss as a function of time and space. Another notable aspect of this program is the use of infinite elements in evaluating the degree of problem boundaries. Increasing the study of seepage problems in infinite boundaries improves the precision of the solution and significantly decreases errors caused by model geometry [6].

2.3. Governing equation of inflow model in SEEP/W

The governing partial differential equation for a two dimensional saturated/unsaturated flow condition can be obtained by coupling the Darcy's law and continuity equation [59] as given below:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right) = C\frac{\partial}{\partial h}(h) + Q \tag{7}$$

Here, Kx and Ky are the hydraulic conductivities in the X and Y directions respectively, Q is the recharge or discharge per unit volume, H is the hydraulic head and t is the time. The hydraulic head is correlated to the volumetric water content (θ) using the following equation:

$$\left(\frac{\partial \theta}{\partial t}\right) = C\left(\frac{\partial h}{\partial t}\right) \tag{8}$$

where C is the slope of the water storage curve.

To solve Equation 7 using finite element method, the SEEP/W model utilises the Galerkin approach to determine an approximate solution.

3. Experimental procedure

3.1. Study area

Peygham-Chay Dam, with the geographical coordinate of 38º N and 45º E, is located in the northern part of the East Azerbaijan Province, in North West of Iran. One of the key goals of the dam construction, is to provide water supply for the agriculture of the area, and beverage service of Kaleybar city. This is an earth-filled dam with a core of central impermeable clay wherein the height and length of the crest are constructed for 46 and 771 m, respectively. The dam is constructed of Peygham-Chay Kaleybar River with a reservoir capacity of about 15 mm^3. Figure 2 presents the location of the dam and the geological setting of the region.

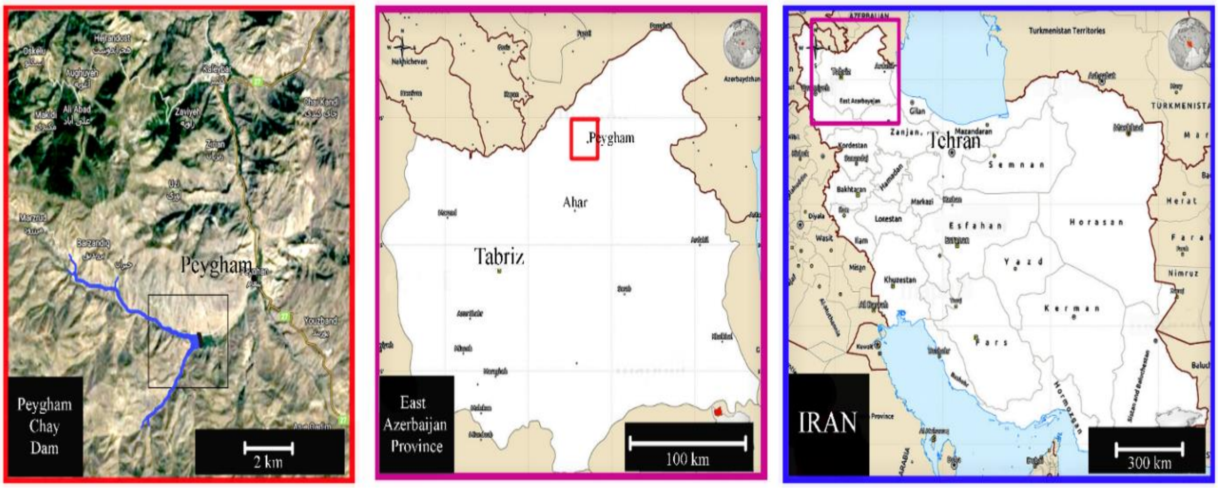

Figure 2: Location and the geological setting of Peygham-Chay dam

3.2. Site description

A big part of Azerbaijan province is located in a zone termed, “Azerbaijan-Alborz”. This area is limited in the north by Alborz’s fault, in the west by Tabriz-Urumiyeh fault, and in the south by Semnan fault [60]. Various sedimentary facies are created based on faulting and fragmentation in Azerbaijan through a structural event in Early Devonian [61]. According to this circumstance, the Tabriz fault was composed and extended from Zanjan depression to the Mishu and Morou mountains in Tabriz and northwest of Caucasus and Azerbaijan in an NW–SE direction [62]. This episode separated Azerbaijan into two blocks, one block is related to the northeast with subsidence and sedimentation in Early Devonian, and the other is placed in the southwest, which remained high until Late Carboniferous [63].

The axis of the Peygham-Chay dam is located in a relatively narrow valley that has an asymmetric shape in this area. The bedrock outcrop causes a steep slope of 28º in the right abutment while the left abutment of the dam has a mild slope of 5º due to the presence of alluvium. The width of the alluvium covers at most 60 m in left abutment, but in the right abutment and riverbed, the thickness is between 5 and 20 m. The stratigraphic rock of the study area is composed of volcanic rocks, clastic rocks (gray sandstone and shale), and intrusive igneous rocks covered by alluvial deposits. Based on the exploratory drillings over the region, water table measurements, data of Lugeon and Lufran tests, and field observations, the hydrogeological setting was investigated. Scrutinizes show that the permeabilities domain is broad in left abutment due to alluvium heterogeneity. The minimum and maximum permeabilities are 2.48e-8 and 1.16e-2 cm/s, respectively. Also, surveys show the permeabilities domain in the right abutment with the presence of a bed river high toward the left abutment. Since the Peygham-Chay Dam site is located on two different types of bedrock and alluvial material, and also due to permeability and thickness diversities of these materials along the dam, 15 sections were considered for water seepage analyses shown in Figure 3.

Table 1 presents the geometric characteristics of the dam site and other information that predominantly required for water seepage estimation.

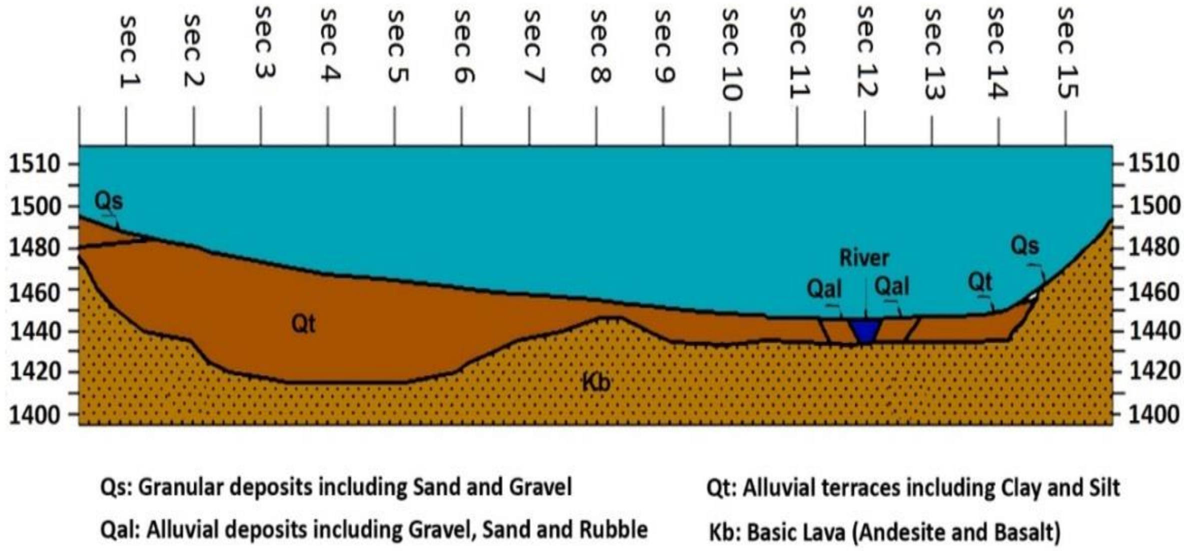

Figure 3: Position of sections in the dam axis

Table 1: Technical characterization of Peygham-Chay dam

Crown length	Crown width	Max. water height	Max. Crown height	Core permeability	Shell permeability	Drainage permeability	Filter permeability
771 m	10 m	45 m	46 m	4e-7 cm/s	1e-3 cm/s	6.25e-5 cm/s	2.5e-6 cm/s

3.3. Hydrogeological conditions

In this research, to examine permeability conditions at the Peygamchai Kleiber dam site some hydrogeological studies were conducted using 17 boreholes drilled in the region's alluvial and bedrock foundations.

- *Alluvial foundation*

The permeability in the left abutment of Peygham-Chay dam is not uniform due to heterogeneity and non-uniformity in the alluvial base of this area. As a result, the conditions in various boreholes vary from highly permeable to impermeable. The permeability of the BH7 borehole (2.48e-8 cm/s) is the lowest in this range, while the permeability of the BK9 borehole is the highest (1.16e-2 cm/s). The abundance of fine-grained elements in these alluviums and clay compositions in some areas explains this condition. In the case of falling head, the alluvial base in the left abutment has a permeability of 9.71e-4 cm/s and in the case of Constant-head, it has a permeability of 2.27e-3 cm/s. The average permeability in boreholes located in the alluvium of Peygham-Chay dam's left axis is shown in Table 2.

Because of the low alluvial coverage (about 0.5 to a few meters), investigation of the permeability of the alluvial segment in the right abutment can be overlooked. As a result, only the Lugean test has been carried out in this portion.

Table 2: The permeability of boreholes in the Peygham-Chay dam's left axis alluvium

The average permeability (Constant-head)	The average permeability (falling-head)	Depth of alluvium (m)	boreholes depth (m)	boreholes
1.29e-5	1.65e-5	60.5	70	BH1
1.06e-5	1.65e-5	53	65	BH2
1.06e-6	2.48e-8	20.9	45	BH7
4.75e-6	-	30	30	BH8
2.06e-6	3.72e-6	30	30	BH9
7.35e-5	6.70e-5	30	30	BH14
1.12e-4	2.07e-6	30	30	BH16
2.35e-3	2.26e-4	16	40	BK6
1.10e-4	1.38e-4	7.2	31	BK7
3.78e-4	4.38e-4	20	40	BK8
5.28e-3	1.16e-2	7.5	32	BK9
3.82e-5	4.76e-5	48	60	BK10
2.76e-5	2.76e-5	45	45	BK11
2.27e-3	9.71e-4	-	-	average

- *Bedrock foundation*

At a depth of 30 to more than 70 meters, bedrock can be found on the left side. These rocks are totally impermeable, and the maximum lugean obtained from this region is 2.5, according to Table 3. Given this, as well as the thickness of the alluvium, it's possible that the bedrock on this side plays no part in the dam's hydrogeological problems and instead serves as an impermeable bed under the alluvium. This problem will be addressed further, and it will be shown using seepage analysis results that not only the bedrock part of the left wing, but also a large portion of the alluvial part of this wing, does not play a role in hydrogeological issues. It isn't very active in this field.

In the riverbed, bedrock can be found at a depth of 10 to 20 meters. As a result of this issue, bedrock in this area's hydrogeology is more critical than alluvial. The maximum number of lugeans obtained in this range is recorded from BK4 borehole with a value of 8.5, while the minimum amount is reported from BH3 borehole with a value of 1 lugean, according to Table 4. The bedrock section of the riverbed falls into the low permeability group, based on the average permeability of the rocks in this part of the dam (around 4.3 Lugean). In other boreholes, the permeability of rocks on the right side is moderate to high, regardless of boreholes BH12, BH10, or BK1. The minimum and maximum lugeans obtained in this region, according to Table 5, are 2 and 173, respectively, and were registered in boreholes BK1 and BH11. Right abutment rocks have an average permeability of 40 lugeans.

Table 3: The permeability in boreholes drilled into the bedrock on the left side of the Peyghamchai dam site

Description	The average permeability (Lugean)	Depth of alluvium (m)	boreholes depth(m)	boreholes
One experiment	0.36	60.5	70	BH1
Two experiments	0.18	53	65	BH2
One experiment	0.062	20.9	45	BH7
Two experiments	2.5	16	40	BK6
One experiment	0	7.2	31	BK7
-	-	20	40	BK8
Eleven experiments	2	7.5	32	BK9
One experiment	2	48	60	BK10
-	1	-	-	average

Table 4: The permeability in boreholes drilled into riverbed alluviums at the Peyghamchai dam site

The average permeability (Constant-head)	The average permeability (falling head)	Depth of alluvium (m)	boreholes depth(m)	boreholes
1.55e-4	1.7e-4	11.5	40	BH3
1.17e-4	1.81e-4	11	45	BH4
2.21e-2	815e-3	11.8	30	BH5
1.96e-3	1.02e-3	12	35	BH13
4.17e-2	1.62e-2	6.6	30	BH15
5.25e-2	2.71e-3	8	30	BH17
3.02e-3	5.77e-3	11	25	BK4
3.02e-3	3.86e-3	9.5	25	BK5
3.02e-2	4.76e-3	-	-	average

Table 5: The permeability in boreholes drilled into the bedrock on the right side of the Peygham Chai dam site

The average permeability (Lugean)	Depth of alluvium (m)	boreholes depth (m)	boreholes
11	0.5	40	BH6
2.5	4.9	20	BH10
173	0.3	25	BH11
7	2.2	30	BH12
2	1	60	BK1
17	0	20	BK2
63	8.75	20	BK3
41	3		BK12-1
40	-	-	average

4. Result and discussion

4.1. Seepage analysis

For a suitable description of the optimum sealing approach, exhaustive and broad investigations of the water flow are of importance. Simulation of complicated hydrogeological circumstances and more detailed evaluations of the seepage through the dam into are feasible by using more sensible material properties and boundary conditions using the numerical method [64-69].

In this case, the dam site presumed to be a continuum. To simulate and evaluate water seepage from dam foundation, FEM was applied using SEEP/W programs in 2D. It is practical for seepage simulations in various hydraulic regimes from the site and transient state to complex saturated/ unsaturated systems.

Different presumptions were considered to streamline the complicated status of the dam site. This presumption were: (1) steady-state regime of groundwater in the saturated area based on Darcy's Law, (2) uniform and homogeneous porous material, and (3) boundary condition concerning the water level in the dam reservoir. The boundary conditions in the model are: 1) Fixed head boundary condition equal to water level for each section assigned to the dam body (upstream area), 2) No flow boundary condition attached to the downstream.

In Figure 4, the finite element mesh of the dam foundation and the adjacent ground can be seen. Figure 5 shows that the numerical modeling is provided as water flow lines through the foundation and potential contours in section 9.

The results of seepage analyses of Peygham-Chay Dam in lack of sealing demonstrate that the flow rate from the dam foundation is 0.0586 m^3/sec (Figure 6). Since the total volume of the dam reservoir is 12e6 m^3, the seepage rate is 15% m^3/year compared to the entire volume of the dam reservoir. According to that, this amount of water seepage significantly reduces the reservoir capacity; therefore, the implementation of sealing measurement is necessary.

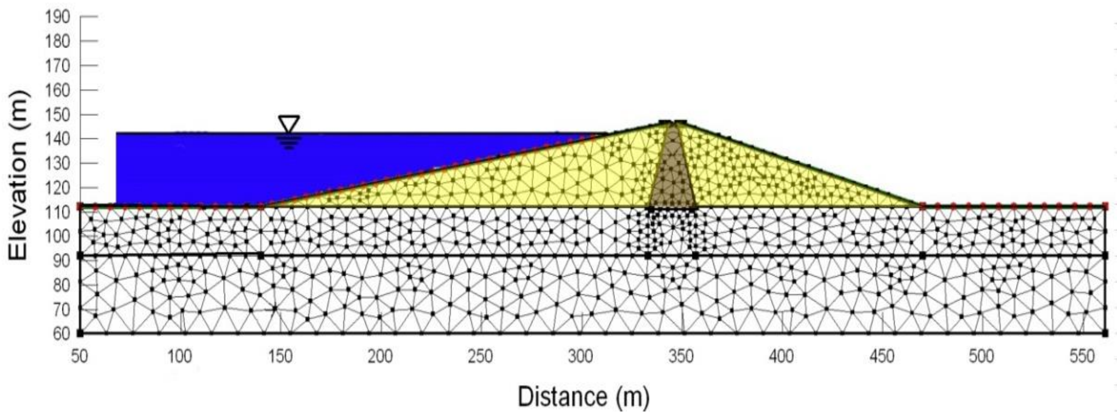

Figure 4: 2D finite element mesh in section 9 of Peygham-Chay dam by SEEP/W

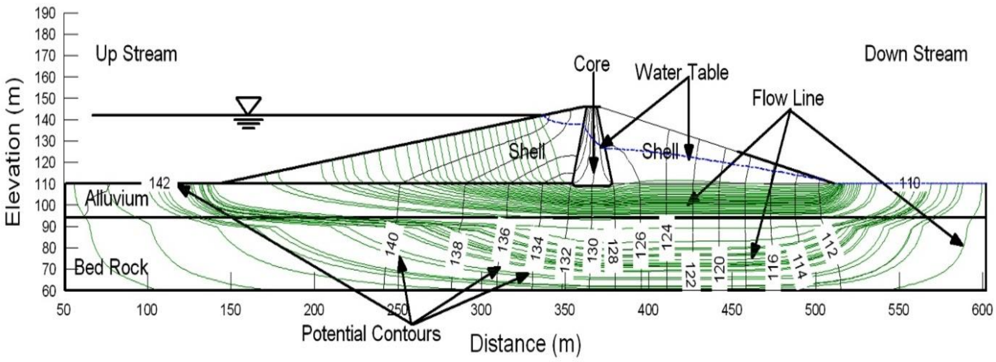

Figure 5: Potential contours and flow line in section 9

As Figure 5 shows, based on low permeability in left abutment, the seepage rates are insignificant from sections 1 to 5. On the other hand, as the average permeability is high in the right abutment of the dam site (sections 6-14), the tremendous amount of seepage rate is estimated, especially in sections 11 and 12. Hence, insufficient sealing is necessary to secure the dam from sections 6 to 14.

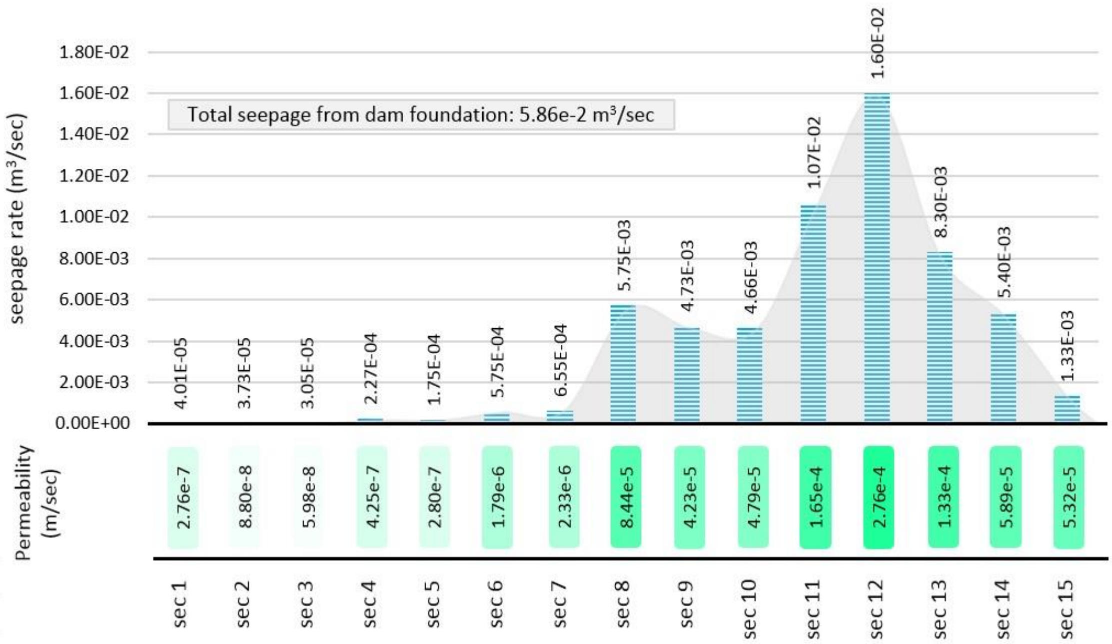

Figure 6: Water seepage in each section at Peygham-Chay dam

4.2. Model validation

Reliability of numerical simulations is more important in practice. Therefore, the phreatic line for seepage through the physical model (according to the dimensions of the dam and regardless of the core) using the two methods, analytical method and numerical method (SEEP/W), is presented in Figure 7. The results revealed that L. Casagrande solution has a plotted seepage line compatible with the SEEP/W model line. The results of the seepage flow rate using the two methods are summarized in Table 6. As shown in the table, the seepage rate through the model from SEEP/W is close to that calculated by the L. Casagrande solution. This difference in results indicates that when seepage flow intersects the downstream slope, water will exit the body of the dam and then follow the characteristics of surface water flow. Moreover, the intersection with downstream slope softens and weakens the soil mass, hence, increases the possibility of piping within the body of the physical dam model that eventually increases the total seepage rate.

The conformity of the phreatic line in the two methods and the close proximity of the dam seepage results show the correctness of numerical modeling using SEEP/W model.

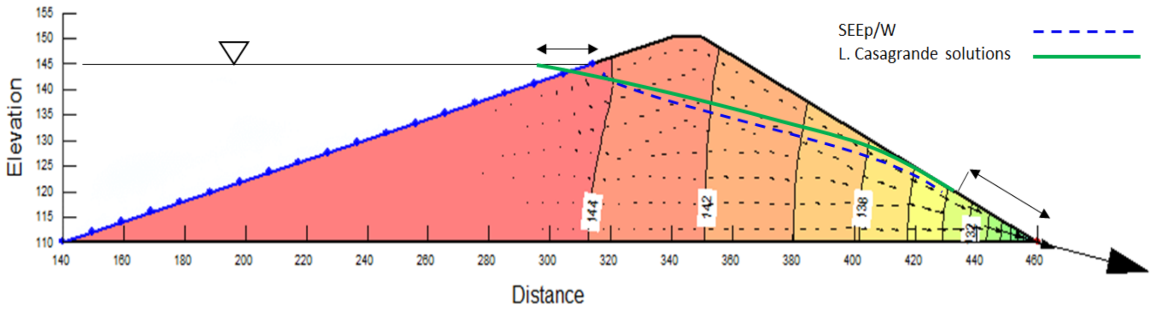

Figure 7: The phreatic line using the two methods.

Table 6: Seepage flow rate using the two methods

Permeability (m/s)	Water head (m)	Q (m3/s/m)	
		L. Casagrande	SEEP/W
1e-5	35	2.156e-5	2.205e-5

4.3. Sealing methods

The sealing of the dam reservoir is of considerable significance to avert water seepage from the reservoir. There are some choices for sealing dams, water channels, and reservoirs of water, for instance, Concrete blanket, Clay blanket, Asphaltic concrete, Geomembrane, cutoff wall and, Grouting [70-76]. Each of those coverings has a particular impact on the efficiency of maintenance and water seepage.

For measuring the optimum sealing by the cutoff wall method, first, it is crucial to indicate the appreciate thickness of the cutoff wall. Therefore, to determine the optimal thickness of the dam cutoff element and the effectiveness of this element on the amount of seepage, SEEP/W program employed. This impermeable cutoff wall (the cut off permeability is 1e-7 cm/s and the thickness of sealing cutoff is 1.5 m) with depths of 10, 15, 20, 25 and, 30 m was individually simulated. It should also be noted that in sections 6 to 14, the cutoff wall only installed on alluvium and depth of cutoff wall increases to it is sewn to the bedrock. The maximum thickness of alluvium is 30 m in the mentioned sections (Figure 3).

The optimization of cutoff wall depth in two different states was investigated. In the first state, the cutoff wall was terminated when directly contact to bedrock (non-infiltration state). But in the second type, the cutoff wall was embedded 3 m into the bedrock (Infiltration state). These analyses carried out to assess the effect of cutoff wall installation on the bedrock as well as its repercussion on the seepage rate (Figure 8). In Figure 8, the rate of seepage was considerably reduced by installing the cutoff wall, which penetrated 3 m into bedrock. So that for cutoff wall depth over 30 m, the seepage rate reduction 6% in the 3 m infiltration state compared to the non-infiltration state.

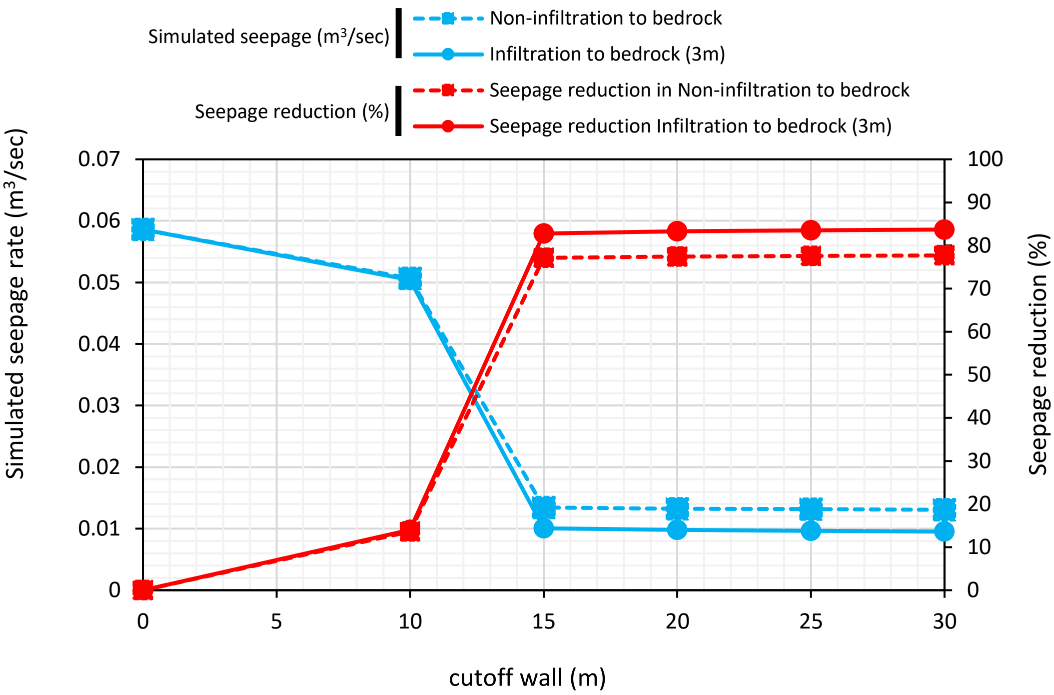

Figure 8: Trend of seepage rate besides seepage reduction percentage versus cutoff wall depth.

Figure 9 shows the equal potential and flow lines of seepage flow in section 9. The optimum cutoff wall depth is 15 m. Since this permeability on the right abutment is moderate to high and the depth of the bedrock in the riverbed in this region is between 10 and 20 meters, the results of the optimization of the cutoff wall were expected to be calculated in this depth range.

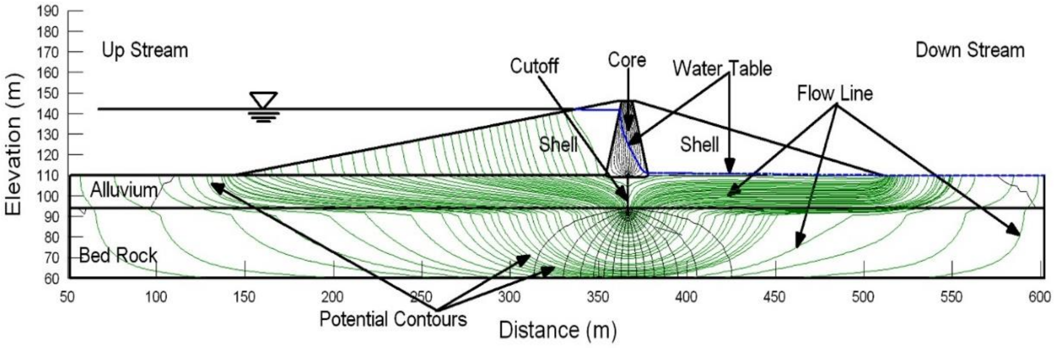

Figure 9: Schematic of the equal potential lines, flow lines and cutoff wall (15m) in section 9 of dam foundation

5. Conclusion

The seepage rate through the foundation of the Peygham-Chay dam can be controlled using the concrete cutoff walls. In the absence of the sealing system, the mentioned rate is 15.4% per year of the total volume of the dam reservoir. To seepage control, numerical modeling was used to investigate the optimum cut off wall depth. Results demonstrate that for the cutoff wall depth in 15 m, the total flow is appreciably decreased.

In case the sealing element with low permeability is used, such as the cutoff wall, in the alluvial part of the dam site, analyses show the cut off wall penetration into the bedrock decreases the total seepage flow. In this study, the penetration depth of 3 m was considered.

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