Numerical Analysis of Groundwater Seepage and Exit Gradients in Hydraulic Structures

Analisis Numerik Gradien Rembesan dan Keluar Air Tanah pada Struktur Hidraulik

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Abstrak

Latar Belakang Umum: Rembesan di bawah pondasi struktur hidraulik menimbulkan risiko signifikan terhadap kegagalan pipa dan ketidakstabilan struktur. Latar Belakang Khusus: Pemasangan tiang pancang vertikal mengubah jalur aliran dan mengurangi tekanan air bawah permukaan pada kondisi ketinggian air hulu yang bervariasi. Kesenjangan Pengetahuan: Kuantifikasi komparatif yang tepat mengenai laju aliran rembesan dan gradien keluar dengan dan tanpa tiang pancang masih kurang terperinci untuk kondisi ketinggian air yang bervariasi. Tujuan: Penelitian ini mengevaluasi debit rembesan dan gradien keluar pada ketinggian hidraulik hingga 10 meter menggunakan pemodelan elemen hingga 2D. Hasil: Menghilangkan tiang penahan meningkatkan laju rembesan maksimum dari $361{,}1\times10^{-3}$ menjadi $491{,}3\times10^{-3}$ m^3/detik/m dan gradien keluar dari 0,41 menjadi 1,21. Keunikan: Pemodelan kuantitatif menunjukkan bahwa menghilangkan tiang penahan meningkatkan debit rembesan sebesar 26,5% dan gradien keluar sebesar 66,6%. Implikasi: Penggunaan tiang penahan sangat penting dalam desain pondasi untuk mencegah erosi bawah permukaan dan memastikan keamanan struktural jangkapanjang.

Kata kunci: Gradien Keluar, Struktur Hidraulik, SEEP/W, Analisis Rembesan, Tiang Penahan

Abstract

General Background: Seepage beneath hydraulic structure foundations poses significant risks of piping failure and structural instability. Specific Background: Installing vertical sheet piles alters flow paths and mitigates subsurface water pressure under variable upstream heads. Knowledge Gap: Precise comparative quantifications of seepage flow rates and exit gradients with and without sheet piles remain insufficiently detailed for varying head conditions. Aims: This study evaluates seepage discharge and exit gradients under hydraulic heads up to 10 meters using 2D finite element modeling. Results: Omitting sheet piles increases maximum seepage rates from 361.1x10-3 to 491.3x10-3 m3/sec/m and exit gradients from 0.41 to 1.21. Novelty: Quantitative modeling demonstrates that removing sheet piles elevates seepage discharge by 26.5% and exit gradient by 66.6%. Implications: Incorporating sheet piles is essential in foundation design to prevent subsurface erosion and ensure long-term structural safety.

Keywords: Exit Gradient, Hydraulic Structures, SEEP/W, Seepage Analysis, Sheet Piles

Introduction

Water control structures, such as dams, canals, and bridges, are crucial for water management. However, they often face problems like leakage, erosion, and pressure from below. These problems can impair the performance of these structures and lead to their collapse, negatively impacting the economy and society. To mitigate these risks, engineers typically use walls to contain the water and implement drainage systems [1-4]. Dawood and others [5] argue that the force of water has always been a significant factor in shaping and stabilizing the land, and it plays a major role in soil formation and the construction of structures. Water leakage is a problem faced by ground-based control structures that allow water to flow through. This phenomenon often occurs due to differences in water levels on either side of the structure.

The detrimental effects of water leaking through can be divided into three ways [6]:

- The uplift force is something that we need to think about because it reduces the friction between the structure and its foundation. This uplift force makes the structure more likely to slide or overturn. We have to consider the uplift force when we are talking about the structure and its foundation.
- Seepage discharge is another thing that changes the water balance. The seepage discharge affects the water balance in a way.
- The exit gradient is very important because it is a design parameter that helps prevent piping. The exit gradient is something that we use to prevent piping when we are designing something.

Piping can occur if the exit gradient gets too high, causing soil erosion and potentially leading to failure. A recent study by Rath et al [7]. Used machine learning to predict exit gradients in structures. They found that anisotropy and cutoff-wall depth are among the important factors. Excessive uplift pressure and piping are known causes of failures in hydraulic structures [8]. Therefore, improving safety requires reducing both the uplift pressure and the exit gradient as they directly affect the stability and performance of these structures.

A common solution to prevent water from damaging structures is to install cutoff walls along their foundation sides. Resistant walls are barriers that prevent the passage of water. They are usually made from materials like steel sheets, concrete trenches, cement curtains or special blankets that keep water out [2]. The placement of these walls reduces water flow and pressure where it exits, which helps prevent the structure from rising and reduces erosion risk [1 2, 9 10]. Drainage systems are also used to control water flow and its effects. These systems include drainage channels, tunnels and wells that work together to regulate groundwater pressure and flow beneath these structures [2, 11]. By using these measures water infrastructure can be made safer and more durable reducing failures and related economic and social problems. Researchers have studied water flow beneath structures extensively leading to theories. Some of these theories were proposed by researchers like Bligh [12] Lin [13]. Khosla and Bose [14]. Blighs theory describes the water path beneath structures assuming a pressure distribution and energy loss proportional to the waters path. Lynn introduced another theory that assigns weights to the waters vertical paths to account for flow resistance variations. Khosla and Bose improved this framework using shapes like ellipses and hyperbolas to understand water pressure effects on the ground. Khoslas method is generally more reliable than Blighs and Lynns. Can become complex and inaccurate with irregular or boundary grounds. Water flow and pressure are factors in the design and construction of these structures. Cutoff walls and drainage systems play a role in managing water flow. The use of these systems helps to prevent erosion and structure failures. Overall understanding water flow and pressure is essential, for building more durable water infrastructure.[6] While mathematics can be used to solve some of these problems, its application in real-world situations is often very difficult due to its complexity. [15] This is why people turn to computers to solve these problems. By dividing the ground into sections, computers can calculate water pressure, how the water moves through it, and where it exits, even when there are irregular boundaries [9, 16, 17]. This simplifies the design of retaining walls and drainage systems for water flow beneath structures. Saleh and his team [18] studied how water moves through the ground beneath the Diyala facility and wanted to know what would happen if some of the waterproofing walls were removed. They used a computer program called SEEP/W for this purpose. Chilling and Sahar [19] conducted some experiments.

Used math to study how water pressure changes under hydraulic structures. Senda [20] made a computer model to see how water moves through the ground under a levee when the river level changes, using a program called SEEP2D. Phanuwat and Pachern [21] looked at something interesting. They found out that you can use graphs to understand how water moves through the ground. These graphs are called normalized seepage-analysis graphs. They are used to study what happens along a single sheet pile in double-layer soils. They used a computer program called SEEP/W to do this. Adel and Mohamed [22] also did some research. They looked at the characteristics of seepage and exit gradient beneath the ground. Phanuwat and Pachern [21] did their research. It is listed as a number. Adel and Mohamed [22] did their research. It is listed as a number.

The study looked at water seeping under a structures floor. We used a computer to do this. The hydraulic structure is shown in Figure 1. We wanted to see how different water levels affect the structure. Specifically, we looked at the water seeping under it. We did this with and without sheet piles. We used software called Geo-Slope SEEP/W to do the study.

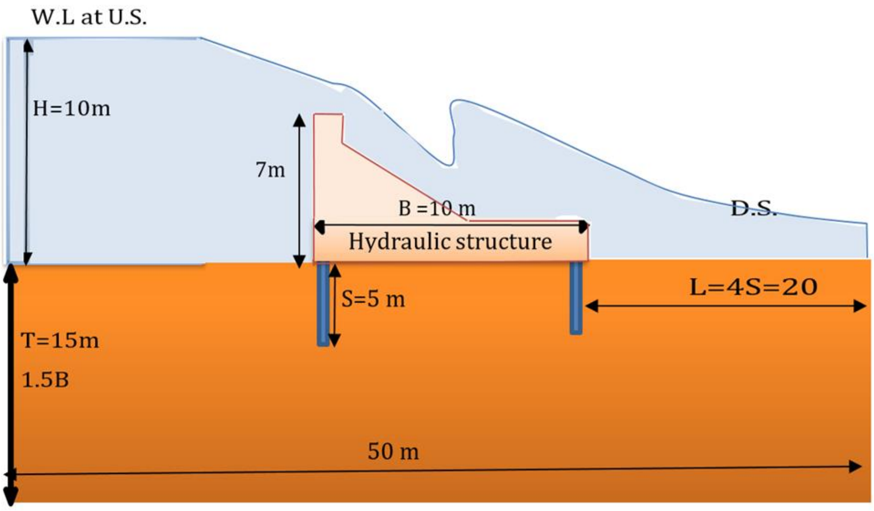

Figure 1. The hydraulic structure profiles

2. Numerical Modeling Methodology

The model was created using Geo-Slope software, the SEEP/W program. To understand water conditions under the foundation, a steady-state analysis was done. The SEEP/W model shows the structure in Figures 2a and 2b. The water conditions under the structure foundation were analyzed using this model. The Geo-Slope software helped to get results. The hydraulic structure is really tall; it is 10 meters high above the riverbed. The sheet-pile goes down 5 meters below the ground. The base of this study is 50 meters wide.

The model sections were split up into parts, and this was done by using a method that uses squares and triangles to help with the division. This created a mesh with 864 nodes and 736 small parts. Each part of the mesh is 1 meter in size. This method was chosen to get a look at the soil under the foundation of the hydraulic structure.

The model was set up to be saturated, which means the soil is filled with water. This was chosen because it is the way to do a state analysis. The soil will stay saturated during the simulation as noted by Shayan et al.[23].

The properties of the soil, like how it lets water through, were entered into the Geo-Slope software. The materials used for the structure and sheet piles were set to prevent water from entering. We picked a head condition for the model because it has water in it. A special boundary condition, called Dirichlet and Neumann, was used on the side of the hydraulic structure as seen in the work of Arshad et al.[24]. The other side of the structure is open, and more water is expected to come in.

The performance of the hydraulic structure was looked at in two situations:

- With sheet-piles
- Without sheet-piles

At different water levels: 2 m, 4 m, 7 m, and 10 m. The comparison of simulations for sheet-piles is discussed. The hydraulic structure and sheet-piles were studied to see how they work. The results of the simulations are compared.

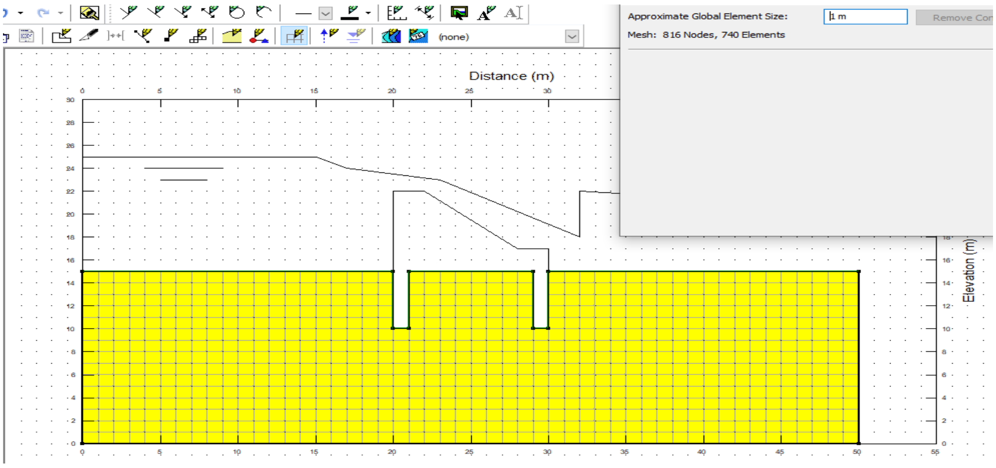

Figure 2. (a): shows the mesh that SEEP/W made for a structure that does not have sheet piles

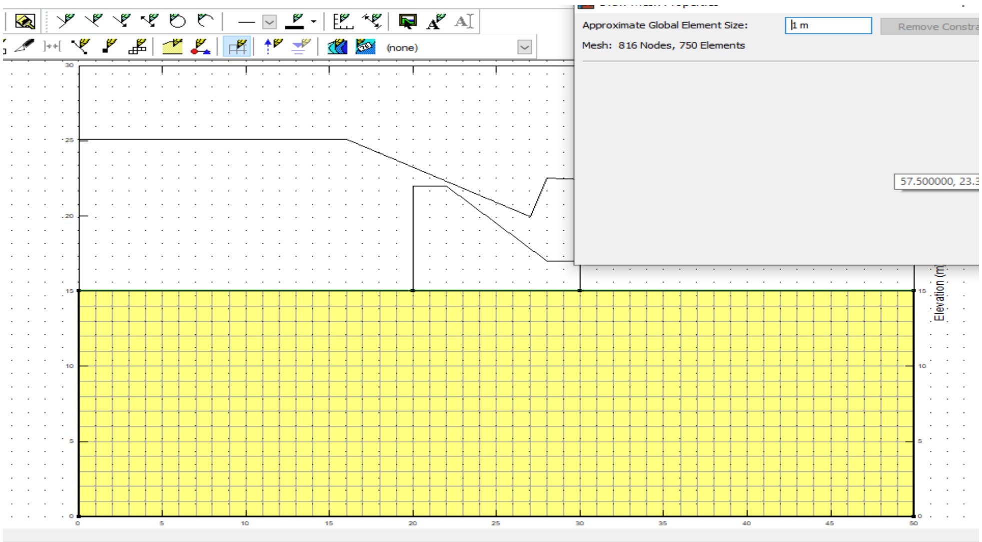

Figure 2. (b): shows the mesh that SEEP/W made for a structure that does not have sheet piles

3. Results and Discussion

The main things we looked at in this research were water seepage and how water exits. We wanted to see what happens to the soil underneath a water structure. This structure had 750 parts and 816 points that we looked at. We used tools to understand how the soil behaves. We studied what happens to the water structure in two situations: when it has strong walls to hold the water back, and when it does not have these walls. We tested this with water levels of 2, 4, 7, and 10 m of water. We saw how the water structure worked normally with amounts of water pressure when it was built as planned. The biggest result we found was related to the structure. The hydraulic structure was the thing we were looking at. We saw how the hydraulic structure worked in its shape and design. The hydraulic structure is very important.

The amount of water that seeps through the ground, which is called seepage quantity and the rate at which water exits the ground, which is called exit gradient, were found to be 361.1×10^{-3} m^3/sec/m and 0.41 in case the total head was 10 m. The total head is a big factor in how much water seeps through the ground. The total head is very important when it comes to erosion under the foundations of hydraulic structures. The biggest difference in water level was under the structure on the side where the water flows out. This difference in water level pushes water through the soil under the structure. The soil under the weir foundation does not let water through, and it does not stick together well, which makes it more likely that seepage erosion will happen under the hydraulic structure, as Al-Saedi said in 2020. Figure 3a to 3e shows what happened when we used SEEP/W to see what would happen if the water level at the reservoir got too low, we did a test. We looked at how water seeps through the ground for two reasons. Firstly, we wanted to figure out how much water actually flows through the soil. Secondly, we wanted to find the areas where the exit gradient is high.

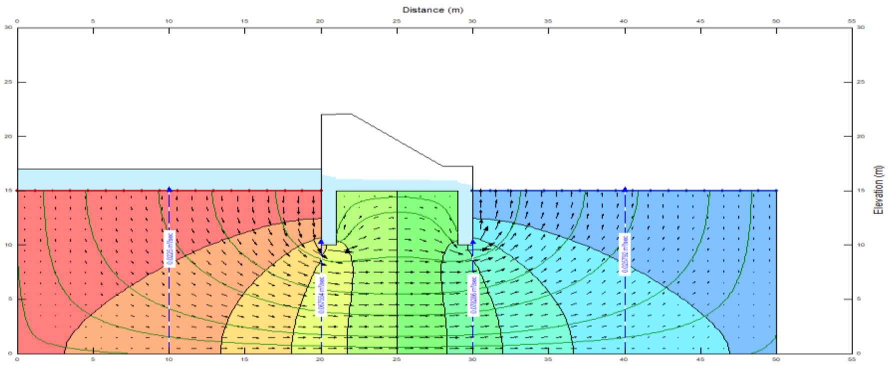

Figure 3. (a): SEEP/W model results for a hydraulic structure with sheet-piles. water level is 2 m

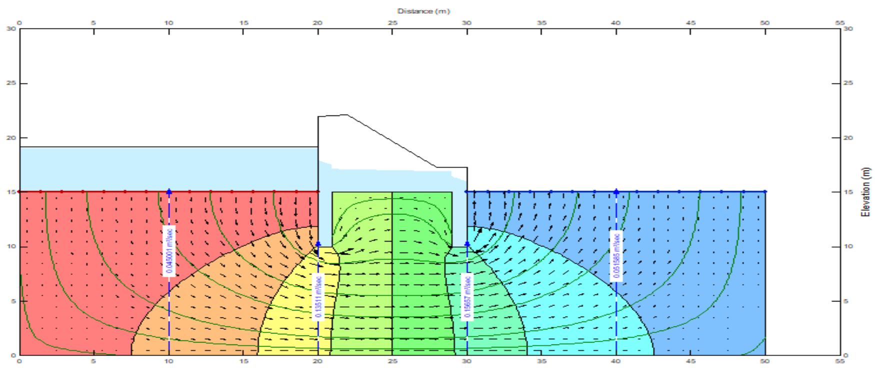

Figure 3. (b): SEEP/W model results for a hydraulic structure with sheet-piles. water level is 4 m

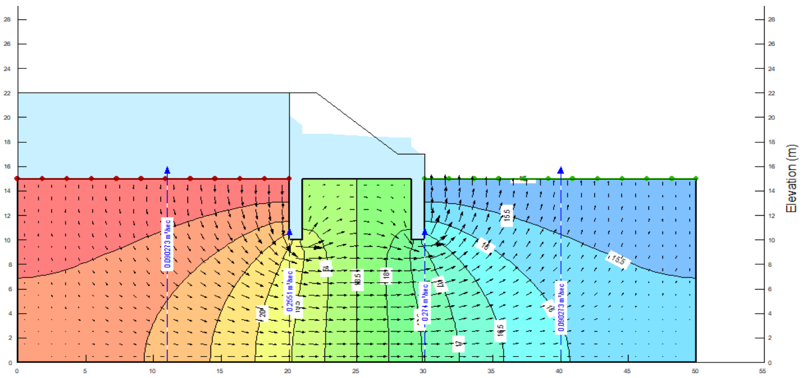

Figure 3. (c): SEEP/W model results for a hydraulic structure with sheet-piles. water level is 7 m

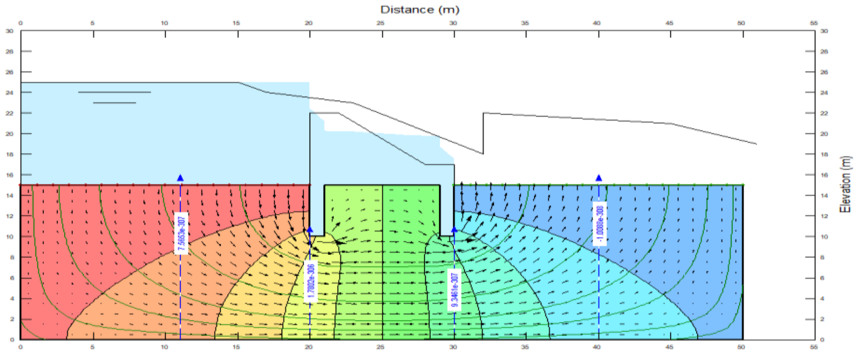

Figure 3. (d): SEEP/W model results for a hydraulic structure with sheet-piles.water level is 10 m

The hydraulic structure was checked to see how water would seep through it without sheet piles when the water level in the reservoir was steady. We found out that the most water that seeped through and the exit gradient were 491.3x10-3 m^3/sec/m and 1.21 when the total head of water was 10 m. We looked at five water level scenarios, and the water flow showed strange behavior. It actually came out of the riverbed on the side of the hydraulic structure. When we compared the two situations, we saw that without sheet piles, the water pressure inside the structure's foundation would increase. This will also increase the leakage rate and drainage slope by up to 26.5% and 66.6%, respectively. Therefore, the hydraulic structure is unsafe without the use of steel plates. We used computer software to simulate what would happen to the structure at different reservoir levels, and the results are shown in Figure 4(a-e). The leakage rate and drainage slope values were similar in both cases. We also found that using steel plates reduces the leakage rate and drainage slope. These results are consistent with those of Nasrallah and Saleh in their 2015 and 2009 studies, where they reported that the pressure under the hydraulic structure increases with the water level when steel plate foundations are used. The exit gradient also increases when there are no sheet piles. The seepage flux decreases when the water level decreases and when sheet piles are installed.

The hydraulic structure and the seepage analysis show that sheet piles are necessary for the hydraulic structure to be safe. The amount of water that seeps through the structure and the exit gradient are things to think about when designing the hydraulic structure. We need to make sure the hydraulic structure can handle the water pressure and seepage, and that is why sheet piles are so important. The hydraulic structure and sheet piles go together to make sure the structure is safe and stable. The results of the seepage analysis for the structure show that sheet piles reduce the seepage flux and exit gradient of the hydraulic structure.

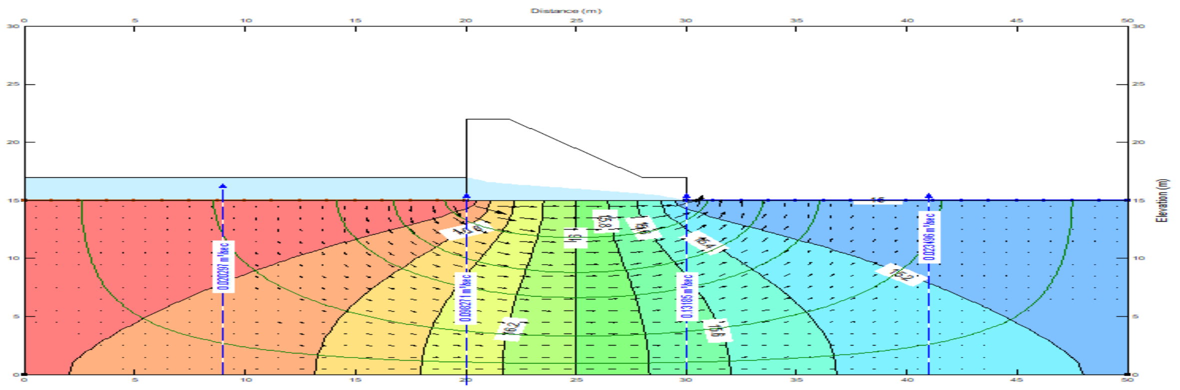

Figure 4. (a): SEEP/W model results for a hydraulic structure that does not have sheet-piles. water level is 2 m

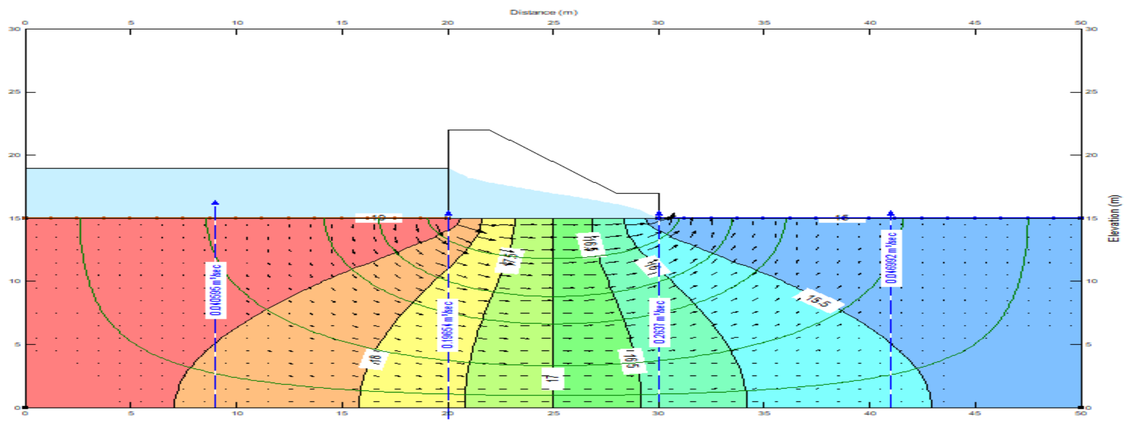

Figure 4. (b): shows the SEEP/W model results for a hydraulic structure that does not have sheet-piles. The water level is 4 meters.

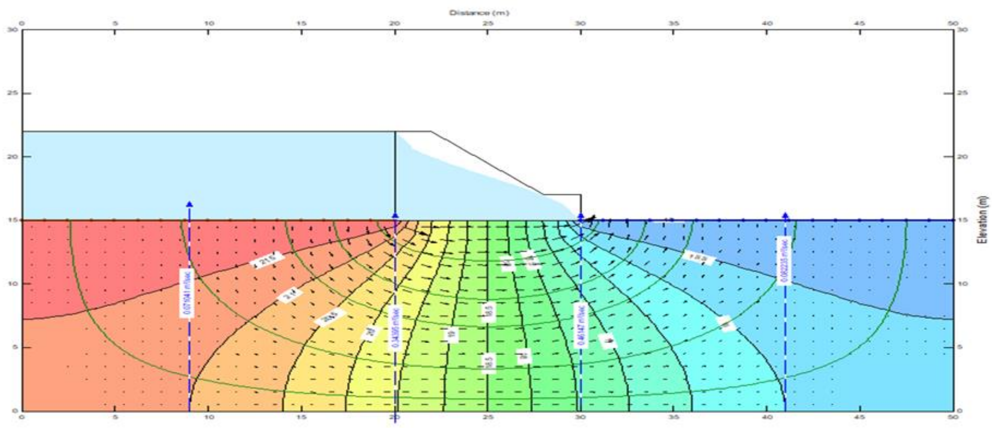

Figure 4. (c): shows the SEEP/W model results, for a hydraulic structure that does not have sheet-piles with a water level of 7 meters.

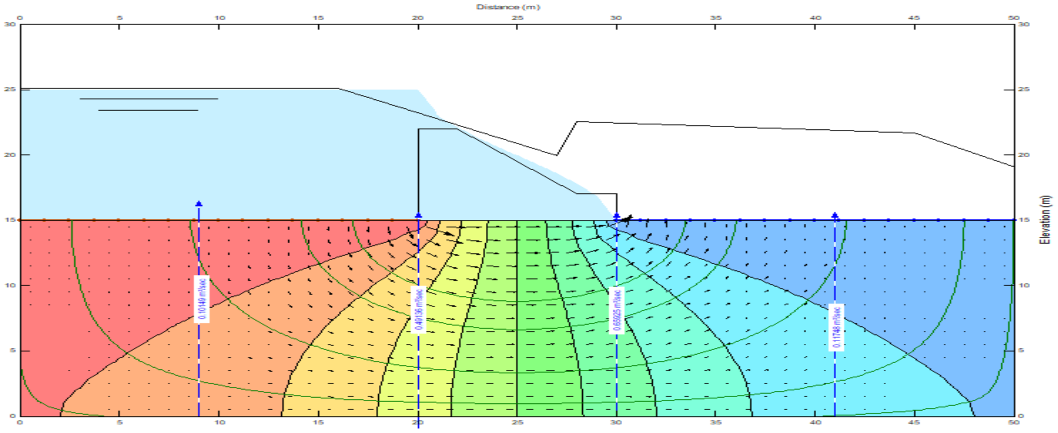

Figure 4. (d): the SEEP/W model results for a hydraulic structure that does not have sheet-piles. The water level is 10 m

4. Conclusions

From the results of the case study, it is clear that to reduce the amount of water seeping through the soil under the foundation of the structure, sheet piles must be used as originally planned. If sheet piles are not used, the amount of water seeping through and the pressure of the water exiting the soil will increase. The results showed that when sheet piles were used in the design, the hydraulic structure worked normally with different water levels. The maximum amount of water seeping through the soil was 361.1 x10^{-3} m^3/sec/m and the pressure of the water exiting the soil was 0.41 when the water level was at 10 meters.

However, when there were no sheet piles and the water level was still at 10 meters, the weir did not work normally. The amount of water seeping through the soil was much higher at 491.3 x10^{-3} m3/sec/m. The pressure of the water exiting the soil was 1.21.

The presence of sheet piles helps to control the amount of water seeping through the soil and the pressure of the water exiting the soil. Without sheet piles, the pressure of the water in the soil under the foundation of the weir increases, and the amount of water seeping through and the pressure of the water exiting the soil increase by 26.5 % and 66.6 %, respectively.

Therefore, the structure is not safe without sheet piles. The study shows that using methods helps us understand problems related to water and soil.

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