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Verification against Failure by Piping on Retaining Structures Applying the Network Method

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Abstract - When designing retaining structures, different phenomena must be studied in order to classify them as safe from a geotechnical point of view. Among them is pipping, a physical process related to seepage under the structure which leads to an unstable situation and might finally cause failure. In order to quantify this risk, a comparison between the critical gradient and the estimated hydraulic gradient is usually accepted. The calculation depends on geometric parameters, geotechnical data and flow boundary conditions, as well as the designed structure. Nevertheless, most of the universal solutions, such as graphics, have not been developed considering an anisotropic medium as foundation soil, so no realistic results are obtained. The aim of this work is to provide a methodology to obtain an estimation of the average gradient using a computational model based on the network method. This consists on the analogy between electrical magnitudes, such as voltage and intensity, and geotechnical variables, which are groundwater head and flow. The safety factor is calculated whether the soil is anisotropic or not, and so, the structure can be classified from a safety point of view.

Keywords: Geotechnics, piping, heaving, safety factor.

1. Introduction

In geotechnics and ground engineering, one of the most common aims is to control water flow both provisionally and permanently. In order to achieve this objective, retaining structures are built in the course of a river or a stream, or in excavations affected by water table. These structures can be concrete and earth dams, which are commonly thought to remain for a long time, or coffer dams, which are employed in sites to work in dry. However, whether building a permanent or a provisional structure, this must be designed according to different geotechnical phenomena (for example sliding, as happened in Aznalcóllar [1], or failure due to poor foundation soil, as in Saint Francis [2]), so it can be classified as safe. Among these phenomena is piping or heaving [3], a process that involves groundwater flow under the structure and leads to a situation that might not be steady and eventually end in failure.

As a mean to quantify the risk of pipping, two different values are compared: on the one hand, the estimated gradient, which depends on the geometry of the designed retaining structure and the piezometry under it (this can be studied with the flow net graphic); on the other hand, the critical gradient, which is a fictional number where the specific weight of the soil and the water are involved. When calculating the estimated gradient, theoretical universal solution graphics can be used [4]. However, these have been developed only for isotropic soils. Therefore, these solutions do not reflect the reality, since the majority of soils have an anisotropic behaviour.

Standards [5] also present methodologies to study whether the structure is safe or not, which depends on the estimated gradient and the total and the pore pressure in the most dangerous zones for this phenomenon. To employ this formulation, a deep knowledge of the process is needed, and this includes understanding the behaviour of the flow when running through anisotropic media.

In order to obtain all the necessary data to use formulations and compare results with theoretical ones, a methodology based on the network method [6] to simulate the flow through porous media under retaining structures has been developed. Network method is a simulation technique applicable to different physical phenomena, such as flow through porous media, soil consolidation [7], solute transport [8] and heat transfer. This model employs the electrical analogy of the variables of the problem. That is, the equivalence of the groundwater head, h, with the electrical voltage, V, as well as the equivalence of the groundwater flux, Q, with the intensity, I. This is feasible since the governing equations in both cases are similar (constitutive equations). In this way, each cell in which the problem is discretized is transformed into a circuit with four resistors whose resistance values depend on the permeability of the medium, as well as the size of that specific cell. Once all the circuits are solved by using Ngspice [9], a specific free software for solving electrical circuits, the solutions are voltage and intensity for all the cells. From this, all the graphical and numerical results are obtained.

In this work, the risk of pipping and heaving is studied for a sheet pile structure in both isotropic and anisotropic media according to the estimated exit gradient obtained by Harr [4], the formulation presented in Eurocode [5] and our simulations. Therefore, the effect of anisotropy in the existing methodology can be observed.

2. Studied Problem

Along this paper, the following example is employed to obtain and compare results according to the methodology presented in Harr and Eurocode. Figure 1 presents the geometrical variables of the modelled problem. That is, a sheet pile of a negligible thickness with a buried length in an almost infinite medium. Upstream and downstream the structure there is a water head difference that induces the groundwater flow.

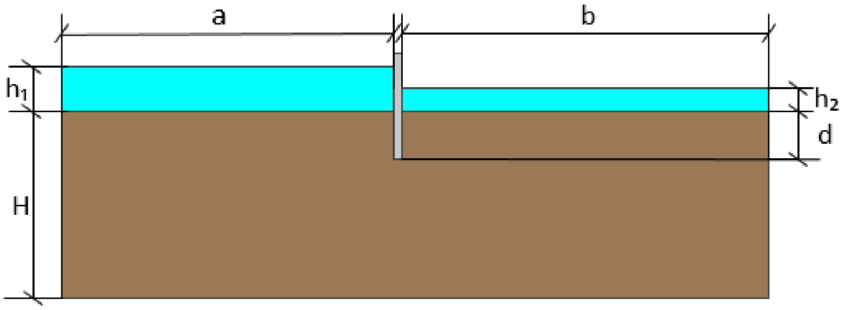

Fig. 1: Sketch and nomenclature of the problem.

According to Figure 1 the dimensions are:

a: upstream length, in meters, 50.
b: downstream length, in meters, 50.
h_1: upstream water head, in meters, 5.
h_2: downstream water head, in meters, 0.
h: water head difference, h_1-h_2, in meters, 5.
H: stratum thickness, in meters, 50.
d: sheet pile buried length, in meters, 6.

When referring to the hydrogeological properties of the medium, these change if the soil is isotropic or anisotropic. For the isotropic medium, both permeabilities, k_x and k_y, take the same value, 0.1 mm/s, this is 10^{-4} m/s (which corresponds to a medium sand). Nevertheless, the anisotropic soil presents the same k_x but lower vertical one, 10^{-6} m/s.

Finally, for both cases, the soil unit weight below phreatic level (γ_{sat}) is the same, 20 kN/m^3, and with water unit weight (γ_w) of 10 kN/m^3, effective weight unit ($\gamma' = \gamma_{sat}$-γ_w) is 10 kN/m^3.

3. References' Solutions

3.1. Harr Solutions

In 'Groundwater and seepage', Harr presents different universal graphics and equations to obtain the value of the exit gradient, I_E right after the retaining structure. In the example studied throughout this work, this gradient is calculated as shown in Figure 2 (red circle).

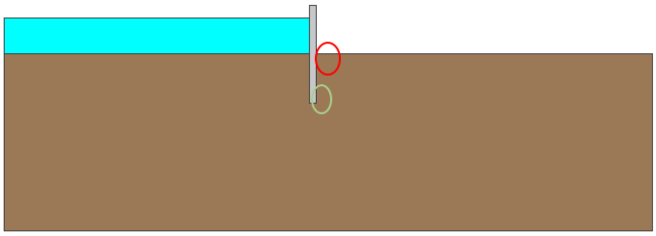

Fig. 2: Location of the point to calculate the exit gradient (red circle) and maximum gradient (green circle).

According to Harr, for this kind of structures, a universal solution exists for I_E, considering an isotropic soil, which is presented in equation 1.

$$\frac{I_E \cdot s}{h} = \frac{1}{\pi} \approx 0.318 \quad (1)$$

where s is the sheet pile buried length, which has been previously named as d.

Therefore, the value of I_E for the problem here presented must be

$$I_E \approx 0.318 * \frac{5}{6} = 0.265$$

As the only solutions presented in this book are for isotropic soils, this value of I_E is later compared with the results obtained with the new methodology for both kinds of media.

The critical gradient, I_c, is defined as a comparison of the gravity forces of a submerged mass of soil (that is, the weight due to the particles minus the weight of the volume of water displaced by the soil particles), and the seepage forces in that same mass of soil due to the water flow. As the volume of the studied area is the same, this comparison is reduced to

$$I_c = \frac{\gamma'}{\gamma_w} \quad (2)$$

According to the properties of the problem, I_c can be calculated as $I_C = \frac{\gamma'}{\gamma_w} = \frac{10\ kN/m^3}{10\ kN/m^3} = 1$.

Defining the safety factor for this phenomenon as in equation 3

$$SF = \frac{I_C}{I_E} \quad (3)$$

the safety factor according to Harr is 3.74. Nevertheless, this exit gradient is not the most harmful one for sheet piles structures, since the maximum gradients are found at the toe of the structure (I_T) on the downstream side (Figure 2, green circle).

In this way, Harr proposed a solution that involves the gradient in the whole buried length of the sheet pile, obtaining an average gradient in the area presented in Figure 3.

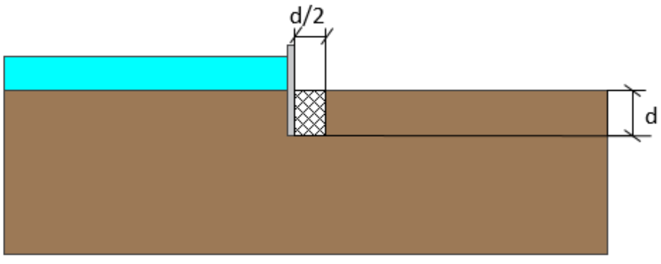

Fig. 3: Average gradient calculation area.

This method is the one employed for the study of heaving or piping phenomenon and the calculation of the safety factor of the sheet pile dam with the solution presented in this paper.

3.2. Eurocode-7 Solutions: Verification against Failure of Hydraulic Heave

In this document, the stability of the structure is studied with two different equations. In both of them, the destabilising actions are compared to the stabilising ones in order to study the safety of the sheet pile. As both kinds of actions are affected by a multiplier factor (partial factors presented in the document) that increase their value if they are negative actions and decrease it when they are positive ones, no safety factors are calculated. Formulations are

$$u_{dst;d} \leq \sigma_{stb;d} \tag{4}$$

$$S_{dst;d} \leq G'_{stb;d} \tag{5}$$

In equation 4, $u_{dst;d}$ is the pore pressure (u_k) at the bottom of the structure (Figure 2, green circle) affected by a multiplier factor ($\gamma_{G,dst}$ = 1.35) that increases this value, as it is a destabilising pressure. $\sigma_{stb;d}$ is the stabilising total vertical stress ($s_{stb;k}$) at the bottom of the structure again affected by a multiplier factor ($\gamma_{G,stb}$ = 0.9) that, in this case, decreases its value, since this is a stabilising pressure. Therefore, the value of the maximum admissible pore pressure u_k can be obtained

$$u_k \leq \frac{0.9*6*20}{1.35}\ kPa = 80\ kPa \tag{6}$$

In a similar way equation 5 can be studied. Here, $S_{dst;d}$ is the seepage force (S_k) in a soil column along the buried sheet pile length with an infinitesimal thickness also affected by $\gamma_{G,dst}$. The seepage force, S_k, is calculated as the product of the average gradient along the pile length, which depends on the hydrology of the given problem (this is, if the soil is isotropic or not), the water unit weight and the volume (V) of the fictional column of negligible thickness. $G'_{stb;d}$ is the submerged weight (G'_k) of this fictional column, affected by $\gamma_{G,stb}$, which decreases the stabilising force. G'_k keeps constant in this paper. Since V appears in both sides of equation 4, it can be removed, leading to a maximum value of the average gradient, i, which takes the value presented in equation 7.

$$i \leq \frac{9}{13.5} = 0.667 \tag{7}$$

All in all, two comparisons must be carried out when employing Eurocode-7: the one involving the value of the pore pressure (equation 6), and another one, which obtains the gradient (equation 7).

4. Network Method Solutions

4.1. Electrical Analogy

The first step to employ this method is to discretize the problem geometry in cells. Each of these cells is transformed in a circuit with four resistors, two in vertical direction and two in the horizontal one, whose resistance values depend on the horizontal and vertical permeabilities, and the size of the proper cell due to the chosen discretization. Moreover, boundary conditions must also be translated into electrical magnitudes. For example, impervious borders are simulated as resistors with very high resistance values, and the constant water head upstream and downstream the sheet pile are modelled in each of those boundary cells with a battery which provides a voltage which is equal to the head value. Once all these data are transformed and the circuits are created, they are introduced in Ngspice. The raw solution of these are the voltage in each cell node, as well as its vertical and horizontal intensity. In this way, as the equivalence with the problem variables is immediate, the values of water head and flux are obtained. From the results, two different kind of solutions can be calculated:

a) Graphical solutions, as flow nets, which show the behaviour of the water flow through the porous medium presenting the equipotential and the stream function lines. Figure 4 shows the flow net for the isotropic soil, while Figure 5 shows the same for the anisotropic problem. It is visible that, because of this lower vertical permeability, Figure 5 presents equipotential and stream function lines closer to the surface, since it is more difficult for the flux to flow in the vertical direction.

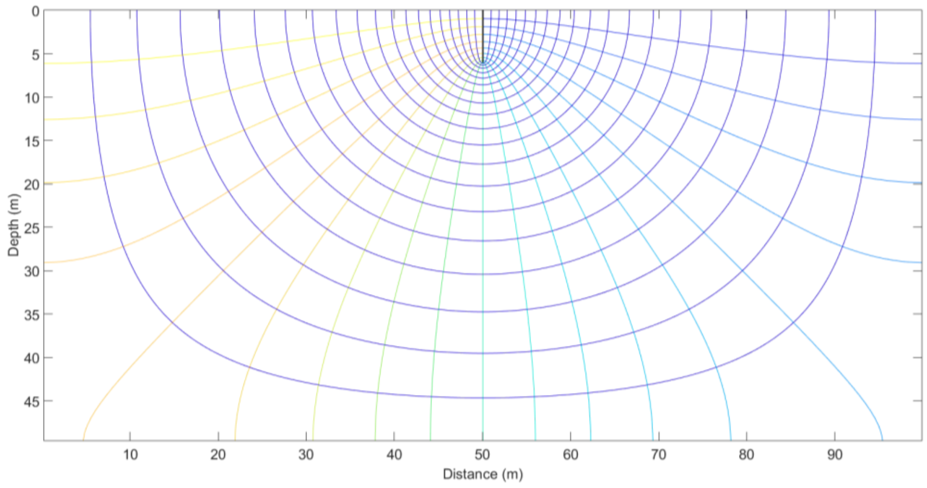

Fig. 4: Flow net for isotropic example.

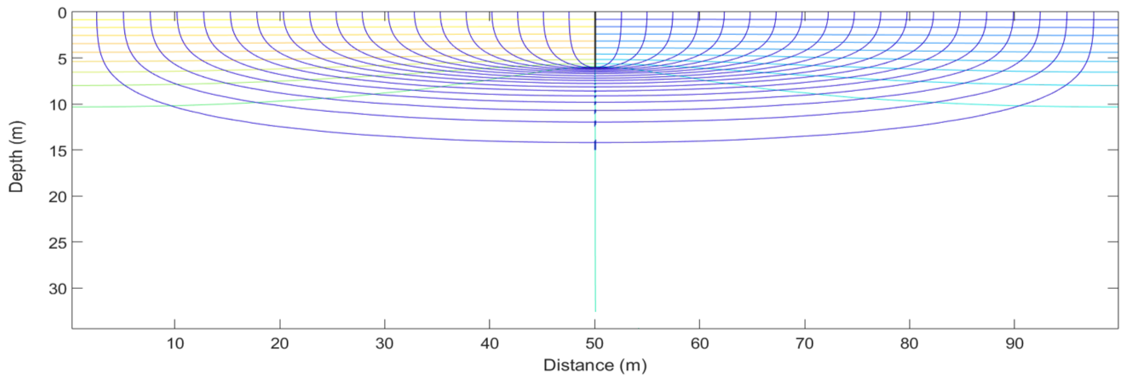

Fig. 5: Flow net for anisotropic example.

b) Numerical solutions, such as total water flux or characteristic lengths. These are obtained by mathematical manipulation of the raw results provided by Ngspice. Among all these solutions, exit gradient (I_E), average exit gradient (i) and gradient at the toe of the structure (I_T) are the one of interest for this work.

4.2. Results and Comparisons

Two values are obtained for each of the studied gradients, one for the isotropic soil and another one for the anisotropic medium. The first comparison presented in this paper is the exit gradient according to Harr with the one obtained with the here presented network method. Previously shown here in equation 1, the value I_E is 0.265. Once the simulation for the isotropic example has been carried out, I_E turned to have a value of 0.258. This is very close to the theoretical one, taking into account that it is highly influenced by the discretization around the sheet pile, since I_E has been calculated in the upper cell closest to sheet pile in the downstream side, as shown in Figure 6 (marked with a red circle).

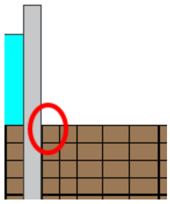

Fig. 6: Cell where exit gradient I_E is calculated.

When simulating the anisotropic problem, however, this exit gradient value changes and goes up to 0.31. This shows that, when a lower vertical permeability appears, exit gradients tend to increase their values. If now the safety factors are calculated employing these two I_E obtained by the simulations, SF for isotropic problem is 3.88, while for the anisotropic problem this value is 3.23. In any case, according to this criterion, the studied sheet pile appears to be safe.

Nevertheless, as also commented in this paper, this zone is not the one where higher harmful gradients appear. can be demonstrated for the two presented examples. If instead of studying the cell in Figure 6, a similar calculation carried out for the two cells at the toe of the structure in the same column, higher values of gradient are obtained both simulations. For the isotropic soil, I_T takes a value of 3.81 (SF = 0.26), while this value is 3.44 in the anisotropic medium (SF = 0.29). If this criterion is followed, none of the cases seems to show a safe structure.

Since both values, I_E and I_T, present such a difference, an average value is decided to be applied. In the proposed method, this value is calculated obtaining a gradient for each of the column of cells conforming the horizontal length d/2, and then calculating the average gradient of all of them. The gradient of each column (I_{Cj}) is calculated as presented in equation 8, and i in equation 9.

$$I_{Cj} = \frac{h_{toe,j} - h_2}{d} \tag{8}$$

$$i = \frac{\sum_{j=1}^{j=n} I_{Cj} * dx_j}{d/2} \tag{9}$$

where:

$h_{toe,j}$: water head at the cell at the depth of the sheet pile and in the column number j.
n: number of columns for d/2.
dx_j: horizontal length of the cell in columns number j.

Following the described calculations, the isotropic problem presents an average exit gradient, i, of 0.3 (SF = 3.36), while the anisotropic one has a value of 0.39 (SF = 2.57). Therefore, it is visible that, although in both cases the safety factor is greater than 1, the anisotropic option has a lower safety factor. The importance of considering the anisotropy of the soil is proved with the examples here presented.

Taking up equations 6 and 7 when describing the methodology employed by the Eurocode-7, the values of u_k and i must be calculated. For both variables, the water head in the cell next to the toe (h_{toe}) downstream the structure is needed. In the first example, h_{toe} = 2.1 m, while in the anisotropic one, h_{toe} = 2.219 m. Although these values are taking from the centre of the cell, not for the lower border, since the discretization is small, the position considered in the calculations is d. In this way, i is calculated as

$$i \approx \frac{h_{toe} - h_2}{d} \tag{11}$$

Therefore, for the isotropic example, i = 0.35, and in the anisotropic one, i =0.37. According to equation 8, in both cases the structure seems to be safe.

For the next verification, u_k must be calculated.

$$u_k \approx (h_{toe} + d) * \gamma_w \tag{12}$$

In this case, for the first example, u_k = 81.00 kPa, while in the second one u_k = 82.19 kPa. So, both scenarios are slightly over the maximum value of pore pressure obtained in equation 6, presenting the anisotropic case the highest value.

5. Conclusion

Employing the network method, a numerical model has been developed, which is able to simulate groundwater flow through both isotropic and anisotropic media and to provide enough information to study the safety of retaining structures from a geotechnical point of view.

When studying the same structure in both isotropic and a possible anisotropic soil, it is visible that, according to most of the methods presented in this work to determine the safety of the retaining structure, taking into account the anisotropy is highly important, since the SF values became lower.

If considering the toe gradient instead of the exit one, the safety factor decreases, because a piping process is more likely to happen in this zone. However, this would only occur in one point, and the average gradient gives an idea of what is happening in a bigger zone.

Finally, employing the pore pressure instead of the gradient leads to safer solutions, since it seems to be more restrictive.

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References

[1] A. Gens, and E. E. Alonso, "Aznalcóllar dam failure. Part 2: Stability conditions and failure mechanism," *Géotechnique,* vol. 56, no. 3, pp. 185-202. 2006.

[2] L. Begnudelli, L. and B. F. Sanders, "Simulation of the St. Francis dam-break flood," *Journal of Engineering Mechanics*, vol. 133, no. 3, pp. 1200-1212, 2007

[3] R. Fell, C. F. Wan, J. Cyganiewicz and M. Foster, "Time for development of internal erosion and piping in embankment dams," *Journal of geotechnical and geoenvironmental engineering*, vol. 129, no. 4, pp. 307-314, 2003.

[4] M. E. Harr, *Groundwater and seepag*e. Courier Corporation, 2012.

[5] CEN (2004) Eurocode-7 Geotechnical design - Part 1: General rules. Final Draft, EN 1997-1:2004 (E), (F) and (G), November 2004, European Committee for Standardization: Brussels.

[6] C. F. González-Fernández, "Applications of the network simulation method to transport processes," *Network Simulation Method*, Ed. J. Horno, Research Signpost, Trivandrum, India, 2002.

[7] G. García-Ros, I. Alhama, and J. L Morales, "Numerical simulation of nonlinear consolidation problems by models based on the network method," *Applied Mathematical Modelling*, vol. 69, pp. 604-620, 2019.

[8] I. Alhama, A. Soto Meca, and F. Alhama, "Simulation of flow and solute coupled 2-D problems with velocity-dependent dispersion coefficient based on the network method," *Hydrological Processes*, vol. 26, no. 24, pp. 3725-3735, 2012.

[9] Ngspice. (2016). Open Source mixed mode, mixed level circuit simulator (based on Bekeley's Spice3f5). [Online]. Available: http://ngspice.sourceforge.net/