A Method for Designing Finger Drains and Assessing Phreatic Lines for Dams

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Abstract. Finger drains are linear drains used to collect and conduct percolated water in embankment dams. They are arranged crosswise into earth dams, either permanently or as a technique to treat clogged filters. Given their easy operation, they are often applied in engineering practice, without the aid of specific dimensioning techniques in many cases. The aim of this paper is to propose a method for designing finger drains for earth dams, considering geometric and hydraulic characteristics (length, width, spacing, height and reservoir level). Moreover, the method allows estimating the phreatic line inside the dam. The method was based on data from small scale physical models and on numerical models, calibrated using the physical model results. Twenty-seven numerical models were developed by simulating seepage for different spacing between drains and lengths of drains, besides three reference numerical models with different lengths of drainage mat. The numerical modeling was validated using the results of four small-scale models processed with software Seep/W.

Keywords: dams, drainage, finger drains, model, small-scale.

1. Introduction

Internal drainage systems contribute to the stability of earth dams. An effective drainage significantly reduces the risk of accidents. Massad (2003) states that most of the accidents involving earth dams are caused by the absence of an efficient flow control system.

Typically, soils with very low permeability are chosen to build earth dams, in order to minimize water flow through the soil mass. Due to the characteristics of the used materials, seepage inevitably occurs through the dam earthfill. According to Cruz (1996), drainage systems are the main defense against concentrated and preferential flows; that is, drainage systems regulate seepage in the dam itself and in its foundation, reducing the pore-pressure and disciplining flow leakage downstream of the dam.

Finger drains are linear elements arranged side by side in the main flow direction, perpendicular to the dam axis, at specific distances from one another. These drainage devices are recommended as an alternative to drainage blankets when the cost of drainage materials is very high or when the volume of granular material required for building a drainage blanket is not available. They are also used in corrective interventions on clogged filters, for maintenance purposes. The drains can be designed with sloped sides to allow an even distribution of ground stress.

The cross-section of finger drains must be large and/or enough permeable to support the flow that percolates without raising the pore-pressures in the earth fill dam. Therefore, it is important to assess the spacing between drains to ensure that the hydraulic heads are dissipated and pore-pressures do not interfere with the structure functioning. Drainage systems should be designed to maintain the stability of these structures and prevent phreatic levels from rising.

The shape of the three-dimensional phreatic surface inside a dam provided with linear drains, as well as the format of the flow network and the way in which pore-pressures are distributed in the earth fill are, strictly speaking, unknown. Nowadays, there are no practical methods to estimate the position of the phreatic line when using finger drains, even though it influences the variation of safety factors of the dam downstream shoulder.

Thus, this paper proposes a method for designing finger drains for earth dams, considering its geometry, such as length, width, spacing, and height, and for obtaining an outline of the phreatic line inside the dam. The method is based on small-scale physical models and numerical models calibrated by small-scale responses. Twenty-seven numerical
models with finger drains were developed, which simulated percolation for different combinations of drain spacing and length, besides three reference models, with different lengths of drainage blanket. The results were processed and design abacuses were developed based on the studied parameters so that, once applied, the estimated behaviors were similar to those provided by the numerical and physical models results.

In general, drainage systems are made with very permeable materials, such as sand, gravel, and crushed stone. As the availability of granular materials is limited in some regions, some designers have chosen to use linear drains, also known as finger drains or stringer drains. There are two requirements regarding the efficiency of finger drains. The first requirement is that filters and drains should avoid internal erosion of soil. This is called filtration criterion. The second, and equally important requirement, refers to the discharge capacity. The drainage system should prevent pore-pressure from increasing in the dam earth fill, this is called drainage criterion.

The water that permeates through the dam earth fill must comply with the overall flow equation, based on Darcy’s law. Methods based on the overall flow equation can identify the flow that percolates through the earth fill. The flow received by each finger drain depends on the spacing between drains.

Finger drains can collect percolation water and transfer it to the downstream slope toe. Figure 1a shows finger drains in a dam. The drains are usually made with surrounding transition elements with a thicker grade, forming a “sandwich” structure, as shown in Fig. 1b. The transition elements also contribute to soil drainage, although this is not frequently considered in drain capacity.

The study carried out to develop a procedure for finger drain design, based on small-scale physical models and numerical models, is described below.

2. Small-Scale Model

The small-scale physical models were built using medium washed clayey sand as earth fill material. The finger drains were built using gravel with a much higher permeability than the sand. Laboratory tests were made to characterize the materials used in small-scale models.

The sand was submitted to particle size analysis according to NBR 7181/1984. Constant head permeability tests were subsequently done, as described in NBR 13292/1995. Furthermore, the sand was tested to obtain minimum and maximum void ratios for non-cohesive soils, as recommended in NBR 12051/1991 and NBR 12004/1990, respectively. For the actual density of the grains, the samples were tested according to the DNER - ME 093/1994 standard. The shear strength of the sand was assessed according to BS 1377-7/9 procedures. Finally, the samples were submitted to drainage column test to determine the soil water retention curve (SWRC), as described by Furlan & Dell’avanzi (2007).

The clayey sand particle-size distribution was: 79.20% of sand, 15.40% of clay, and 5.40% of silt particles.

The sand hydraulic conductivity obtained was equal to $1 \times 10^{-2}$ cm/s. To account the drainage criteria, gravel with a particle size between 4.8 mm and 9.5 mm was used, having material had a hydraulic conductivity equal to $1.9 \times 10^{-1}$ cm/s.

The tests to evaluate the sand void ratios resulted in 0.73 and 0.61 for maximum and minimum void ratios, respectively. The minimum sand void ratio was used to calibrate the pluviation height and thus obtain specific gravity of sand in order to construct the small-scale models of the dam. Three samples were modeled with three different fall heights, in terms of dry specific gravity, the behavior of the material resulted in the curve shown in Fig. 2.

The adopted fall height for constructing the models was 12 cm, which is related to a specific gravity equal to 1.60 g/cm$^3$, as shown in Fig. 2. The particle density values for sand and gravel were 2.50 g/cm$^3$ and 2.43 g/cm$^3$, respectively.

The clayey sand samples were submitted to direct shear tests. Three samples, modeled by the sand pluviation method, with a fall height of 12 cm, were tested with normal stresses of 54 kPa, 74 kPa, and 114 kPa, under saturation. Given the permeability of the material, the shear test was performed at a displacement rate equal to 0.30 mm/min, to...
ensure drained conditions during shearing. The shear test resulted in a friction angle equal to 34° based on the equation: $\tau = 0.68\sigma + 5$.

Figure 3 shows the moisture retention curve for the clayey sand soil, obtained by column test. The residual moisture content was about 16%, corresponding to 31.50 cm of capillary height.

The small-scale physical dam model was built inside a 2.50 m long, 44 cm wide, and 60 cm high metal box, with a frontal acrylic wall. The dam model was 1.90 m long, 50 cm high with a 10 cm wide crest, as shown in Fig. 4. More details about the physical models can be found in Araújo (2013).

Three longitudinal sections were used to evaluate the piezometric lines, as shown in Fig. 5. Thus, the models were split into front section (S1), middle section (S2) and rear section (S3), to obtain the pore-pressures inside the dam.

Regarding the instrumentation, some open pipe piezometers were installed to measure the pore-pressures inside the dam model. The piezometers consisted of polyethylene hoses with a 3 mm internal diameter, fixed to the
steel plate of the base of the box and crossing it. The inlet end of each piezometer was covered with filter paper and non-woven geotextile.

Nine pairs of piezometers were positioned on the front, middle and rear sections of the dam, in the upstream and downstream slopes and also under the crest, as shown in Figs. 4 and 5. The small-scale model allowed simulating the flow behavior in an earth fill dam where finger drains are installed.

Four small-scale models of dams were built and tested, each one simulating a specific internal drainage system. The dimensions of finger drains were: 6 cm at the base, 3 cm at the top, 3 cm high and 50 cm long. Table 1 shows the different drain types and spacing between drains for each of the 4 tested models.

The piezometers were kept saturated until the dam reservoir was filled, to facilitate construction and ensure the good performance of piezometers.

After the reservoir filling, the water tap, located downstream of the model was opened to initiate the water percolation through the earth fill. After the flow was established, the drainage of the dam was then measured during a time “t” by using a graduated cylinder, the piezometers were read and the flow rate was calculated.

In Model 1 (dam with drainage blanket), the reservoir reached the elevation 47 cm and then the water percolation started, advancing downstream through the sand. No signs of rupture or internal erosion were detected, and the flow discharged through the middle of the slope toe. The use of the drainage blanket, in this case, proved to be efficient for drainage, and the water percolated preferentially through the center of the device rather than through the side walls of the acrylic box.

In Model 2 (one finger drain, at 88 cm spacing), despite the absence of signs of rupture, a slight deformation was observed in the downstream slope. Regarding the device functionality, the simulation showed that the finger drain is efficient since the flow was mostly discharged through it. In this case, due the smaller drainage section, compared to the Model 1, some erosion (particles movement) was observed in the drain outlet.

In Model 3 (2 finger drains, at 44 cm spacing), the draining material was arranged along both sides of the dam to enable a linear flow. The functionality of devices proved highly efficient since the outflow occurred preferentially through the finger drains. Minimal erosion was observed in the outlet of both drains, as observed in Model 2.

In Model 4 (3 finger drains, at 22 cm spacing), the draining material was arranged along both sides and the middle of the downstream slope of the dam to enable a linear flow. The functionality of devices proved highly efficient, the outflow occurring initially through the middle drain, followed by the left drain and, lastly, the right drain.

The average flow rate in the four models was $3.53 \times 10^{-6}$ m$^3$/s. The highest value was recorded in Model 1 (with the drainage blanket) and the lowest in Model 2 (with 1 finger drain), indicating that the greater the space between the drains, the smaller the drainage area and, consequently, the lower the outflow.

Physical modeling of dams with drainage blankets and finger drains clearly demonstrated the differences in flow behavior. Analysis of cross section of each model showed that piezometric heights were fairly consistent with the situations observed in the modeling.

In Model 2, an observed slight deformation was noted downstream of the dam. In Model 3, minimal erosion was observed, indicating efficient drainage. In Model 4, with 3 finger drains, the outflow occurred in a linear manner, with minimal erosion.

Table 1 - Tested physical model setup.

| Model | Drainage device | Spacing (S) (cm) | Drainage area (cm$^2$) |
|-------|-----------------|------------------|------------------------|
| 1     | Drainage blanket| -                | 132                    |
| 2     | 1 finger drain  | 88               | 13.5                   |
| 3     | 2 finger drains | 44               | 27                     |
| 4     | 3 finger drains | 22               | 54                     |

Figure 5 - Positioning scheme of longitudinal sections.
Results from the models with finger drains at different distances indicated that the smaller the distance between the drains, the greater the energy dissipation and the lower the hydraulic heads inside the dam. Figure 6b illustrates Section S2 that was the section where the highest piezometric levels were observed in all models.

Finally, the piezometric readings in Section S3 (Fig. 6c) were similar to those in Section S1, as both are in sections with drains - except for Model 2 (with 1 finger drain along Section 1). In the models where drains were at 22 cm and 44 cm spacing, the water percolated from the earth fill center to the model lateral walls, resulting in very similar piezometers readings in Sections S1 and S3.

3. Numerical Modeling

Parametric analyses regarding the seepage behavior were conducted using numerical models with the software Seep/W. Numerical modeling is a simulation of a real phys-
tical process based on theoretical equations, allowing comparisons between different not-physically-tested scenarios. When calibrated, models reproduce the real physical process with good accuracy.

Although the employed software is not based on three-dimensional equations, it allows to model seepage in a plan. It means that gravity is considered perpendicular to modelled plan and flow can be evaluated from one side to the other side of the model by imposing convenient boundary conditions. The authors considered that using a 2D model, is the best way for modelling dams with finger drains, despite the fact that water flows in a three-dimensional way.

In 2D numerical models, the pressure head of reservoir is imposed at the upstream side of the model and zero pressure head is applied at the end of the finger drains, at the downstream side of the model, as boundary conditions. The phreatic surface elevation is, then, assumed as the values of hydraulic head obtained by computation.

The results of small-scale tests were used to calibrate seepage numerical models, which were based on the finite element method. Calibrated numerical models enabled additional analyses considering physically untested scenarios.

The parameters of materials used on numerical modelling are based in characterization tests with those materials used on small-scale models and calibration of anisotropy ratio, \( K_z/K_x \), prior to doing parametric analyses.

For stage 1 (Numerical modelling of physical model) the procedures followed the imposition of piezometric heads found in the small-scale model as boundary condition and \( K_z/K_x = 1 \); stage 2 (Calibration of \( K_z/K_x \) ratio for numerical modelling) was based on the assessment of piezometric heads and comparison with those obtained in small-scale models up to results are similar and stage 3 (Parametric analyses by numerical model) solved the simulation of drains with different lengths and spacing, using the \( K_z/K_x \) ratio obtained in stage 2.

Considering the geometric parameters of the model, a matrix (Table 2) of the simulation scenarios was built, by varying the drain length and spacing between drains and keeping unchanged the total head at the reservoir and the model width.

The mesh of finite elements of the numerical model is shown in Fig. 7. The model represents the horizontal section of the dam at its base. It was adopted \( K = 1.10 \times 10^7 \) cm/s for earth fill material and \( K = 2.0 \times 10^5 \) cm/s for drain material. As a boundary condition, the hydraulic head equal to 47 cm was adopted at the upstream side, and a null hydraulic head was adopted at the downstream side. Moreover, the application of elevation heads was considered in the entry of the piezometers.

For calibrating the \( K_z/K_x \) anisotropy ratio, two-dimensional numerical analyses were performed considering a dam with blanket drain. The \( K_z/K_x \) ratio was changed until the found results for pore-pressure were similar to those obtained in piezometers in the small-scale test.

Figure 8 shows the phreatic line position obtained in numerical models where the piezometric readings from the small-scale model were applied as a boundary condition and the phreatic line obtained from the calibrated numerical model, considering \( K_z/K_x = 0.3 \), respectively. One can note that phreatic lines are very similar, validating the parameter calibration in the numerical method. The same comparison was made for all sections of the models and the same similarity between the physical and numerical results for piezometric lines was observed.

To carry out the parametric analysis, it was sought the \( K_z/K_x \) ratio value (0.3) that best suits the behavior of the flow in the analyzed models for the initial configuration applied in physical modeling.

### 4. Method for Designing Finger Drains for Dams

The abacuses for designing finger drains for earth dams are shown in Fig. 9. They allow to find the relationship between the maximum total head at the upstream and downstream ends of the finger drains and the total head at the dam reservoir \( (H_{max,U}/H \text{ and } H_{max,D}/H) \), considering the datum at the dam base. The input data are the ratio \( S/H \), where \( S \) is the spacing between the drains and \( H \) is the total head at the dam reservoir. Each abacus is associated to a \( C/H \) ratio, where \( C \) is the drain length. Abacuses were developed for the ratios \( C/H = 1, 1.4, \) and \( C/H = 2.0 \).

Based on Fig. 10, the necessary parameters for designing the finger drains can be identified. The transverse sections of the finger drains have a width equal to \( 2b \) and height equal to \( H_{f} \) as shown.

In case of using drainage blanket, water flow in the finger drains can also be assessed according to two condi-

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**Table 2 - Matrix of modelled scenarios.**

| Dams | C1  |
|------|-----|
| 50   | 70  | 100 |
| 1    | 88  | 88  | 88  |
| 2    | 144 | 144 | 144 |
| 3    | 44  | 44  | 44  |
| 4    | 22  | 22  | 22  |
| 5    | 36  | 36  | 36  |
| 6    | 50  | 50  | 50  |

| C1  | Drain length; | S2 - Spacing between drains. |
|-----|---------------|-----------------------------|
| Blanket drain | 50  | 70  | 100 |
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Figure 7 - Numerical model of the hypothetical dam – Plan view.

Figure 8 - Phreatic line based on the physical model piezometer readings.

Figure 9 - Abacus to design finger drains for earth dams.
tions: a) phreatic line above the drain (Fig. 10b) and b) phreatic line inside the drain (Fig. 10c). Eq. 1 to Eq.3 are applied when the confined flow condition, inside the drain, is assumed (Fig. 10b). Eq. 4 is used when the unconfined flow is assumed (Fig. 10c). The designer of the drains must choose one of these two conditions in order to obtain the finger-drain height.

\[ Q \cdot FS = \frac{b \cdot H^2}{c} K_f \]  

(1)

Since:

\[ Q = q_{unit} (S + 2b) \]  

(2)

then:

\[ H_f = \sqrt{\frac{q_{unit} (S + 2b) \cdot C \cdot FS}{K_f \cdot b}} \]  

(3)

and:

\[ H_f = \sqrt{\frac{2q_{unit} (S + 2b) \cdot C \cdot FS}{K_f \cdot b}} \]  

(4)

where \( H_f \) - Height of finger drain (m); \( Q \) - Total flow rate for the area of influence of the drain (m³/s); \( q_{unit} \) - Unitary flow rate for the area of influence of the drain (m³/s/m); \( S \) - Spacing between finger drains (m); \( 2b \) – Width of the finger drain (m); \( C \) – Length of finger drain (m); \( K_f \) - Permeability of draining material (m/s); FS – Safety factor, normally adopted equal to 10.

As mentioned, each abacus presented in Fig. 9 shows two curves featuring the relationship between the ratio \( H_{max,U}/H \) (maximum height of the phreatic surface between finger drains / total height of the reservoir) and the ratio \( S/H \) (spacing between finger drains / total height of the reservoir). Those abacuses are used for estimating the position of the phreatic line in dams between two finger drains.

The following step-by-step procedure can be used to estimate the piezometric heads:

1. Define the input data concerning drain geometry; that is, length of the drain \( (C) \), the spacing between drains \( (S) \), and total head of the dam \( (H) \);
2. Identify the abacus which best suits the condition \( C/H \) and, with the input data, calculate the ratio \( S/H \). Project vertically up to the upstream pressure curve (curve \( H_{max,U}/H \)) and downstream pressure curve (curve \( H_{max,D}/H \));
3. With the entry point of the phreatic line in the earth fill, the head \( H_{max,U} \) at the upstream end of the drain and the head \( H_{max,D} \) at downstream the end of the drain, outline the phreatic line inside the dam.

5. Final Comments

Data obtained from the small-scale physical models and numerical models were analyzed to assess the behavior of finger drains in dams and better understand the three-dimensional flow in these works. Based on presented work, the following comments can be stated.

Finger drains efficiently improve internal drainage in dams, mainly because they can be built using materials with greater permeability than those used in blanket drains. However, the position of the phreatic surface when finger drains are used is higher than when blanket drains are employed.

Longer drains help to better dissipate hydraulic heads. Thus, there is an inverse relationship between the length of drains and the elevation of the phreatic line.

To improve the efficiency of finger drains, it is important to limit the space between drains or to increase its drainage area.

It is recommended that the total area of finger drains should be between 20% and 40% of the corresponding area for the solution with conventional drainage blanket and that the drainage capacity should be, at least, equal to the capacity of the drainage blanket. The increase in drainage capacity can be obtained using more permeable materials.

The recommended spacing between finger drains, in order to ensure water table inside the drains, is about 40% to 70% of the dam height.
As the length of finger drain increases, hydraulic head at the inner side of the drain increases. However, the difference in head between inner and outer ends of drain also increases.

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