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Francisco Sousa, Vanda Tereza Costa Malveira and Antonio Anderson Fontenele Araújo

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NUMERICAL MODELING FOR PERFORMANCE EVALUATION OF GRANULAR FILTER BASED ON CONSTRICTION SIZE DISTRIBUTION

Francisco David Mariano de Sousa*, **Vanda Tereza Costa Malveira**† and Antonio Anderson Fontenele Araújo‡

*Universidade Federal do Ceará – UFC
Departamento de Engenharia Hidráulica e Ambiental, Bloco 713 – 1º Andar, Centro de Tecnologia, Campus do Pici, 60451-970 Fortaleza – CE, Brasil
e-mail: sousa_david@alu.ufc.br, webpage: www.posdeha.ufc.br

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Abstract. *In the present situation of the Brazilian semiarid region, which depends highly on the hydraulic reservoir structures, an adequate design of water resource structures and maintenance of those already in operation is an essential factor to guarantee water supply and ensure the safety of the population living in the downstream of the dams. A proper structural filter design is necessary granting its efficiency to the ability in preventing any internal erosion process. However, most of the dams in operation were designed before the publication of the filter design criteria presented in this paper and those structures either do not have filters or have not a proper filter design, becoming more vulnerable to an eventual internal erosion process. The situation is further aggravated for embankments in the region with frequent droughts, due to constant drying and filling cycles of the reservoir, resulting in drainage system failure concerning to the soil fatigue during those cycles. It is very important the use of robust methodologies for evaluate the risk of these structures against internal erosion process. This study describes an estimation for the effectiveness of the filter structure in the embankments through a numerical simulation of the contacts between the different soils and the structure using the geometric-probabilistic methodology with input data of the grain size distribution of the soils according to the field studies for the dam design. The numerical modeling uses an alternative method of sizing filters, which correlates a theoretical approach of the subject. The dams select for the case study are Taquara, Olho Dagua, Figueiredo, Monselhor Tabosa, Itauna and Gangorra, all of them located in Ceara State, Brazil.*

1 INTRODUCTION

An important factor when projecting a dam is to drain the interior from excessive water. The influence of water in the embankment and foundation of the dam may reach to irreversible situation to the structure, and when not properly drained can result an eventual internal erosion process due to the excess of poropressure. This process occurs when soil particles from the compacted material of the dam are removed and carried by

†Universidade Estadual Vale do Acaraú - UVA
‡Universidade Federal do Ceará - UFC

the seepage due the inefficiency of a filter element. This phenomenon is responsible for several critical cases of rupture based on historical data of eventual problems in the embankments.

At the early of 20th Century, Terzaghi[1] presented basic criteria for designing a filter structure according to the solid particles retention properties and filter permeability. These criteria were obtained from laboratory tests and served as basis for subsequent methodologies, with the aim to prove or establish new relations in terms of particle size. However, the use of these criteria becomes limited to the uniformity coefficient of the soil increases.

A new filter design approach was introduced by Silveira[2], who presented theories concerning the designing of filters based on constriction size distribution, and the comparison between these constrictions and the particles size distribution of the protected soil. The result of this comparison creates washing paths of individual fine particles of the base soil inside the filter and can be used in the analysis of the vulnerability of the dam to an internal erosion process. Based on constriction size methodology Indraratna and Raut[3] established a criterion to limit the particle diameter of the base soil in order to ensure an auto filtering zone and the retention of the particles.

This research aims to evaluate the effectiveness of the filter in forming auto filtering transitional zones, responsible for filter stabilization. The study was carried out through numerical simulations of the contacts of the different base soils with the drainage filter structure.

2 METHODOLOGIE

The methodology used for the evaluation of filter effectiveness to prevent an eventual internal erosion process is based on filter Constriction Size Distribution (CSD), once the constriction size rather than the particle size affects filtration. The method used in the analysis was presented by Raut and Indraratna[4], in which uses constrictions parameters to limit the base soil Particle Size Distribution (PSD) that participates in the filter stabilization process.

Two parameters are used in this method: the controlling constriction size, Dc_{35} and the self-filtering constriction size, Dc_{95}. Dc_{35} and Dc_{95} are respectively 35% and 95 % of the filter constrictions finer than the corresponding parameters.

According to Raut and Indraratna[4], the parameter Dc_{35} relates to the largest base particle that can erode through the filter. This parameter uses surface areas of the filter particles and considers in its measure the filter PSD, the filter gradation and the level of compaction, providing satisfactory results for both well-graded soils and uniform soils.

The parameter Dc_{95} represents the largest effective constriction size of the filter, and base particles larger than this constriction would not enter the filter, having no influence in self-filtration (Indraratna and Raut[3]). As a result, the base particles larger than Dc_{95} are neglected and a modified base soil grading curve is obtained.

Raut and Indraratna[4], based on Terzaghi retention criterion, defined that the filter will archive its stability if the parameter d^*_{85} is equal to or above the controlling constriction size of the filter, Dc_{35}. Where d^*_{85} represents the value of d_{85} of the modified base soil grading curve. Therefore, Raut and Indraratna[3] defined the basic criterion to design a filter using Equation 1[4].

$$d^*_{85} \geq D_{c35} \qquad (1)$$

3 MODELING

3.1 Method of simulation

The base soil presents in its composition a predominance of fine soil, and its main form of characterization is by soil sedimentation test. The fine fraction of the soil has fundamental importance in the evaluation of the filter efficiency, because it is responsible for the filling the filter voids and forming the autofiltration zone, having a direct participation in the filter stabilization.

In the present study is used as input data the PSDs of the soils that implement the embankment and the filter of the selected dams. For each dam, representative PSDs were selected for every soil material. Using the two extremes of the distribution, in order to characterize the finer and coarse soil grading curves of the dam elements. In this way, during the numerical simulation, we proceed with the interactions between the extreme soil graded curves of the filter and the base soils interfaces. Thereby the critical condition is considered during the numerical simulation.

As the Silveira's[2,5] methodology presents limitations for well-graded materials, the representative PSDs of the filter were converted in terms of surface areas of the particles, as purpose by Humes[6]. For each distribution, ten representative nominal diameters were selected, associated with a probability of occurrence equal to 10%.

The representative nominal diameters and their respective probability of occurrence were used in the design of the filter's CSD for the conditions of minimum and maximum compaction based on constriction models presented by Silveira[2] and Silveira *et al.*[5]. In an effort to achieve the densest particle arrangement observed in filter designs and by using the methodology presented by Locke *et al.*[7], the filter CSD was designed with a relative density of 60%, based on the conditions of minimum and maximum compaction.

It was proceed with the selection of the controlling constriction size, Dc_{35} and the self-filtering constriction size, Dc_{95}. These values were used to evaluate the effectiveness of the filter in forming auto filtering transition zones by using the criterion established by Equation 1[4].

3.2 Numerical Modeling

The numerical modeling of the selected dams takes into account the soil PSD of the field studies, obtained in the geotechnical report for the design of the embankments structures. The data distribution varies for each project, as well as the amount of information about the soil material. In this way, the number of simulations varies for each dam.

In the analysis of the Mosenhor Tabosa Dam the geotechnical studies classify four types of soil that materialize the embankment, a Clay sand (SC), a Lean clay (CL), a Silty sand (SM) and a Silty clayey sand (SC-SM). Considering that the PSD ends of each soil type are simulated with the filter CSD in the conditions of minimum and maximum compaction, a total of 16 simulations were performed and the results are presented in Table 1.

The Figueredo and Itauna dam present three types of soil in the composition of its embankments, a Clay sand (SC), a Lean clay (CL) and a Silty sand (SM), obtaining a total of 12 simulations for each dam, presented in Table 2 and Table 3.

The geotechnical studies of Taquara Dam present the results of the PSD for three borrow materials used in the construction of the embankment, for each borrow material the PSD ends were selected for the simulation, obtaining a total of 12 simulations, presented in Table 4. Olho dagua dam presents the PSDs arranged to represent a single material that composes the embankment. Thus, the PSD extremes of the base soil were used, obtaining a total of 4 simulations as presented is Table 5.

The geotechnical studies of the Gangorra dam present only soil sieving analysis, and do not present any characterization of the finer fraction of the soil. Since the parameter d^*_{85} is obtained from the modified grading curve, the finer fraction of the soil, its value can not be identified, making it impossible to apply it in the methodology studied.

Scenario	Filter	Base Soil	Dc_{35}	d^*_{85}	Dc_{35}/d^*_{85}	Analysis
01	Filter_Min	SC_Min	0.062	0.145	0.42	√
02	Filter_Max	SC_Min	0.114	0.145	0.79	√
03	Filter_Min	SC_Max	0.062	0.165	0.37	√
04	Filter_Max	SC_Max	0.114	0.165	0.69	√
05	Filter_Min	CL_Min	0.062	0.075	0.82	√
06	Filter_Max	CL_Min	0.114	0.075	1.53	X
07	Filter_Min	CL_Max	0.062	0.110	0.56	√
08	Filter_Max	CL_Max	0.114	0.110	1.04	X
09	Filter_Min	SM_Min	0.062	0.178	0.35	√
10	Filter_Max	SM_Min	0.114	0.178	0.64	√
11	Filter_Min	SM_Max	0.062	0.160	0.38	√
12	Filter_Max	SM_Max	0.114	0.160	0.72	√
13	Filter_Min	SC-SM_Min	0.062	0.136	0.45	√
14	Filter_Max	SC-SM_Min	0.114	0.136	0.84	√
15	Filter_Min	SC-SM_Max	0.062	0.040	1.54	X
16	Filter_Max	SC-SM_Max	0.114	0.040	2.86	X

Table 1: Analysis of the effectiveness of the Mosenhor Tabosa dam.

Scenario	Filter	Base Soil	Dc_{35}	d^*_{85}	Dc_{35}/d^*_{85}	Analysis
01	Filter_Min	SC_Min	0.025	0.05	0.49	√
02	Filter_Max	SC_Min	0.027	0.05	0.53	√
03	Filter_Min	SC_Max	0.025	0.055	0.45	√
04	Filter_Max	SC_Max	0.027	0.055	0.48	√
05	Filter_Min	CL_Min	0.025	0.042	0.59	√
06	Filter_Max	CL_Min	0.027	0.042	0.63	√
07	Filter_Min	CL_Max	0.025	0.044	0.56	√
08	Filter_Max	CL_Max	0.027	0.044	0.60	√
09	Filter_Min	SM_Min	0.025	0.045	0.55	√
10	Filter_Max	SM_Min	0.027	0.045	0.59	√
11	Filter_Min	SM_Max	0.025	0.067	0.37	√
12	Filter_Max	SM_Max	0.027	0.067	0.40	√

Table 2: Analysis of the effectiveness of the Figueiredo dam.

Scenario	Filter	Base Soil	Dc_{35}	d^*_{85}	Dc_{35}/d^*_{85}	Analysis
01	Filter_Min	SC_Min	0.034	0.050	0.67	√
02	Filter_Max	SC_Min	0.038	0.050	0.77	√
03	Filter_Min	SC_Max	0.034	0.096	0.35	√
04	Filter_Max	SC_Max	0.038	0.096	0.40	√
05	Filter_Min	CL_Min	0.034	0.015	2.24	X
06	Filter_Max	CL_Min	0.038	0.015	2.56	X
07	Filter_Min	CL_Max	0.034	0.045	0.75	√
08	Filter_Max	CL_Max	0.038	0.045	0.85	√
09	Filter_Min	SM_Min	0.034	0.100	0.34	√
10	Filter_Max	SM_Min	0.038	0.100	0.38	√
11	Filter_Min	SM_Max	0.034	0.090	0.37	√
12	Filter_Max	SM_Max	0.038	0.090	0.43	√

Table 3: Analysis of the effectiveness of the Itauna dam.

Scenario	Filter	Base Soil	Dc_{35}	d^*_{85}	Dc_{35}/d^*_{85}	Analysis
01	Filter_Min	Dep1_Min	0.052	0.070	0.74	√
02	Filter_Max	Dep1_Min	0.143	0.070	2.05	X
03	Filter_Min	Dep1_Max	0.052	0.230	0.22	√
04	Filter_Max	Dep1_Max	0.143	0.230	0.62	√
05	Filter_Min	Dep2_Min	0.052	0.070	0.74	√
06	Filter_Max	Dep2_Min	0.143	0.070	2.05	X
07	Filter_Min	Dep2_Max	0.052	0.170	0.30	√
08	Filter_Max	Dep2_Max	0.143	0.170	0.84	√
09	Filter_Min	Dep3_Min	0.052	0.074	0.74	√
10	Filter_Max	Dep3_Min	0.143	0.074	2.05	X
11	Filter_Min	Dep3_Max	0.052	0.127	0.40	√
12	Filter_Max	Dep3_Max	0.143	0.127	1.10	X

Table 4: Analysis of the effectiveness of the Taquara dam.

Scenario	Filter	Base Soil	Dc_{35}	d^*_{85}	Dc_{35}/d^*_{85}	Analysis
01	Filter_Min	Base_Min	0.036	0.105	0.34	√
02	Filter_Max	Base_Min	0.050	0.105	0.44	√
03	Filter_Min	Base_Max	0.036	0.125	0.29	√
04	Filter_Max	Base_Max	0.050	0.125	0.37	√

Table 5: Analysis of the effectiveness of the Olho Dagua dam.

The results of the simulations show that the filtering structures of the Monsenhor Tabosa, Itauna and Taquara dams are inefficient in retaining the finer fraction of the base soil (CL and SC-SM) according to the adopted design criterion, compromising filter stability, giving margin to a possible fine transport by the structure and eventual erosion of the embankment. The results also highlight the importance of the sedimentation test for the filter effectiveness analysis, since it is the finer fraction of the soil that will be washed during the internal erosion process.

Figure 1 to Figure 5 show the adjusted PSDs of the base soils and the CSD of the filters arranged in graphs. Through the arrangement of the curves it is possible to observe those that are most susceptible to an eventual internal erosion process by means of the distances between the curves of the base soil and the CSDs of the filter. The base soil PSDs of Mosenhor Tabosa, Taquara and Olho Dagua are close to the filter CSDs, confirming the susceptibility of the base soil of Mosenhor Tabosa and Taquara dams to erosion, and showing the need for more information on the base soil of the Olho Dagua dam.

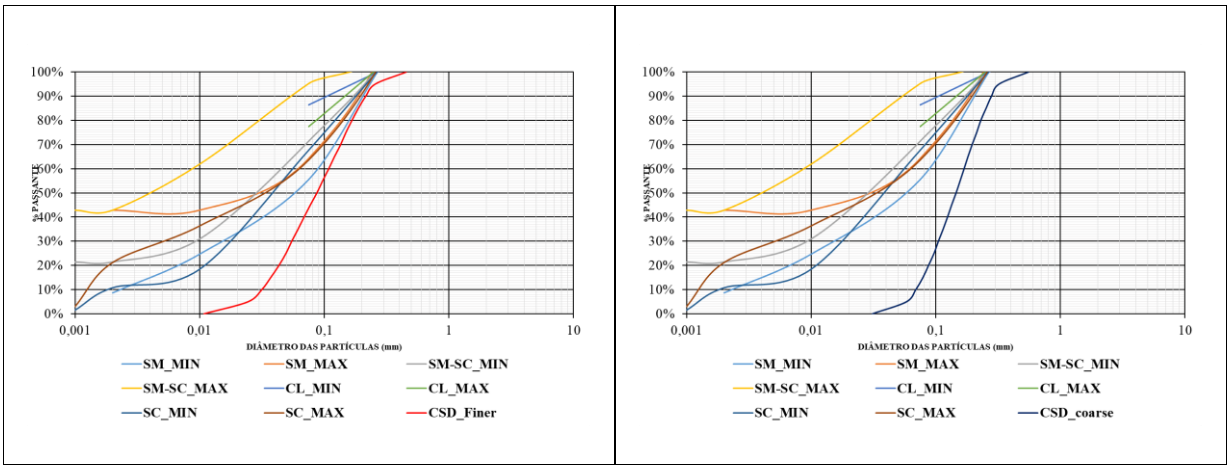

Figure 1: Adjusted PSD of the base soil for each CSD of the filter of Mosenhor Tabosa dam.

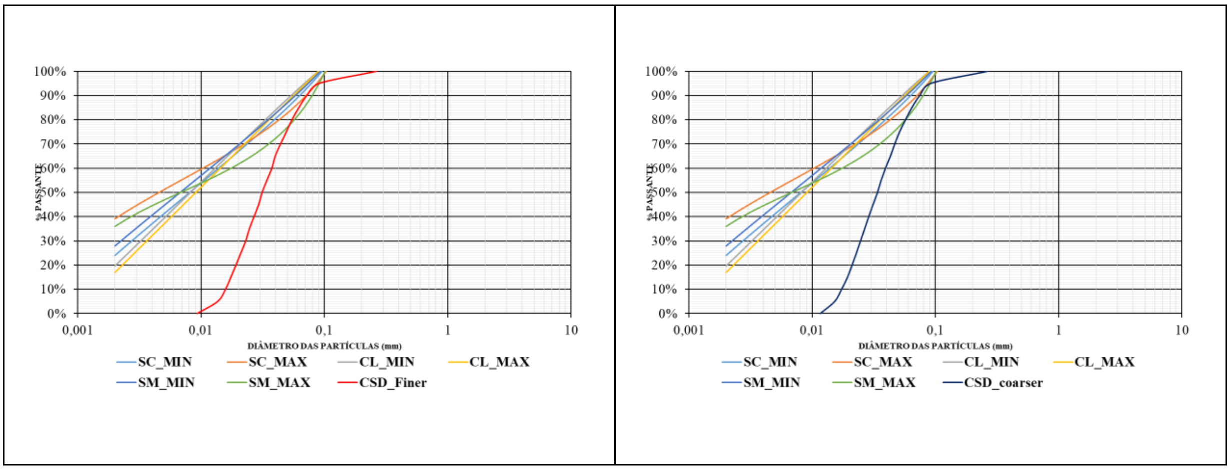

Figure 2: Adjusted PSD of the base soil for each CSD of the filter of Figueredo dam.

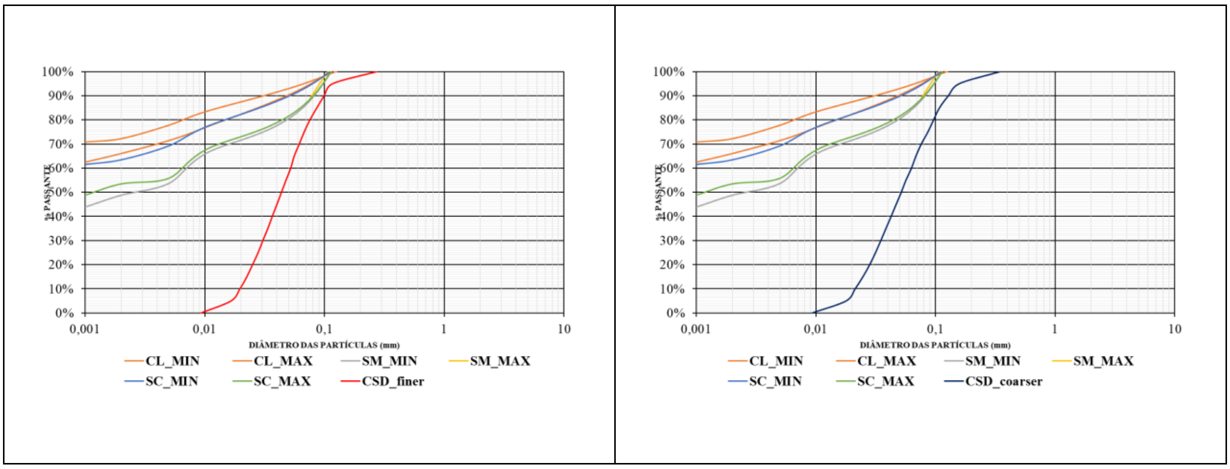

Figure 3: Adjusted PSD of the base soil for each CSD of the filter of Itauna dam.

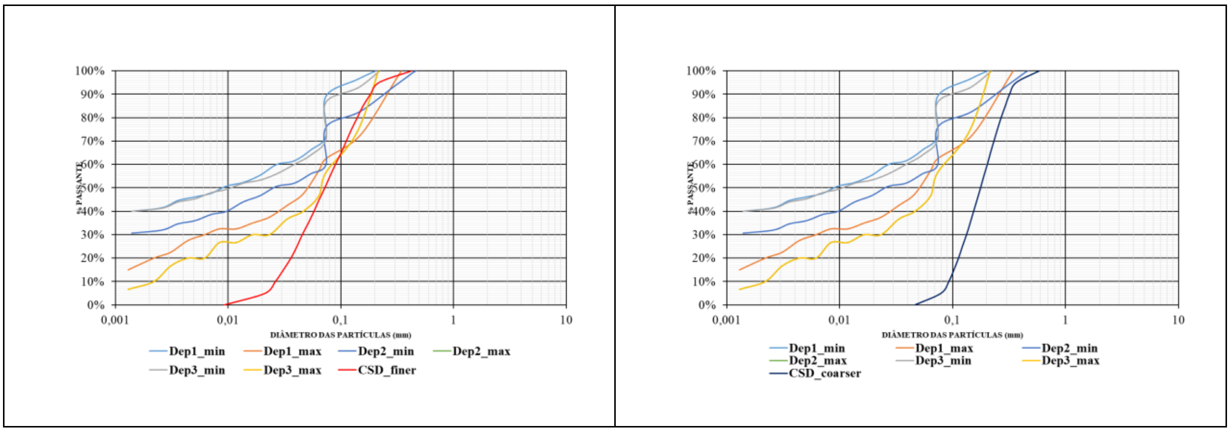

Figure 4: Adjusted PSD of the base soil for each CSD of the filter of Taquara dam.

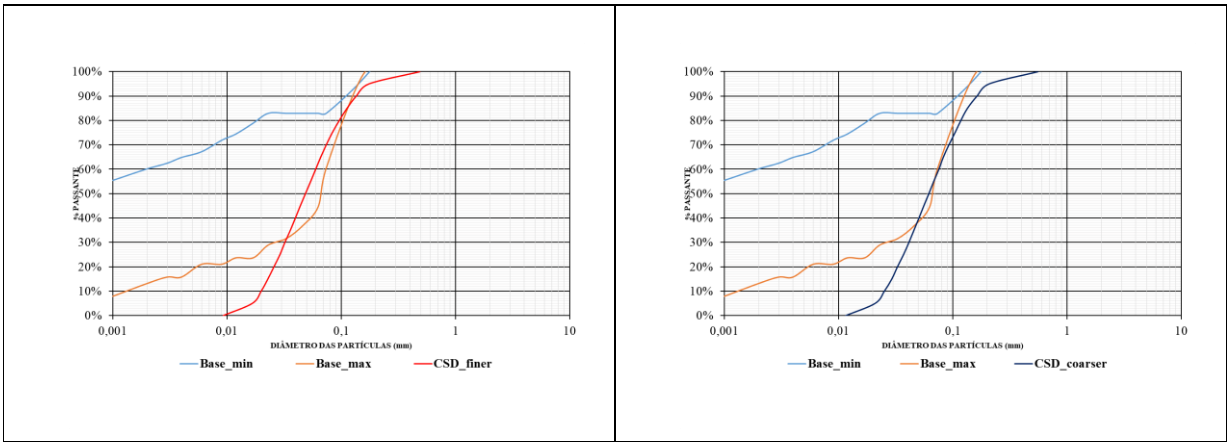

Figure 5: Adjusted PSD of the base soil for each CSD of the filter of Olho Dagua dam.

4 CONCLUSIONS

Using the analysis result is possible to conclude that most of the studied dams presents limitation in the filter-drainage structure in retaining the finer fraction of the base soil. It is necessary an evaluation of the structure together with inspection routines, with the objective of identifying an eventual internal erosion process and its stage of development, adopting interventions measures to inhibit its development.

As presented, the design method applied in this study can be used as an instrument for the detection of internal erosion, by means of simulation of the dam filtering structures, using as input data the geotechnical studies. Through these simulations, it is possible to foresee probable internal erosion process in the dams in operation.

The relevance of the results is emblematic in the semi-arid region of Brazil, which strongly depends on hydraulic reservoir structures. The research seeks to modernize and innovate filter-sizing methods, and to present contributions in the areas of dam safety and risk analysis.

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