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Proposal to use new methods of design and construction in mobile riverbed physical models: the Salto do Paraopeba dam case

Proposta de uso de novos métodos de desenho e construção de modelos físicos de fundo movél: o caso da barragem do Salto do Paraopeba

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ABSTRACT

The study of the interaction between hydraulic structures in mobile bed river systems is complex because it involves sediment transport and dynamic changes in the boundary conditions, requiring the use of physical models. This article presents the procedure for the design and construction of a physical model of the reservoir and dam of the Small Hydroelectric Power Plant (SHPP) of Salto Paraopeba. In the design phase, computational modelling of sediment transport was used to reconstitute the primitive geometry of the river, and simulations of the flow regime and the transport capacity along the course of the river were also carried out; both results allowed to delimit the model extension. Considering the choice of scale and the similarity criteria between the model and the prototype, the use of a new alternative material was proposed, composed of crushed tire rubber particles, with a lower specific mass and a larger diameter than the prototype's sediment. In the construction phase, a new constructive method of the physical model was applied using fiberglass, the method presents constructive advantages, such as better representation of the morphology, lower weight, simple installation and uninstallation through modules, and simple and fast repairs, among others.

Keywords: Silting of reservoirs; Physical modelling; Sediment transport.

RESUMO

O estudo da interação entre estruturas hidráulicas em sistemas fluviais de leito móvel é complexo pois envolve transporte de sedimentos e mudanças dinâmicas nas condições de contorno, sendo necessário o uso de modelos físicos. Este artigo apresenta o procedimento para o desenho e construção de um modelo físico do reservatório e da barragem da Pequena Central Hidroelétrica (PCH) de Salto Paraopeba. Na fase de desenho, foi utilizada a modelagem computacional de transporte de sedimentos para a reconstituição da geometria primitiva do rio, também foram realizadas simulações do regime do escoamento e da capacidade de transporte ao longo do curso do rio; ambos os resultados permitiram delimitar a extensão do modelo. Considerando a escolha da escala e os critérios de semelhança entre o modelo e o protótipo, foi proposto o uso de um novo material alternativo, composto por partículas de borracha de pneu trituradas, de massa específica menor e diâmetro maior do que o sedimento do protótipo. Na fase de construção, foi aplicado um novo método construtivo do modelo físico empregando fibra de vidro, o método apresenta vantagens construtivas como melhor representação da morfologia, menor peso, instalação e desinstalação simples mediante módulos, e reparações simples e rápidas, entre outras.

Palavras-chave: Assoreamento de reservatórios; Modelagem física; Transporte de sedimentos.

INTRODUCTION

The construction of dams and reservoirs significantly affects the balance of a river's regime. Upstream of the dam, conditions are favourable for a deposition process, which accelerates the silting up of its reservoir, thereby reducing its lifespan. Downstream of the dam, an increase in erosion and degradation is observed, due to the increase in sediment transport capacity (Yang, 1996). These factors can generate instabilities in the structure of the dam or have an impact on the riverbed and other downstream hydraulic structures. The physical modelling that has been applied to the hydraulic structures mentioned above facilitates the study of the sediment transport process within the reservoir, and the assessment of the effectiveness of new proposals on the original project. For example, sediment control valves can be used to reduce siltation and erosion and better utilization of water resources.

According to ASCE recommendations (American Society of Civil Engineers, 2000), physical modelling is involved in three phases: design, construction and operation of model hydraulics. For the design phase, the following steps are contemplated: a) a collection of primary and secondary information required for the development of the design of the model (including topography, bathymetry, discharge history, water level measurements, etc.); and b) design of the appropriate model, where the processes and forces affecting the hydraulic problem must be identified, in addition to that, information to be obtained by the model must be clearly defined; c) extension of the model which allows the problem to be studied fully and at a minimum cost; and d) determination of the scales of the model, aiming to consider the scale restrictions that allow the measurement and/or visualization of the physical phenomena (for example, distorted scales are commonly employed in estuaries and reservoirs). Other aspects to be taken into account are the physical space of the lab used, the limitations of instruments performing measurements, and the constructional considerations available (i.e.) model building; model automation; instrumentation, and data acquisition (flow, velocity, pressure, water levels, etc.); flow visualization; and model operation (calibration, validation, and uncertainties).

In the development of the design of physical models of moving bed reservoirs, the longitudinal and vertical delimitation of the model is required. For this purpose, the data of the variables linked to the boundary conditions of the area of influence of the model are required. Input and output variables such as flow, sediment discharge, physical and granulometric properties of sediments, variation in water levels, etc. Also, the variables related to the internal part of the model, such as the definition of the non-erodible bottom, the cross sections, the physical and granulometric properties of the material deposited on the bottom and on the edges of the model, model morphology (bathymetric data series), hydraulic structures present, etc. Depending on the possible size of the model's area of influence and the complexity of the physical modelling of the sediment transport process with a mobile bed, it is necessary to carry out simulations with computational modelling in sediment transport that allows a better delimitation of the model extension. After defining the extension of the model, similarity criteria are applied to define the scale of the model, but due to technical restrictions, sometimes it is not possible to choose a sediment of equal density in the model and prototype. Instead, an alternative sediment material is used, generally of lower density and larger diameter. The designers suggest different alternative sediments (charcoal, PVC, Nylon, Polystyrene, Bakelite, etc.), but it is possible to innovate by proposing a new low-cost material, more durable in water, non-dirty, non-deteriorating, non-floating, non-porous, non-hydrophobic, and with low density and a larger diameter than the prototype. The construction and operation of models follow a traditional technique that normally employs specialized personnel and civil construction craftsmen, who are increasingly scarce in the market. It uses civil construction materials such as sand, mortar, concrete, steel strips, and bars that require a high effort in their application. Some authors (Olgun, 2013; Ma & Zhang, 2022; Hager et al., 2020) describe how these models are built and the difficulties in their implementation. The development of techniques with modern materials that allow the models to be made more quickly and use less labor specialized in civil construction is a worldwide demand and presents itself as one of the obstacles to the advancement of physical modelling in the coming decades.

Considering the above, this paper presents the physical modelling of the mobile bed of the Salto do Paraopeba Small Hydroelectric Power Plant (PCH) dam reservoir, where computational modelling of sediment transport was used to define the extent of the physical model, and new techniques and materials were used in the design and construction phases of the model.

MATERIAL AND METHODS

The flowchart in Figure 1 shows the different steps of the methodological procedure throughout the phases of design and construction of the physical model of the Salto Paraopeba SHPP dam.

Case study

The SHPP Salto do Paraopeba started operating in 1956. The geographical coordinates of its location are 20°30'24" South (latitude) and 43°59'10" West (longitude). The plant is located approximately 120 Km from Belo Horizonte. Originally, it was equipped with two generating sets; the first included a 1,500 kW generator and a Francis-type turbine, and the second consisted of a 970 kW generator and a Francis-turbine generator (Planejamento, Engenharia e Consultoria LTDA, 2011). In 2000, the reservoir was already completely silted up and the company 'Centrais Elétricas de Minas Gerais' (CEMIG), responsible for its operation, decided to develop a rehabilitation project. They designed a rehabilitation process for an SHPP with 12.4 MW of installed capacity, to be equipped with two upstream horizontal-axis Kaplan turbines and a unit power of 6.20 MW (Planejamento, Engenharia e Consultoria LTDA, 2011). In addition, Figure 2 shows, it was meant to increase the capacity of the spillway with the implementation of a segment-type floodgate. The floodgate would be 9.20 m wide and 7.00 m high, in the place where the water intake is currently located; next to the left abutment, moving the powerhouse towards it. The floodgate also had the function of reducing the silting up of the reservoir. Due to the complexity of the phenomena of sediment transport, a study was carried out with a physical model to evaluate both the process of sediment transport inside the reservoir and the efficiency of the floodgate in controlling siltation.

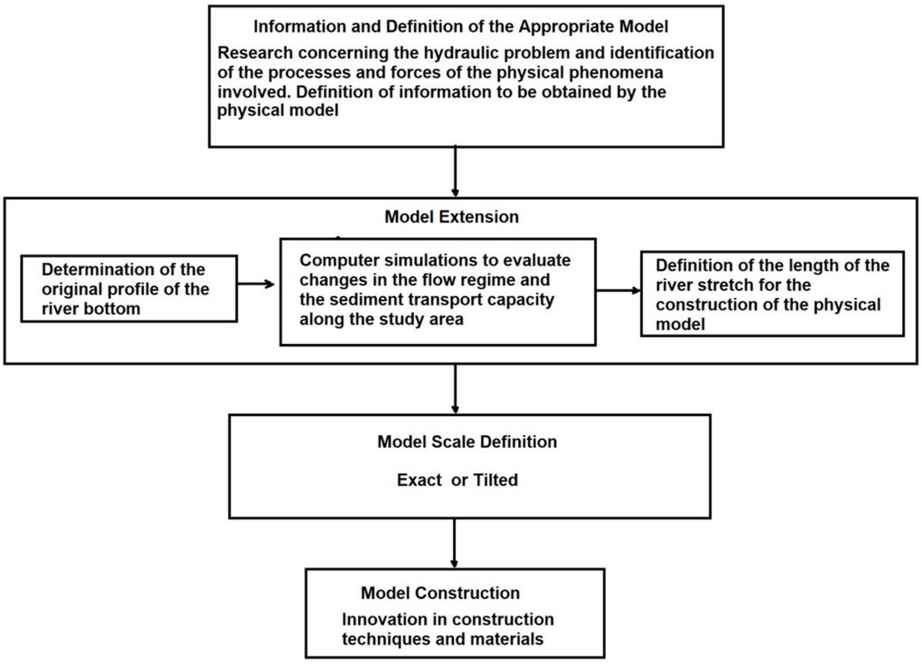

Figure 1. Flowchart of the methodological procedure in the phases of design and model building.

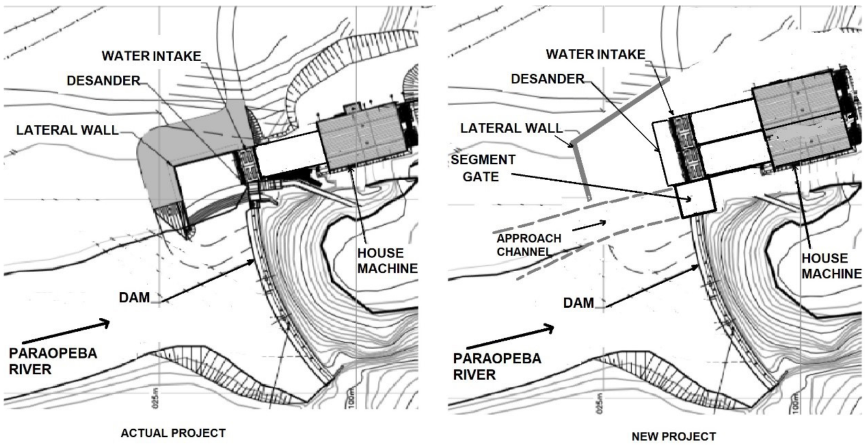

Figure 2. Drawing of the project as it is currently (on the left) and the new proposal with the segment gate in the left shoulder pad. (Note: the drawings are illustrative and do not correspond to the original drawings of the project but represent the proposed changes).

Model extension

According to Carvalho et al. (2014), the model has three control sections. These were identified by this author (Figure 3) through map analysis and field visits, which were used as the upstream limit of the model. These included the following:

a) A crossing bridge to Jeceaba (point 1): the bridge causes a significant bottleneck (from about 50 m to 10 m of surface width), and it is a control point for the model. It configures the maximum possible extension of the model of the reservoir; approximately 2,600 m upstream of the dam;

b) River course deviation (point 2): this section corresponds to the Paraopeba River, which undergoes a significant course deviation, in the form of a zigzag, and continues with the extension of the course in alignment with Serra da Moeda. However, during the field trip, it was identified that this section does not create an effective control. At this point, the model would have an extension of about 1,600 m (value of the prototype);

c) Narrowing of the river (point 3): the narrowing in this stretch transposes the alignment of the Serra da Moeda. This point was inspected, and the occurrence of rock on both banks was confirmed. On the left bank, a bedrock outcropping was observed, which accentuates the narrowing in the shallow water. There is also a condition for the formation of a critical flow in flood situations in this section. At this point, the model would have to represent about 1,000 m in length, starting from the dam.

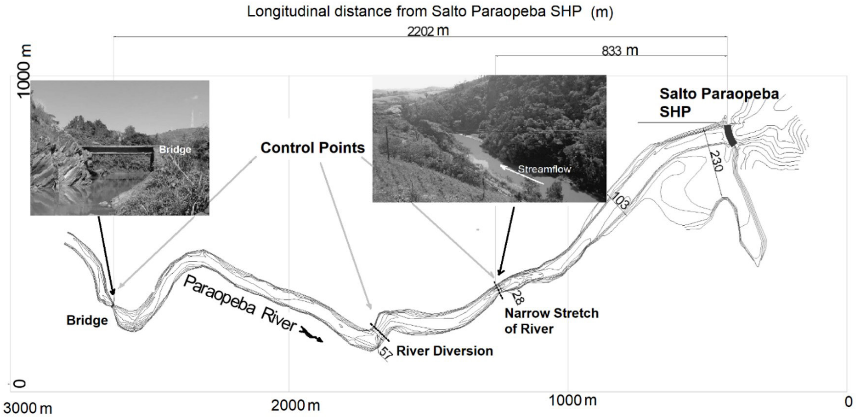

Figure 3. Possible control sections and their maximum widths (Carvalho et al., 2014).

To evaluate these three points, simulations were carried out by using software that allows the modelling of sediment transport in the area. Additionally, it was necessary to determine the original riverbed position.

Determination of the River's Primitive Geometry

Calculations were made using Julien's equations (Julien, 2010, 2002) starting from the current condition of the reservoir to determine the changes in the geometry of the river bottom material and obtain the original profile. This was done without the hydraulic restriction imposed by the dam, ir order to allow the possibility to simulate the erosion of the reservoir until the natural flow condition was established. The profile of the riverbed of the reservoir was determined by bathymetry and is presented in Figure 4. In this figure, one can notice the reduction of the bottom slope caused by siltation.

In this segment, the average slope found is 0.01%, whereas in the natural stretch upstream the slope found is 0.18%. It is noteworthy that the project was installed in a waterfall stretch with a steep slope with a declination next to the slope of the downstream stretch of the dam (1.93%), proving the significant alteration of the riverbed in the reservoir stretch.

As a premise for the definition of the primitive geometry of the river, Julien's equations of morphodynamic equilibrium (Julien, 2010) were used to define the stretch of the reservoir simulated. Additionally, it was assumed the bottom of the dam was the limit for reservoir erosion. This condition was imposed, as the project reports indicated that the dam was implanted on the basaltic rock over a waterfall area part of its stream.

It is known that there is an *equilibrium* between the slope of the channel and the median diameter of the transported sediment in water streams (Pinheiro, 2011). A series of phenomena may happen when this *equilibrium* is made unstable until a new condition of stability is reached (Federal Interagency Stream Restoration Working Group, 1998). In this case, the hydraulic depth will increase, thereby reducing the slope of the flow and providing a morphodynamic imbalance. This imbalance is offset by the reduction of the slope of the section of the reservoir and the diameter of the deposited material, to re-establish *equilibrium*.

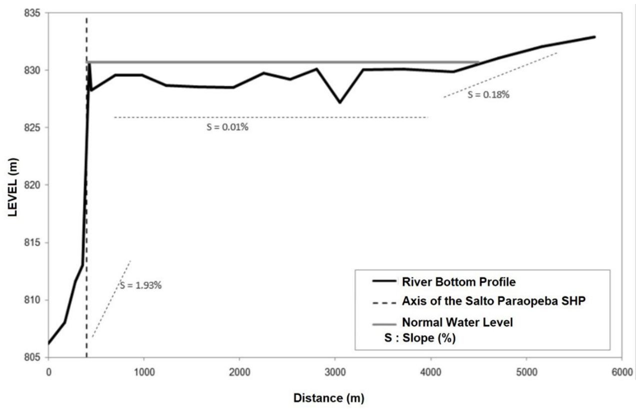

Figure 4. Profile of the riverbed of SHPP Salto Paraopeba reservoir.

Julien's equations (Julien, 2010, 2002) enabled the development of quantitative relationships to determine changes in the geometry of alluvial channels by assessing the stability of the material from the bottom. These equations were achieved by combining the equations of uniform flow (Equation 1), flow resistance (Equation 2), drag tension (Equation 3), and Shields number (Equation 4) and Equation 5, which presents a parameter (m) that composes Equation 2, and that is a function of the flow depth and the average diameter of the particle.

$$Q = WhU \tag{1}$$

$$U = W\sqrt{8g}\left(\frac{h}{d_s}\right)^m h^{\frac{1}{2}} S^{\frac{1}{2}} \tag{2}$$

$$\tau_0 = R_h \rho g S \tag{3}$$

$$\tau_* = \frac{\tau_0}{\left(\rho_s - \rho\right) g d_s} \tag{4}$$

$$m = \frac{1}{\ln(1.2\frac{h}{d_{50}})} \tag{5}$$

In these equations, Q is the dominant flow rate (m^3/s), W is the section width (m), h is the flow depth (m), U is the flow velocity (m/s), g is the gravitational acceleration (9.81 m/s^2), S is the energy slope (m/m), τ_0 is the drag tension (Pa), ϱ is the water density (kg/m^3), ϱ_s is the sediment density (kg/m^3), R_h is the hydraulic radius (m), d_s is the diameter of the sediment (m), d_{50} is the average sediment diameter (m) and τ_* é is Shields' number (dimensionless).

Simulations to assess the flow regime and transport capacity

One-dimensional flow simulations were carried out in the program Hydrologic Engineering Center - River Analysis System (HEC-RAS), considering: i) the domain presented in Figure 3; ii) the result of the primitive geometry of the river, which was obtained in the previous item; iii) the information obtained from Carvalho et al (2014), Planejamento, Engenharia e Consultoria LTDA (2011), Do Vale et al. (2013) and Fundação Christiano Ottoni (2013). The inflows to the reservoir that were considered in this study are presented in Table 1. In this table, Flow $Q_{7,10}$ is the 10-yr minimum, 7-day moving average flow, Q_{95} is the flow which is exceeded during 95% of the flow record, and "Average" means the average flow.

Since the one-dimensional version of the HEC-RAS program was used and there was evidence of two-dimensional processes in the deposition of sediments in the Salto Paraopeba reservoir, with the formation of banks on both margins, two-dimensional simulations of the flow were also performed using the Surface-Water Modelling System (SMS) program. The simulations resulted in an estimative of the capacity of sediment transport along the Paraopeba River in the section, which was obtained by applying the Meyer-Peter equation (Graf, 1984):

$$G_{sa} = B\left(\frac{\tau_* - 0.047}{0.25}\right)^{1.5}\left(\frac{d}{\sqrt[3]{\rho}}\right)^{1.5}(\gamma_s - \gamma)^{0.5}\gamma_s \qquad (6)$$

In this equation, Gsa is the solid discharge (kg/s), B is the average width (m), and D is the diameter of the representative sediment particle, in this case, considered equal to d50 (0.06 mm = $6x10^{-5}$ m). Yet, ϱ is the density of water (1,000 kg/m^3), γs is the specific mass of the solids (25,996 N/m^3), γ is the specific mass of the water (9,810 N/m^3) and τ* is the Shields parameter (dimensionless), defined in Equation 4. The values of diameter and specific mass of the material were obtained by consulting the bibliography (Carvalho et al, 2014; Fundação Christiano Ottoni, 2013).

Determining the scale of the models

Flow over a mobile riverbed has a fully developed turbulent regime. It was noticed, in the experiment, the formation of a velocity profile that is affected by the resistance to the flow due to the roughness of the bottom. Both the grain size of the sediment and the shape of the bottom play a role in its formation. In flows where sediment transport is happening and the bottom forms have an almost flat shape, one can consider that the flow resistance is mainly caused by roughness due to the grain size (Graf, 1984; Julien, 2002; O'Brien & Julien, 1985). The equation for the average velocity can be expressed by the following equation:

$$\frac{V}{U_*} = a\left(\frac{R_h}{d_s}\right)^b \qquad (7)$$

Where, $U_* = \sqrt{gR_hS}$ is the shear velocity and d_s is the diameter of the sediment.
When $100 < \frac{R_h}{d_s}$, the value of b=1/6, and the value of a = 5 and $R_b \approx h$ (depth of the flow).

For sediment concentrations of less than 20% in volume, one can assume the values of kinematic viscosity and fluid density to be equal to those of pure water ($1x10^{-6}$ m^2/s and 1,000kg/m^3) (O'Brien & Julien, 1985).

Hydraulic similarity involves achieving correspondence in the geometric, kinematic, and dynamic aspects. Geometric similarity involves defining the scales used to represent the dimensions of the plane and the vertical direction of the model.

Table 1. Expected inflows and water levels in the spillway of SHPP Salto Paraopeba.

Minimum Flows (m^3/s) and Water levels (m)	**Historical**	**5.6**	**830.83**
	$Q_{7,10}$	**10.5**	**830.89**
	95%	**13.8**	**830.92**
	Average	**47.8**	**831.20**
Maximum flow (recurrence years – m^3/s) and Water levels (m)	**2**	378.7	832.66
	5	606.1	833.38
	10	778.2	833.87
	25	1,005.6	834.46
	50	1,177.7	834.87
	100	1,349.7	835.27
	500	1,749.3	836.13
	1,000	1,921.3	836.48
	10,000	2,492.9	837.57

Source: SPEC (Planejamento, Engenharia e Consultoria LTDA, 2011).

According to Julien (2002), distorted models can be needed when addressing the sediment transport problem and the sediment weight can't be exactly scaled.

Kinematic similarity (Julien, 2002) can be obtained when the Froude numbers in the prototype and the model present a unit ratio As the following equation shows:

$$Fr_r = \frac{Fr_p}{Fr_m} = 1 \therefore U_r = z_r^{0.5} \quad (8)$$

In this equation, Fr is the Froude number, r indicates the ratio between the scales, m indicates the value in the model, p indicates the value in the prototype or real structure, z represents the vertical dimension, U is the average velocity (m/s).

Dynamic similarity refers to the parameters involving mass, that is, the forces acting on a fluid element must have the same proportion. An important relationship arises from the ratio between inertial and viscous forces acting in a fluid element. This is represented by the Reynolds number (Julien, 2002) as follows:

$$Re_r = \frac{Re_p}{Re_m} = \frac{U_r z_r}{\nu_r} = z_r^{1.5} \quad (9)$$

In this equation, ν is the kinematic viscosity of water (m^2/s), which is the same in both the model and in the prototype. When the kinematic and dynamic similarities are maintained, the following formula can be considered:

$$Fr_r = 1 \text{ and } Re_r = z_r^{1.5} = 1 \therefore z_r = 1 \quad (10)$$

It is only possible to maintain the two similarities, kinematical (Fr_r) and dynamical (Rer) in the real scale. As such, it was decided to only maintain the kinematic similarity and not the dynamic relationship, $Re_r \neq z_r^{1.5}$. However, the Reynolds number values were always kept in the transition or turbulent zones.

Basic model design

Details and sections of the experiment were designed based on both the definitions of the physical model, the domains and scale, and the drawings of the arrangement. The model was built of fiberglass on a Styrofoam base, which allowed it to accurately represent contour lines, and the geomorphology of the river channel and surrounding areas. Additionally, the use of this material reduced the weight of the model. Due to the light weight, the models could be placed on a tilted metal structure, which allows the slope of the model to be changed if required. The use of this new technique of constructing physical models has several benefits compared to conventional construction methods, such as assembly, labor, execution time etc.

Subsequently, research was conducted to identify the possible sediment materials that would allow the study of the sediment transport process in the physical model. In this context, it was decided to use shredded used tire rubber, which is an innovation in physical modelling techniques. A study was performed to select the material, considering the advantages and disadvantages of rubber compared to materials such as coal, nylon, slag and polyacetal.

RESULTS AND DISCUSSIONS

The primitive geometry of the river

There are no hydrosedimentometric stations located upstream of the dam, therefore it was necessary to regionalize the following information: sediment load versus flow curve, total grain size curve, and flow series. This was done by using data from the Belo Vale hydrosedimentometric station (code 40710000). This station is operated by The Brazilian Geological Service (CPRM), located 15 km downstream of SHPP Salto Paraopeba, where the flow and concentration of solid material suspension are recorded.

The Colby Method was applied (Oliveira Carvalho, 2008) to calculate the total solid discharge. The method is based on the concentration of solid material in suspension, the hydraulic characteristics of the flow, and the granulometric characterization of the solid material from the bottom, found in the studies performed for this research. Due to the proximity of this station to the SHPP Salto Paraopeba, and the silted condition of the reservoir, it was possible to use the same key curve of the sediment. Consequently, three hydrosedimentometric studies (Fundação Christiano Ottoni, 2013) were conducted upstream of the dam. Their data was plotted on the key curve of the Belo Vale station (Fundação Christiano Ottoni, 2013), and as can be seen in Figure 5, the measurements of the campaigns fall within the sediment load versus flow curve.

A study of the proportion by drainage area between the Belo Vale station and the SHPP Salto do Paraopeba for each monthly average flow was carried out to define the series of flows upstream of the reservoir. Considering the premise that, after the construction of the dam, the silting of the reservoir is in an *equilibrium* state, without much morphological alteration, mathematical simulations were carried out in search of the best sediment transport model. These simulations presented the lowest morphological variation over a series of 41 years (data available), and the Toffaleti model (Fundação Christiano Ottoni, 2013) was selected. The result of these simulations are presented in Figure 6.

To reconstruct the original geometry of the reservoir, Fundação Christiano Ottoni (2013), carried out sediment transport simulations without considering the hydraulic restriction imposed by the dam to allow the increase in flow velocity and, consequently, the erosion of its bed. Subsequently, a HEC-RAS modelling used data from the natural inflows into the reservoir in its current condition, obtaining the primitive bathymetry (Figure 7), used on the physical model.

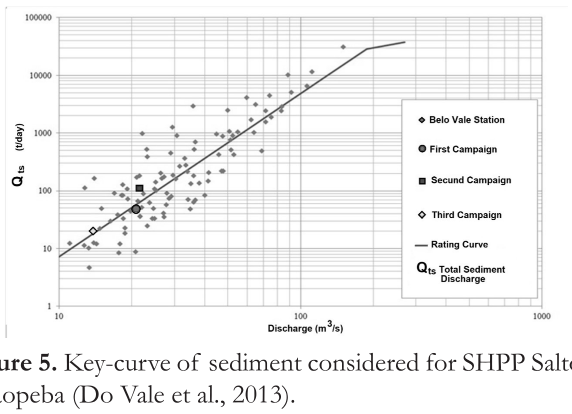

Figure 5. Key-curve of sediment considered for SHPP Salto do Paraopeba (Do Vale et al., 2013).

A new simulation of the siltation process of the reservoir was carried out to validate the results, based on the primitive geometry obtained (Figure 7). The results indicate that after 62 years the siltation process would reach a geometry that is similar to the one found in the bathymetry of 2013, after 56 years of the natural flow.

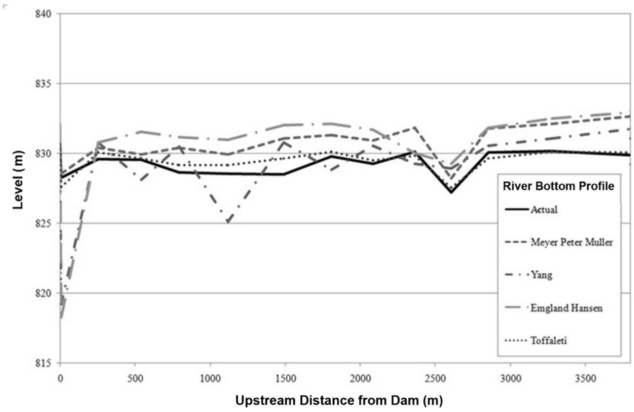

Figure 6. Profile of the river channel obtained from the simulations of model calibration (Fundação Christiano Ottoni, 2013).

Simulations to evaluate the regime flow and transport capacity.

Figures 8 and 9 show the beload discharge for 10-yr, 100-yr and 1,000-yr recurrence floods. The figures indicate that if a physical model is built including the entire simulated length (3.7 km), parts of the sediment will be deposited, respectively, in the stretch upstream of the bridge (about 2.6 km upstream of the dam), in the section between the bottleneck and the bridge (between 1.0 and 2.6 km upstream of the dam), and in the reservoir region up to the bottleneck (about 1.0 km upstream of the dam). This remains true in both simulated scenarios, the original and the silted reservoir.

Based on the analysis of the results of the hydraulic models described above, the bottleneck at 1.0 km upstream of the dam was considered the upstream limit of the model, since it is a hydraulic control section. This can be checked on the water profiles for different simulated flows (Figure 10). Critical flow conditions are indicated, which also limits a sedimentation zone in the reservoir in the simulated domain.

When analyzing Figure 9, it can be seen that after the sedimentation zone, there is a siltation zone, approximately 300 m upstream of the dam. It is in this zone that the construction of a channel approaching the floodgate is planned to be performed.

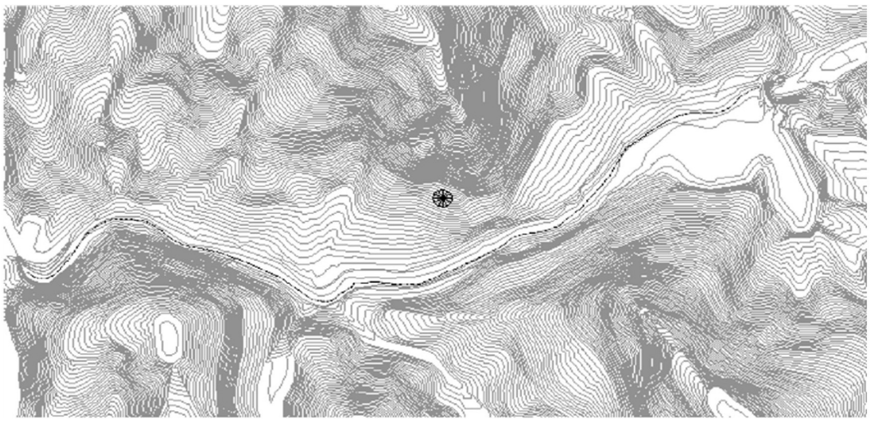

Figure 7. Primitive topography (Fundação Christiano Ottoni, 2013).

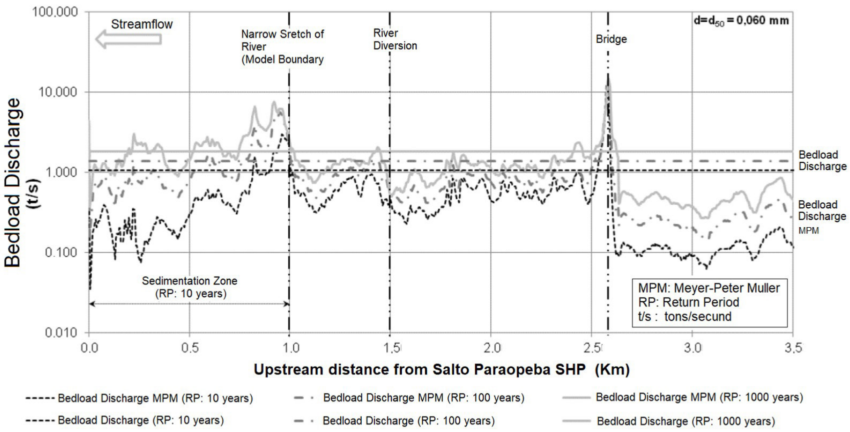

Figure 8. Bedload discharge for 10-yr., 100-yr and 1000-yr recurrence floods using original topography data (Fundação Christiano Ottoni, 2013).

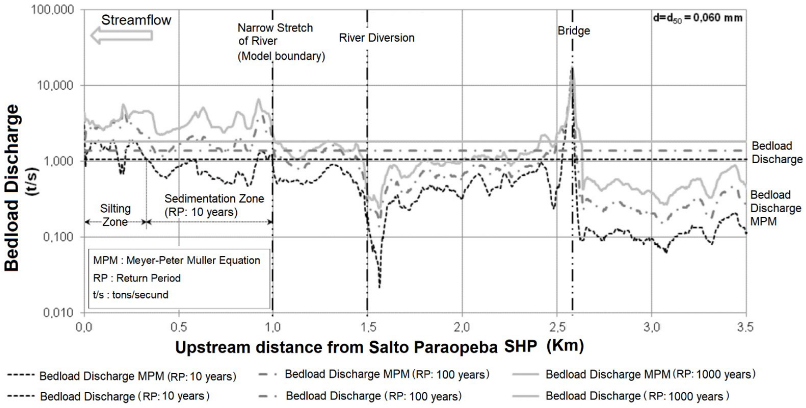

Figure 9. Bedload discharge for 10-yr., 100-yr and 1000-yr recurrence floods using the silted reservoir topography.

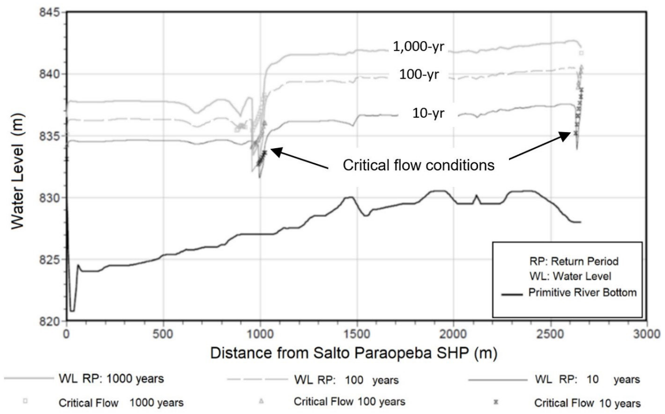

Figure 10. Water profiles for the 10-yr, 100-yr and 1,000-yr floods.

The operation of the floodgate has a direct influence on the reduction of siltation. As such, in addition to its function in controlling the flow, the floodgate is useful for controlling the siltation process in the reservoir, especially in the approaching channel, reducing the risk of siltation of the intake.

Scales of the models

Two physical models were designed. The first (Model 01) focused on the dynamics of sediments in the reservoir, with the objective of evaluating measures for coping with siltation processes. It involved influencing the total length of up to 1,000 m upstream of the dam. The second model (Model 02) was designed to evaluate the impact of the proposed structural changes, as it was designed to increase the capacity of power generation. In this case, the model is limited within the siltation zone, 200 m upstream of the dam. Model 01 is a distorted model, in which different scales are applied in the horizontal plane (xr= yr= 99.3) and the vertical direction (zr=25), as studied by Teixeira et al. (2020). Model 02 is scaled with exact scales (xr= yr= zr=40) in all three dimensions. The dimensions and scales of Model 02 are presented in Table 2.

Sediment scale

Once the scale of the bottom shear stress is defined as $\tau_r = z_r$ and the scale of the dimensionless diameter of the grain is equivalent to $d_{*r} = 1 = ds_r \left(G-1\right)_r^{1/3}$, Equation 11 is obtained as:

$$ds_r^3 = \frac{1}{\left(G-1\right)_r} \tag{11}$$

In Equation 11, G is the specific gravity of the sediment and ds is the representative sediment diameter.

Meanwhile, the dimensionless shear stress is the same in the model and the prototype, $\tau_{*r} = 1$, independently of the differences in the diameter and density of the sediment. The initiation of motion in both the prototype and the model should happen under the same hydraulic conditions, respecting geometric, kinetic and dynamic similarity. Therefore, the dimensional parameter of scaled Shields is defined as Equation 12:

$$\tau_{*r} = 1 = \frac{\tau_r}{\left(G-1\right)_r ds_r} = \frac{z_r}{\left(G-1\right)_r ds_r} \tag{12}$$

After combining Equation 12 with Equation 11, we find Equation 13:

$$ds_r = z_r^{-0.5} \tag{13}$$

At the entrance of the intake at the silted reservoir, a sample of sediment was collected during a field trip to the dam, in 2016. The distribution of the particle sizes of the collected material was determined in the lab; that is d_{50} = 0.2 mm (as detailed in Campello, 2017). This allowed the calculation of the diameter of the sediment in the model through Equation 14:

$$ds_r = \frac{d_p}{d_m} = z_r^{-0.5} \rightarrow d_m = z_r^{0.5} d_p = 0.2\,mm\,x\,40^{0.5} = 1.26mm \tag{14}$$

To be able to determine the density of the sediment that was used in the model, Equation 11 can be used, which will lead to Equation 15:

$$ds_r^3 = \frac{1}{\left(G-1\right)_r} = z_r^{-3/2} \rightarrow z_r^{3/2} = \frac{\left(G_p-1\right)}{\left(G_m-1\right)} = 40^{1.5} = \frac{\left(2.65-1\right)}{\left(G_m-1\right)} \rightarrow G_m = 1.06 \tag{15}$$

Hence, the density of the sediment of the model is $\rho_m = 1,061 \frac{kg}{m^3}$.

Different materials were analyzed, such as carbon, polyacetal, acrylic balls, and crushed rubber. Camppelo et al. (2017) examined the different advantages and disadvantages of these materials and chose crushed rubber, as it has a density of ϱ_{rubber}= 1,140 kg/m^3 and ds_{50}= 1.5 mm, which are values that come close to the density and diameter that were required in the model. Additionally, it was also determined for different classes of rubber: the angle of reclination; factors of the form; the terminal velocity of this material; and its motion onset. The results allowed Campello (2017) to validate the use of the material in the physical model (Figure 11).

Based on the bathymetry of 2011, the total volume of sediments in the silted reservoir was calculated to be 73,885 m^3. Given that, the limit of the bottom of the primitive surface, this volume represents about 300 liters of sediment (approximately 350 kg of crushed rubber material) on the scale of the model.

In both models, the granulated rubber particles are intended to reproduce the natural bedload movement, and it is essential to keep the scale of the related parameters (Re_*, τ_*, d_*). Despite the model was originally designed to keep the scales in these parameters equal to unity, their obtained values were 1.83, 2.28 and 2.77, respectively, after considering sediment and rubber properties. These values were considered close enough to unity as the model and the prototype operates in the hydraulic rough regime where the critical shear stress is constant.

The use of granulated rubber was preceded by saturation of the grains so that material that could form floating flakes was removed from the process. Despite this, it must be taken into account that there is always a limitation regarding the representation of materials in scale and this is one of the factors to be considered in the analysis and final results.

Constructive aspects of Model 02

From the definitions of the domains and the respective scale of the model, the arrangements, details, and section drawings were drawn. These are presented in a simplified form, in Figure 12.

Model 02 is built by carving the primitive surface of the reservoir on polystyrene (Styrofoam) blocks of high density (30 kg/m^3) with different dimensions (Table 3), using a CNC milling machine.

These blocks are placed on stages positioned at 1.50 m and 1.00 m high about the lab floor, made of 25 mm thick plasticized laminated wood. This laminated wood is commonly used in the construction of reinforced concrete slabs and can be easily purchased. This structure has the advantage of being dismountable, thus it can be reused in other models. Moreover, it allows for precise levelling of the support planes of the Styrofoam blocks. Once the material arrived and the platform was ready, the assembly of the polystyrene blocks (Styrofoam) took three weeks of work.

Table 2. Dimensions and scales used in the design of Model 02.

Variable	Scale symbols	Scale value	Prototype value	Model Value
Depth	z_r	40	30 m	0.8 m
Length	x_r	40	240 m	6.0 m
Width	y_r	40	240 m	6.0 m
Slope	S_r	1	0.21%	0.21%
Froude number	Fr_r	1	1	1
Shields parameter	τ_{*r}	1	1	1
Grain diameter	d_{*r}	1	1	1

Notes: scale symbols come from the variable symbol added to the subscript "r".

Table 3. Quantities for the construction of physical Model 02.

Item	Quantity	Units
Polystyrene blocks (Styrofoam) 1.60 x 1.00 x 0.50 m	50	un.
Polystyrene blocks (Styrofoam) 1.60 x 0.50 x 0.50 m	14	un.
Polystyrene blocks (Styrofoam) 0.80 x 0.50 x 0.50 m	6	un.

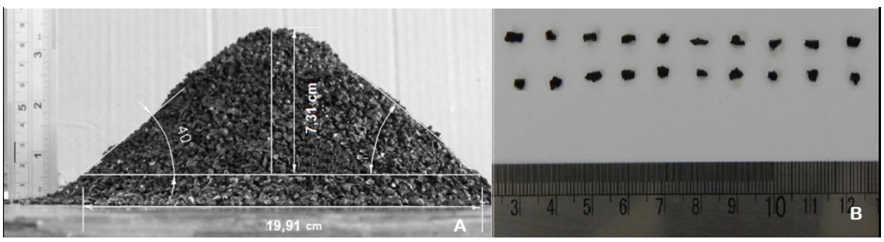

Figure 11. Crushed rubber: A) cone formation for rubber, class R1 (1.70 mm to 2.00 mm); B) details of the angular shape of the material from different perspectives, class R2 (2.00 mm to 3.00 mm).

Some of the surfaces of the Styrofoam blocks are carved superficially to match the primitive contour lines of the reservoir. The machined surfaces have a roughness of 5mm x 5mm. Over these surfaces, the fiberglass (composed of epoxy resin, a fiberglass mesh, and a coating gel) is moulded (Figure 13). The surface of the model was coated with epoxy paint, which had the purpose of additional waterproofing and reducing the porosity and surface roughness, which remained at 0.1 mm.

The floodgate was built in acrylic (Figure 14) according to the scale $z_r = 40$. Its activation was performed manually because of the time it took to open the gate for the scaled model, in comparison to that of the prototype ($t_r = \frac{t_{prototype}}{t_{model}} = z_r^{0.5}$). For example, for the opening maneuver floodgate of $t_{prototype}$ = 0.5h of duration in the prototype, the corresponding time for the model is t_{model} = 4.74 min.

In the physical model, the dam was built with a 3:1 ratio mixture of crushed tire rubber and ACS III mortar, respectively.

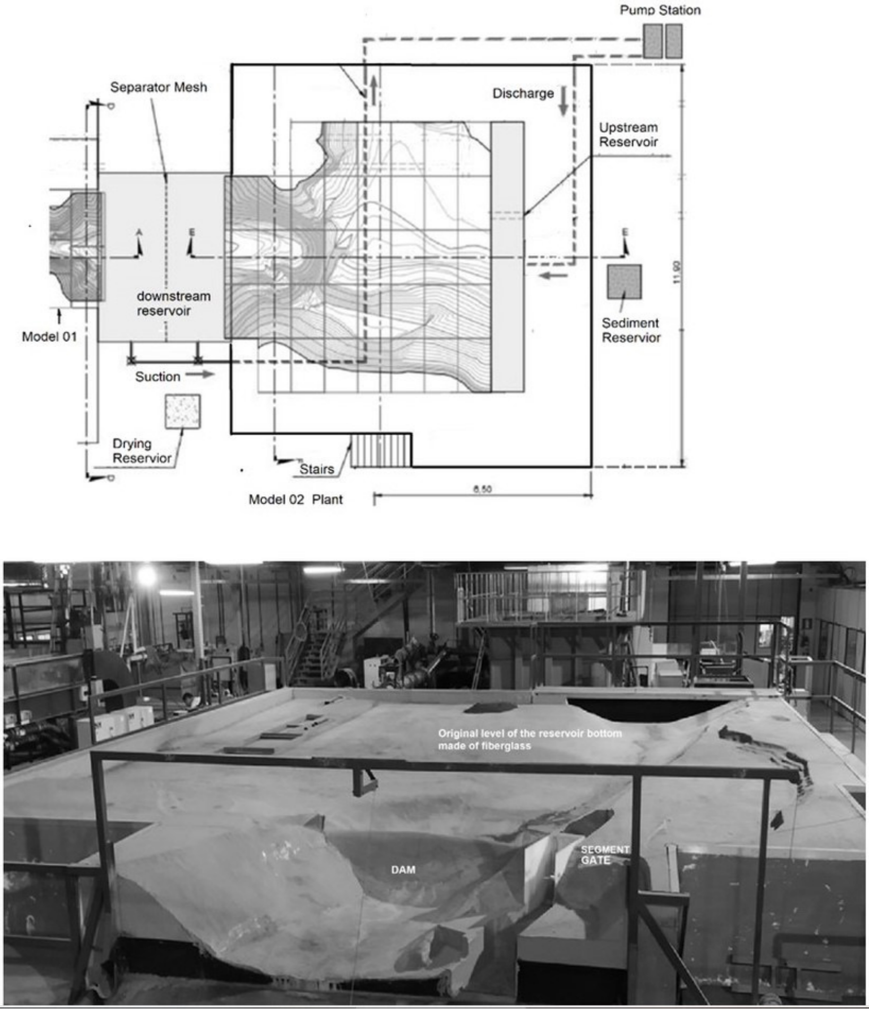

Figure 12. Top view of the reduced Model 02 of SHPP Salto Paraopeba (Fundação Christiano Ottoni, 2013) and physical Model 02, where the fiberglass is already installed.

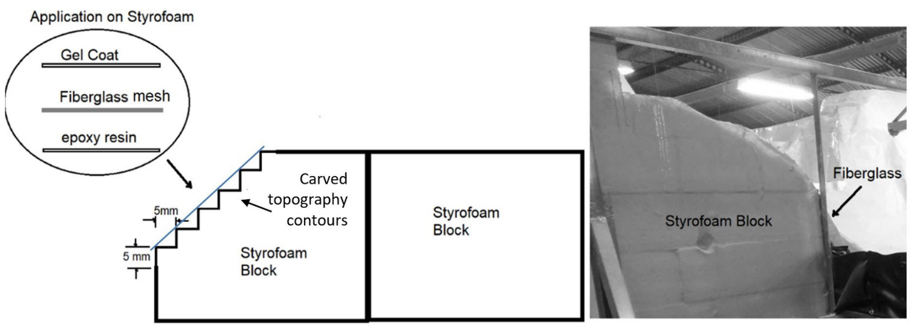

Figure 13. Application of fiberglass over polystyrene blocks (Styrofoam).

Contour lines were indicated on the model surface. Additionally, the Normal Water Level (El. 830.71 m) was set as the spillway crest. The construction process took approximately one week (Figure 15).

The flow of the model is supplied by two pumps, in parallel. These pumps were selected by considering the flows of 47.8 m^3/s (average) and 2,492.9 m^3/s (maximum for TR=10,000 years), corresponding with the scale of the model of 4.7 l/s and 146.3 l/s, respectively. The flows were controlled by using frequency inverters.

Constructional differences between the conventional method and the new method

The differences in the process of designing and building physical models, between conventional methods and the proposed new method, are presented below.

Structure base

In the conventional method, the model is built of masonry on the lab floor. In the case of the distorted model, the structure cannot be adjusted or modified. In the new method, the body of the model is composed of a processed Styrofoam base and is laminated with fiberglass, which makes the model very light and allows placing it on a metal structure. The undistorted model was placed on a mobile metal structure (Figure 16A), and the distorted model was placed on a fixed structure. This fixed structure was equipped with a mechanical or hydraulic tilting system that allows the slope of the model to be modified and adjusted (Figure 16B).

Process of creating the morphology

In the conventional method, the process of constructing the contour lines required cross-sectional moulds of the river

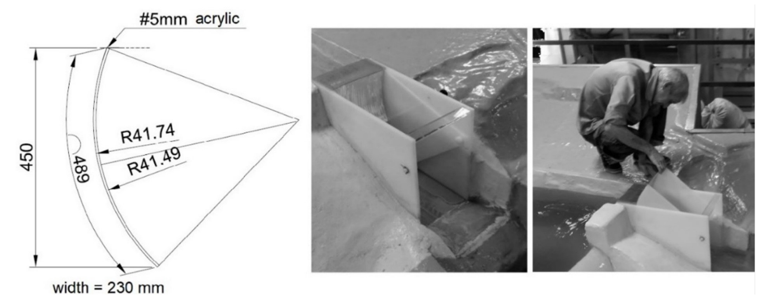

Figure 14. Details of the acrylic segment of the gate and its manual activation.

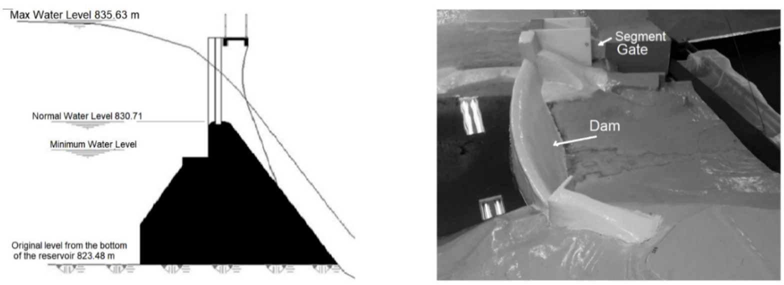

Figure 15. Water levels over the dam (prototype) and detail of the construction of the dam, at the scale of the physical model (executed with a mix of mortar and crushed rubber).

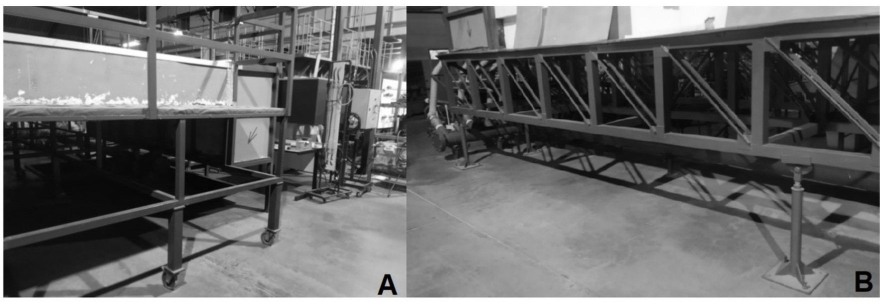

Figure 16. Type of structural base: A) Mobile frame for the undistorted model; B) Fixed frame with tilting system and mechanical jacks for the distorted model.

section (Figure 17A), placed at a distance. Gravel and sand (or another filling material) are placed within each mould (Figure 17B), and, then, mortar is placed over this filling (Figure 17C). The construction process requires a skilled crew; has to be done with care; and is time-consuming (Sharp, 1981).

In the new method, contour lines are carved directly on a high-density Styrofoam basis. According to the Brazilian Standard n° 8082 (Associação Brasileira de Normas Técnicas, 2016), the high-density Styrofoam supports a compression of 230kPa (2.3Kgf/cm2 or 23 m.c.a.), presenting a deformation of 10%. In the physical models that have been studied, the water columns are smaller than 1 m. The contour lines smoothing on Styrofoam supports constructive aspects of the model's morphology, allowing for the continuous modelling of the terrain surface, following the contour lines (Figure 18A). The contour lines on the Styrofoam blocks are carved in the form of steps that have different sizes, ranging from 10 mm, 5 mm, and 2 mm (Figure 18B). The process of placing the fiberglass requires a team with some experience, but expertise in physical model building is not required.

Changing the Roughness in the model

With the conventional method, a change in roughness is performed by placing macro roughness (small blocks) on the bottom, producing an inhomogeneous roughness. With the new method, the change of roughness can be done during the finishing process of the fiberglass surface, by placing more roughened fiberglass fabrics. This will lead to a more homogeneous roughness.

Modifications and repairs

With the conventional method, modifications and repairs must be done with masonry material. By applying the new method, the fiberglass presents problems such as blistering, cracking, discoloration and staining. The process of correcting and repairing fiberglass can be done with the fiberglass itself as well as with other materials such as acrylic putty, mortar etc. Manufacturers of fiberglass structures, specifically those who manufacture swimming pools, mention that such structures can last up to 30 years.

Deconstruction

With the conventional method, it is not possible to relocate the model and the deconstruction process is destructive, generating waste that can only be partially reused. With the new method, the model can be fragmented and disassembled into parts, allowing the model to be transferred to another location.

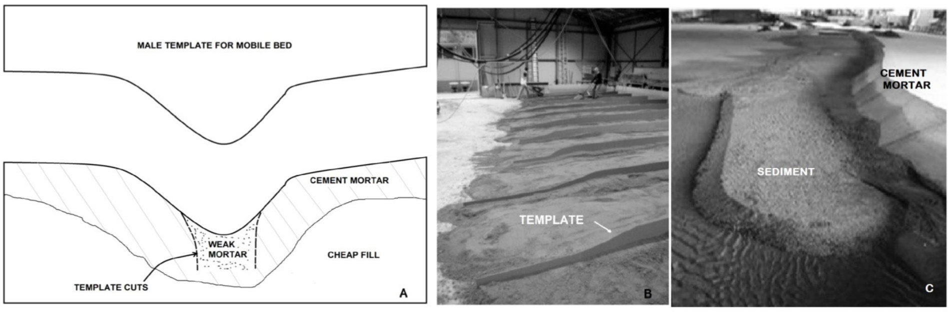

Figure 17. The construction process of the morphology in the conventional method: A) Use of templates for the construction of the model (Sharp, 1981); B) Placement of the templates (Water Research Laboratory, 2022); C) Physical model of the mobile bottom (Luo et al., 2018).

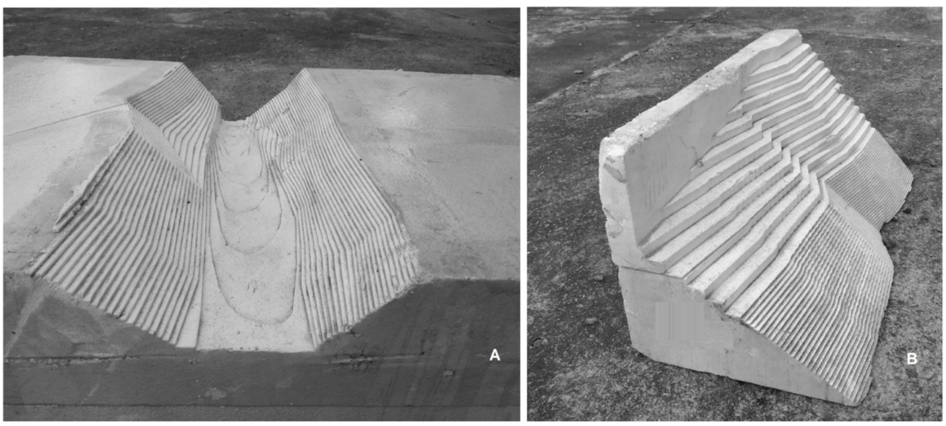

Figure 18. Types of machining Styrofoam blocks: A) Detail in the machining of the river channel; B) Variability in the machining of the steps in the same Styrofoam block piece.

Model feeding and drainage system

The models presented operate in a closed circuit with water recirculation. In this way, the waste from the tests can be collected by the drainage system and treated before being discarded, taking care not to cause environmental damage.

CONCLUSIONS

The computational modelling used to evaluate the transport of sediment and the offset regime flow along the stretch of the river upstream of the dam allowed the building of two physical models. One of them, in the section located 1000 m from the dam, served to design a distorted model aimed at the study of the process of silting the reservoir. A second model was designed, taking into account the silting zone, to study the impact of the implementation of a floodgate segment on the control of flood, protection of the water intake, and reduction of the siltation process. Regarding sediments, an innovation was carried out by using crushed tire rubber as sediment in the model. Moreover, a new method of construction technique was applied, which presented advantages over the conventional construction method: the physical fiberglass model. This model has a light structure that can be placed on a fixed or mobile metal structure.

When dealing with a distorted model, the structure can be tilted by using a mechanical or hydraulic system. The process of machining Styrofoam blocks allowed for the continuous shaping of the topography of the terrain and the morphology of the river channel, dispensing the use of moulds. The placement of fiberglass layers could be performed by a team that had no experience with physical models. The repairs can be made with fiberglass or with the use of other materials, and the model can be deconstructed into several parts to be relocated to a different environment. The use of synthetic materials, such as styrofoam and granulated tire rubber, greatly facilitates model building. The fact that it is possible to dispense with the hiring of craftsmen and civil construction personnel is an advantage that should be explored since these professionals are almost non-existent in the market. The possibility of reusing the model material and artificial sediments is also a fact that must be taken into account given current environmental limitations. The material used to make the surface of the model is light and easy to handle, dispensing with heavy transport and lifting equipment, allowing smaller teams to work quickly and efficiently, reducing the time to build the models. The limitations of using this technology are related to i) acceptance of the methodology; II) acceptance of the procedures used in building the models, and, iii) training teams to replace the current model-building technique. It is suggested that new models be built incorporating the experience gained to have a future alternative to physical modelling without the dependence on large teams and heavy equipment for its construction.

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Edna Maria de Faria Viana: Performed the methodology and revised the text and the results.

Jorge Luis Zegarra Tarqui: Performed the methodology and revised the text and the results.

Eder Daniel Teixeira: Revised the text and the results.

Mary Elma Ferreira Costa: Contributed with technical notes and revised the text.

Adriano Silva Bastos: Revised the text and the results.

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