International Symposium on Hydraulic Structures

Jan 1st, 12:10 PM

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Recommended Citation
Universidade Estadual de Campinas (2018). The Importance of Erosion Concrete Tests for Hydraulic Surfaces. Daniel Bung, Blake Tullis, 7th IAHR International Symposium on Hydraulic Structures, Aachen, Germany, 15-18 May. doi: 10.15142/T3VW7Q (978-0-692-13277-7).

ISBN: 978-0-692-13277-7 DOI: 10.15142/T3VW7Q

The Importance of Erosion Concrete Tests for Hydraulic Surfaces

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Abstract: *The population growth requires improvements in water availability for consumption, food and energy. There are many challenges to achieve this. However, in many cases, one solution resolves all needs: reserving the water for supply, irrigation of crops and energy generation. In particular, the current demand for clean energy generation has encouraged some governments to invest in the construction of new hydropower plants. This scenario results in building a dam and its appurtenances. The concept of accumulating water for human use dates back to antiquity, but it was only during the 19th century that the technological development allowed the advent of hydropower plants. Since then, ongoing efforts on this field have developed technologies and the systematic construction of dams. More recently, there has been an increasing concern regarding the safety of dams. In Brazil, the safety legislation began to operate only in 2010. Malfunctioning of dams can lead to failure and even to catastrophic consequences. When an accident occurs, not only are the costs for repairing high, but it also compromises operation and the environment. A dam failure may be related to a poor performance of the spillway. Erosion is one of the main causes of spillways failure. In this sense, it is essential to characterize the composition and resistance of the concrete to be used in the spillway. Cavitation and water solid mixture are among the main causes of erosion that put spillways into risk. Cavitation is the formation of bubbles within the liquid, if the vapor pressure is reached. Once the pressure rises, the bubbles implode and eventually cause damage, noise, vibration and pressure fluctuation. Water solid mixture causes erosion by the impact of particles. The particles are carried in the flow, and it is especially important, because the damage is irreversible and progressive. The objective of this paper is to show the importance of testing concrete samples to erosion before using them in prototype. The concrete samples are submitted to erosion due to cavitation and water-solid mixture. The tests were performed at the Laboratory of Hydraulics and Fluid Mechanics at Unicamp, Brazil. The method for evaluating cavitation erosion resistance is based on the use of a high velocity cavitating jet. The other method, for evaluating water solid mixture erosion resistance, is based on the use of a mixing tank, where an impeller propels solid particles in the water over the sample. In both cases, the erosion resistance is associated with the mass loss of the sample through time. The results highlight the erosion that can occur in prototypes and the importance of testing concretes before construction or repairing of concrete spillways.*

Keywords: *Erosion, cavitation, water-solid, experimental study, dam safety.*

1. Introduction

Hydropower is globally the main renewable source of electricity generation and, according to the Water Energy Council (2016), hydroelectric plants provide 71% of all renewable energy. In 2016, among all sources, hydroelectricity accounted for 16.4% of the world's total energy generation. The Water Energy Council report (2016) further indicates that total installed capacity has grown by 39% from 2005 to 2015, focusing on emerging markets, where the creation of hydroelectric plants makes water supply services available, among others.

Brazil has great water potential and the largest part of the country's energy depends on a good performance of hydroelectric plants. Currently, despite the investment in new energy sources, such as wind and solar, hydroelectricity accounts for 69.8% (Ministry of Mines and Energy 2016) of the energy used in the country. However, Legislation regulating the construction and maintenance of dams in Brazil is quite recent (Brazil 2010). For example, in the sixth volume of the Entrepreneur's Manual on Dam Safety, in "Guidelines for the Construction of Dams" (2016), no tests are required to characterize the erosion of the hydraulic concrete surfaces of a dam. Thus, one loses the opportunity to adopt criteria to avoid serious damage to the structure. The damage caused to a surface in a hydraulic structure, in most cases, has irreversible consequences, or high costs for repair, leading to the need of investigation of the erosive effects that will act in the hydraulic structures.

Hydroelectric plants have discharge structures, such as spillways and dissipation basins, where water flows and eventually carries a large quantity of solids (Branco et al. 2017). Another issue is the high velocity flow that can lead to the onset of cavitation, depending on the pressure of the flow. Thus, one of the susceptibilities of these structures is the erosion of the surface. This is a major problem since repair costs in a functioning hydraulic structure are very high and dam operation may be compromised during maintenance periods. It is essential to characterize correctly the composition and, in addition, the resistance of the concrete to be adopted in the hydraulic surfaces.

Tatro (2007) presents a series of hydraulic structures that have suffered erosion. In the report, it is clear that 55.7% of the cases were eroded by the action of the water-solid mixture, 25.3% by a combined action of the water-solid mixture and cavitation, 15.2% by cavitation, 1.3% by chemical attacks.

Erosion by mixing solid water is one of the main problems in hydraulic systems with transport of fluids and solid particles. This process can be understood as the progressive disintegration of the material caused by solids, sand, gravel, ice or debris carried by water (Graham 2007). According to Liu et al. (2006), the loss of mass caused by abrasive erosion in hydraulic concrete is a three-stage process. Initially, the water pressure causes a peeling of the concrete surface. Subsequently, the impacts of the solids transported along with the water result in the removal of the mortar and, subsequently, exposure of the large aggregates. Finally, the continuity of this cycle leads to the deepening of erosion. Tatro (2007) shows that hydraulic structures, although withstand the wear and tear caused by the mixing of solid water, are generally not prepared for events in which larger quantities of solids are carried, something common in the present scenario of intense use changes of the watersheds.

Among the methods used to study the resistance of concretes subjected to water-solid erosion, the submerged method, ASTM C1138M (2012) consists of a cylindrical tank, filled with water, at the bottom of which a concrete sample is placed. A rotor with vertical blades keeps the water-solid mixture in rotation by means of a motor. The solid part consists of 70 steel balls of nominal size between 12.6 and 25.3 mm, responsible for eroding the concrete surface. In literature, several authors have used similar methods to investigate the relative resistance of different concretes under erosive action such as Dalfré Filho et al. (2000), Horszczaruk, (2005, 2008, 2009), Kumar and Sharma (2014), Mohebi, Behfarnia and Shojaei (2014), among others. In particular, a modified version of the submerged method was developed to model real field conditions, by substituting the sphere balls by sand. Preliminary single phase simulations (Malavasi et al. 2013) allowed verifying the effectiveness of the new equipment; later, a prototype was built at the Laboratory of Hydraulics and Fluid Mechanics, School of Civil Engineering, Architecture and Urbanism (Unicamp). Later on, Messa et al. 2017 confirmed the effectiveness of this approach after confronting the experiments with initial CFD analyses.

In hydraulic systems, the cavitation effects are almost always harmful. Five basic problems exist created by the cavitation phenomenon that are the noise, the vibrations, the pressure fluctuations, the erosion and the efficiency loss. Cavitation is, among the possible causes of erosion in hydraulic structures, the most destructive. As high velocity flow passes over a solid boundary damages may occur. Several factors determine whether the surface will be eroded including the intensity, the location of the damage, the flow velocity magnitude, the air content of the water, the surface resistance and the length of time the structure is exposed to the phenomenon (Falvey, 1990).

Erosion by cavitation can initiate from the inadequate finish of the surfaces or from the presence of structural elements, such as chute blocks. Moreover, cavitation can be formed when there are offsets, transverse grooves or protruding joints resulted from inadequate concrete work (Dalfré Filho et al. 2006). An alternative test for concrete erosion evaluation uses water cavitating jet technology (Conn et al. 1984; Cheng et al. 1990; Dalfré Filho et al. 2006; Dalfré Filho and Genovez 2008, 2009). The cavitating jet apparatus uses a nozzle specially designed to produce cavitation, combining high-velocity flows and cavitation (appropriate cavitation index), as ordinarily present in hydraulic structures.

Each type of erosion process has different origins, function principles, thus different consequences. The main sources of cavitation erosion are the wave shocks with pressure magnitude above 69 MPa and micro jets with speed above 100 m/s (Tullis 1989; Knapp et al. 1970) which are generated during the bubbles implosion. Once erosion by cavitation occurs, after bubbles collapse perpendicularly to the concrete surface, it becomes rough. Meanwhile, erosion by water-solid mixture occurs due to particles impact, being the angle between surface and particle direction smaller than 90º, causing smooth surfaces (Malavasi et al. 2013). The scale of damage for each type of erosion is also distinct. Cavitation causes severe damage in the short term due to the magnitude of forces, while the erosion impact of particles becomes severe in the long term. In both cases, the tendency is to withdraw the aggregates from the cement mortar.

According to the characteristics of the erosion in a brittle material, such as concrete, only through experimental studies the damage can be evaluated and recorded, as well as determining correlation parameters between the severity of erosion and flow conditions. Thus, it is essential to characterize the composition and resistance of the concrete to be used in a spillway or in a stilling basin. The objective of this work is to highlight the need of further development in the dam safety area, in refer to the erosion in hydraulic surfaces, especially when submitted to the water-solid mixture erosion

2. Material and Methods

The water solid mixture equipment and the cavitating jet equipment are installed in the Laboratory of Hydraulics and Fluid Mechanics at the School of Civil Engineering, Architecture and Urbanism at University of Campinas (Unicamp), Brazil.

2.1. Water-solid Erosion Tests

The equipment for water-solid erosion tests is displayed in Figure 1. A 370 W motor power (WEG-Brazil, W22 model) is connected to an impeller specially designed to rotate (900 rpm) the water-solid mixture above the concrete sample, causing the surface erosion, inside an acrylic tank. The tank is provided with 4 radially disposed acrylic baffles. The baffles guarantee stability to the samples and increase turbulence, causing the samples to be eroded faster (Malavasi et al. 2013; Messa et al. 2017). The distance between the impeller and the sample surface is named clearance, *c* and kept constant at 0.056 m. The impeller has four inclined rods, on a 45º angle to produce the impact of the solids. Righini (2014) investigated tests with different impeller speeds and clearances to study the pressure distribution in the bottom of the tank. Messa et al., 2017 determined both rotational speed and clearance after previous experiments with low resistance concrete, in short time tests.

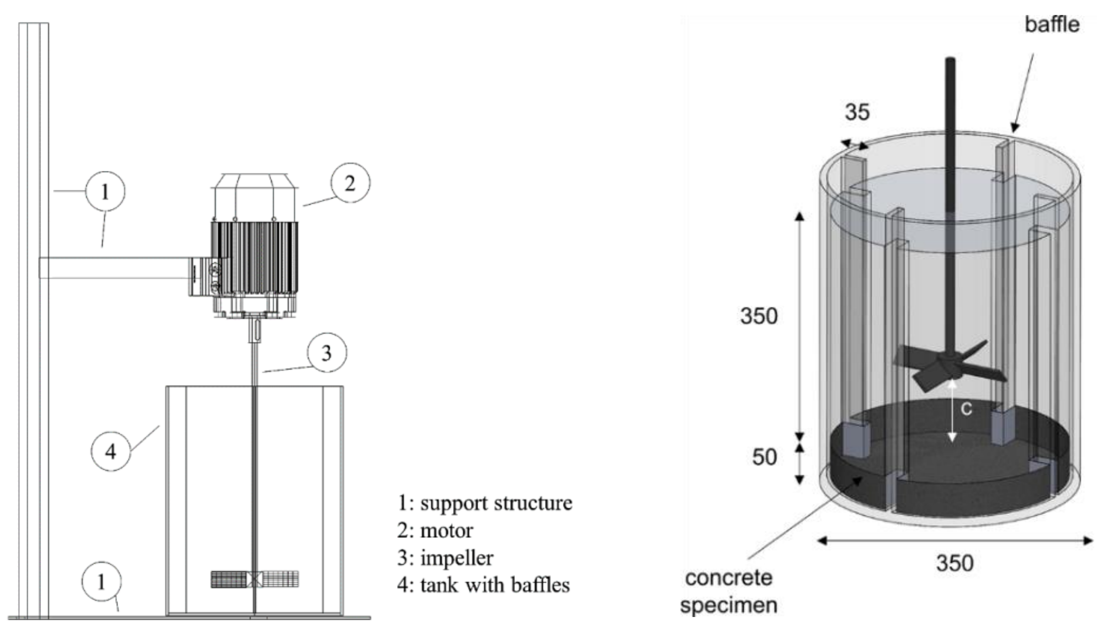

Figure 1. Equipment for water-solid erosion tests (measures in mm)

2.2. Cavitation Erosion Tests

The equipment for cavitation erosion tests is displayed in Figure 2. A 9,200 W motor power is coupled to a positive displacement pump (PROMINAS, Brazil, model BPS-327-025-MP), set at pressure 15.00 MPa. A pipe connected to the pump has a specially designed nozzle (see Figure 2, being D equal to 0.0015 m) in its end and it is located inside the reservoir of (Φ) 0.680 m and (h) 0.740 m. The test pressure was recorded by an absolute pressure transducer with a range of 0.00 to 20.00 MPa (HBM, Germany, model K-P8AP-231B-17A5), placed upstream the nozzle. During the tests, the cavitation index σ (Eq. 1) was kept constant.

$$\sigma = \frac{p_0 - p_v}{pv_0^2/_2} \tag{1}$$

where p_0 is the set pressure, p_v is the vapor pressure and v_0 is the velocity of the jet flow. The water inside the tank is at 24°C. Considering p_0 equal to 15.0 MPa, v_0 equal to 175 m/s, a σ of 0.14 was then obtained. The equipment setup was determined in previous studies (Dalfré Filho 2005; Dalfré Filho and Genovez 2008, 2009), by performing several tests in aluminum and concrete samples, adjusting nozzle geometries, pressure tests, jet speeds and clearances.

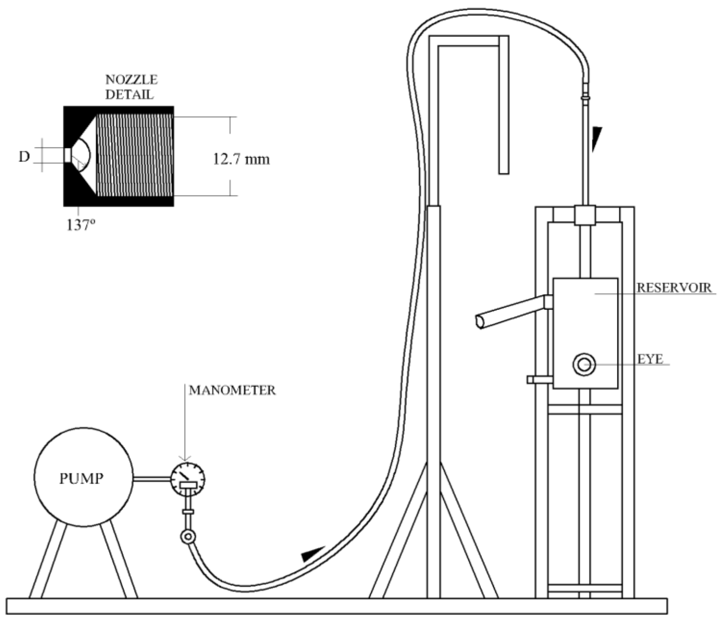

Figure 2. Equipment for cavitation erosion tests (measures in mm)

2.3. Test Procedures

The tests occurred in steps. In step 1, concrete samples were tested to evaluate water-solid erosion (sample dimensions of (Φ) 0.325 m x (h) 0.050 m and in step 2, concrete samples were tested to evaluate cavitation erosion with dimensions of (Φ) 0.180 m x (h) 0.040 m). For each test step, three concrete samples were used. Five additional compressive resistance samples, dimensions (Φ) 0.100 m x (h) 0.200 m, were also prepared to determine compressive resistance and modulus of elasticity in 28 days. All samples were made at once, that is, using the same concrete recipe. In this sense, compressive resistance and modulus of elasticity of the samples were kept constant during the study. The samples were prepared according to the Brazilian procedure NBR 5738 (2003) at the Laboratory of Structures, School of Civil Engineering, Architecture and Urbanism, Unicamp. Erosion was characterized by loss of sample mass over time.

For the water-solid erosion, the samples were positioned at the bottom of the tank and the tank was filled with the water-solid mixture at four-time tests: 6, 12, 24 and 36 hours. At each time test, the sample was removed from the equipment, weighed in the dry saturated condition and photographed. First, the concrete sample is weighted using a mass balance (Toledo, model PRIX III Fit, range 0.050-15.000 kg, accuracy of 0.005 kg) and its initial mass is recorded. Sequentially, the sample is positioned again at the bottom of the tank and the gap between the sample and the tank wall is filled with sealant material. Clean water is poured into the tank up to a static level of 0.350 m above the sample and the solid phase is added. After positioning the impeller-shaft motor assembly at the desired clearance, the motor is turned on and the rotational velocity is adjusted. At all the time tests, the water-solid mixture is replaced to avoid self-enhancement of the erosion process. The abradant (solid phase of the fluid) used in the initial tests consists of 0.950 kg of silica sand particles with density equal to 2650 kg/m³ and size within 0.0012 m and 0.002 m, yielding a static solid volume fraction of 1%. The carrier fluid is water at 20°C.

For the cavitation erosion, the samples were positioned at the bottom of the tank which was then filled with clean water, at three-time tests: 1, 5 and 10 minutes. At each time test, the sample was removed from the equipment, weighted in the dry saturated condition and photographed. The concrete sample was weighted using a mass balance (Toledo, model PRIX III Fit, range 0.050-15.000 kg, and accuracy of 0.005 kg) and its initial mass was recorded. Sequentially, the sample was positioned again at the bottom of the tank. Clean water is poured into the tank up to a static level of 0.30 m. After positioning the nozzle, being c kept constant at 0.050 m, the pump was turned on and the pressure test is set at 15.00 MPa.

Horszczaruk (2005) to estimate the temporal evolution of concrete erosion used the power law in Eq. 2 and it was also used in this work.

$$\frac{\Delta M}{M_0} = 1 - \left(\frac{a}{a+t}\right)^{-b} \tag{2}$$

where ΔM is the mass loss, M_0 is the initial mass of the sample, both measured in kilograms; t is the test time in hours; a [h] and b [-] are coefficients, obtained by curve fitting of experimental data. For a clearer analysis of the results, one can derive the relative mass loss (ΔM) in time, as it is in Eq. 3.

$$\dot{E}_{r_0,exp} = \left.\frac{d(\Delta M)}{dt}\right|_{t=0} = \left.\frac{d\left\{M_0\left[1-(1+t/a)^{-b}\right]\right\}}{dt}\right|_{t=0} = M_0 b\left(1+\frac{t}{a}\right)^{-b-1}\left.\frac{1}{a}\right|_{t=0} = M_0\frac{b}{a} \tag{3}$$

where $\dot{E}_{r0,exp}$ is the mass flux of the erosion in grams per hour; the numerical coefficients, a and b, have been determined by curve fitting of experimental data, a is given in grams per hour and b is dimensionless; M_0 is the initial mass of the samples.

The mass flux of the erosion is an important parameter to compare erosion resistance of different materials submitted to the tests. Literature (Hozazuk 2005; Kryžanowski et al. 2009; Kumar and Sharma 2014; Mohebi et al. 2014; Messa et al. 2017) shows that mass loss erosion is not linear over time. However, at the beginning of the tests, the erosion loss can be considered linear, although, as time increases, mass loss becomes gradually smaller. Eq. 3 was constructed for time t tending to zero, representing the erosion at its initial phase to allow comparison among different materials.

3. Results and Discussion

The tests were carried out according to the procedures described in Section 2. Concrete compressive resistance and modulus of elasticity were used to define the samples that were later submitted to the erosion and cavitation erosion tests. The result is showed as the average of the individual samples. The compressive resistance in 28 days is equal to 30.00 MPa and the modulus of elasticity is 3.17 MPa.

The mass loss in elapsed time caused by water-solid mixture erosion, and by cavitation erosion was obtained from Eq. 2 and the results are presented in Figures 3 and 4, respectively. The erosion mass loss ($\dot{E}$) is obtained by applying the factors a and b in Eq. 2. These factors were determined by adjusting the curve of Eq. 2 to the experimental values, for each erosion test methodology.

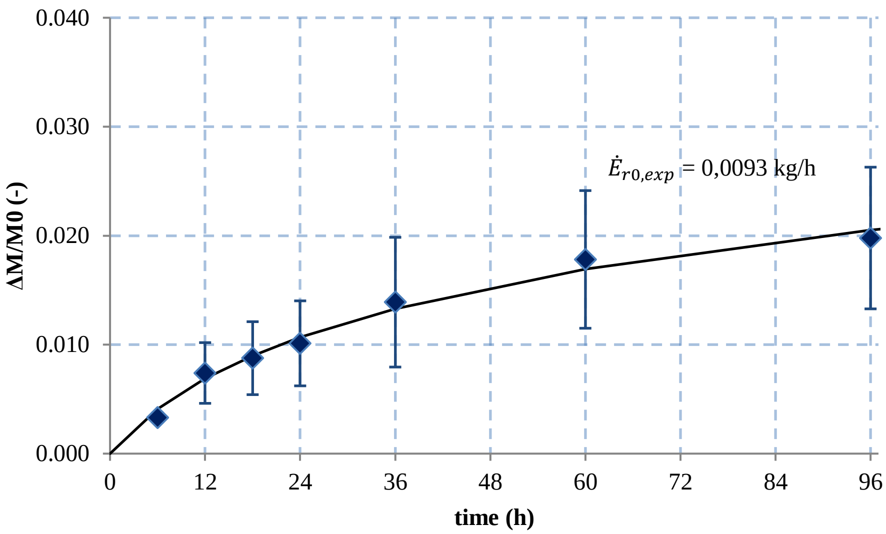

Figure 3. Mass loss in elapsed time for water-solid mixture erosion test

Figure 3 shows a decrease in the rate of concrete mass loss over time, in particular a flattening of the erosion rate curve. This may occur due to the changes in the surface of the sample over time. At the beginning of the erosion, a lot of cement mortar is withdrawn to the impact of solids and the surface becomes more heterogeneous. This phenomenon occurs by degrading the bond between mortar and aggregates. As long as cement mortar is available, erosion continues and is a concern, although in a lesser rate than the initial times.

For the case of erosion by water-solid mixture presented in Figure 3, by adjusting Eq. 2, we obtain the curve described by Eq. 4.

$$\frac{\Delta M}{M_0} = 1 - [\frac{10.242}{10.242+t}]^{0.009} \tag{4}$$

In this sense, the mass flux for the erosion (Eq. 3) by water-solid mixture assumes the value of 0.0093 kg/h, once the values *a* (10.242 h), *b* (0.009) and M_0 (11.040 kg) were obtained. Figure 5 shows visually the development of the erosion in time tests. The smoothed surface is observed in the samples and the progressive, accumulated erosion process is evident.

For the case of erosion by water-solid mixture presented in Figure 4, by adjusting Eq. 2, we obtain the curve described by Eq. 5.

$$\frac{\Delta M}{M_0} = 1 - [\frac{28.672}{28.672+t}]^{4.654} \tag{5}$$

Accordingly, the mass flux for the erosion (Eq. 3) by cavitation assumes the value of 0.3851 kg/h, once the values *a* (28.672 h), *b* (4.654) and M_0 (2.373 kg) were obtained. Figure 6 visually shows the development of the erosion in time tests. As cavitation damage sources occur perpendicularly to the surface. This effect has an impact on the texture of the surface, producing a grainy texture (Figure 6) and the direction of the flow cannot be detected.

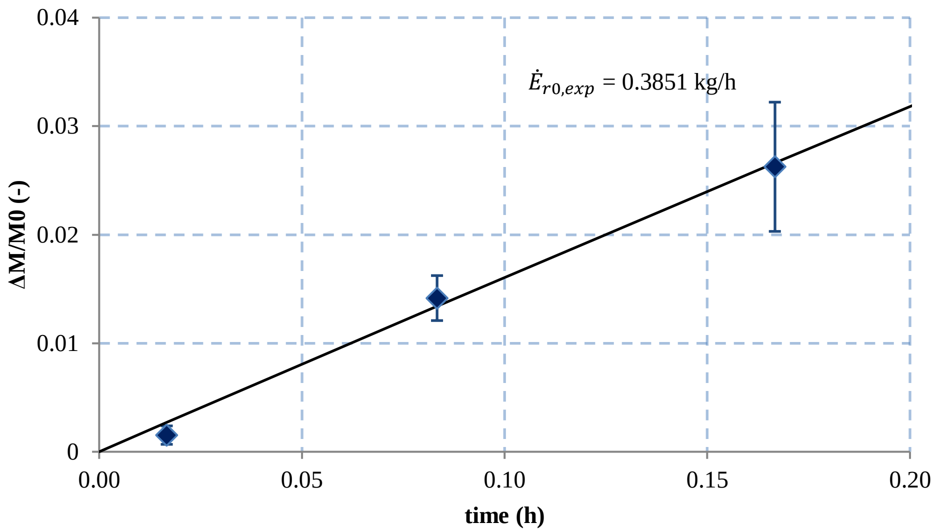

Figure 4. Mass loss in elapsed time for cavitation erosion test

Comparing Figures 5 and 6, each process of degradation is evident. While erosion by cavitation is a process of high intensity and short duration, erosion by the impact of particles carried by water is a slow one, long duration, gradually reducing the service life of the structure, often without being clearly a threat to the dam safety.

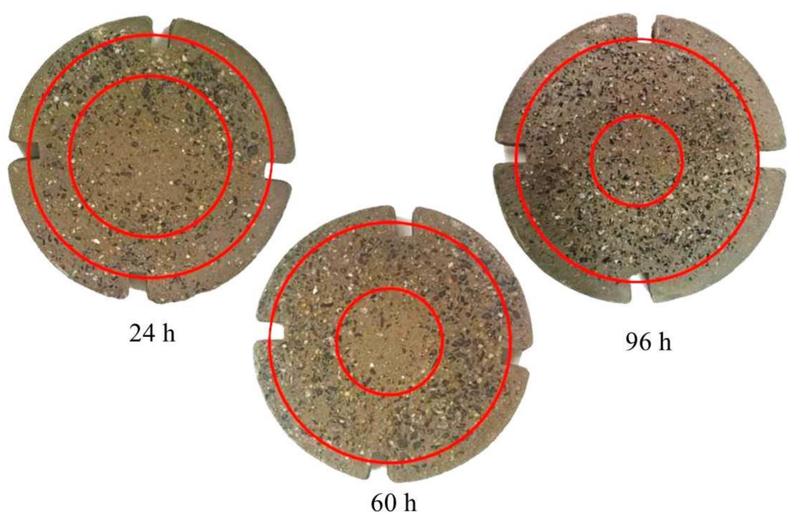

Figure 5. Surface erosion in time tests

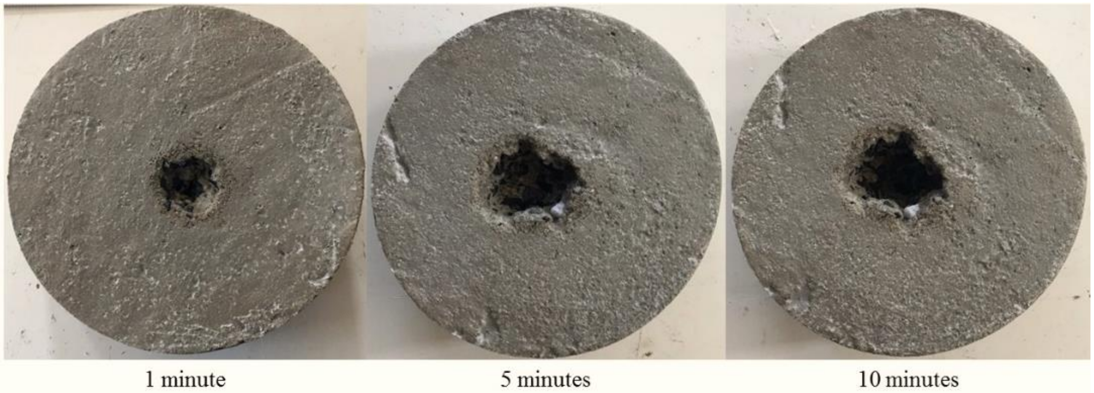

Figure 6. Samples after determined time under erosion by cavitation test

For the water-solid erosion, with the equipment running at 900 rpm, clearance of 0.056 m, the mass loss flow is $\dot{E}$ = 0.0093 kg/h. For the cavitation erosion, with the equipment at a cavitation index, $\sigma = 0.14$, the mass loss flow is $\dot{E}$ = 0.3851 kg/h. To further investigate the mass loss and the influence of time, Eq. 6 was derived from Eq. 2, for $\Delta M < M_0$.

$$t = \frac{a}{\sqrt[b]{1} - \sqrt[b]{\left(\frac{\Delta M}{M_0}\right)}} - a \tag{6}$$

From Eq. 6, by applying the respective factors, it is possible to obtain the total time in which a sample would suffer complete degradation, either by water-solid mixture or by cavitation. Considering a deterioration of 99% of the initial mass, the total water-solid erosion time of 113883.6 hours is obtained, while for cavitation, only 367.3 hours were obtained for the samples tested here. By comparing degradation times, it is noticed that cavitation degradation of the samples occurs about 300 times faster than for water solid degradation. However, considering that both processes can occur at the same time, self-enhancing the erosion, the complete degradation would occur in less time.

4. Conclusions

Spillways and stilling basins are essential structures to guarantee the dam safety, as they discharge the overflows. The malfunction of these structures, whether due to an error in operation or lack of maintenance, can cause accidents, which can even lead to the dam break. One of the causes of the failure of these structures is the malfunction due to the concrete erosion. Among the possible causes of erosion, two of them can be highlighted, cavitation erosion and water solid mixture erosion.

Among the criteria to classify a dam in a category of risk lies with the reliability of the spillways and stilling basins, which must have no obstructions or erosion. But, the evaluation of the structure has been made only through visual periodic inspection. Considering the state of the art, there should be defined criteria to avoid erosion process based on the quality of the water and the concrete composition, besides the typical hydraulic and hydrological parameters.

The results presented in section 3 confirm that cavitation is the most detrimental erosion process. Nevertheless, this may lead to the idea that the erosion caused by water-solid mixture could be negligible. Cavitation itself may origin high pressures and cracks around individual pieces of aggregate, swept away by the flow, initiating erosion by the impact of solids. As erosion from high velocity flow continues, reinforcing bars may be exposed. Bars may begin to vibrate, which can lead to mechanical damage of the surface. Both phenomena are serious, but each has its specific physical processes, its consequences, footprints and scales in time and space are also different, but these differences do not make any of them less important. Cavitation brings almost instantaneous consequences, but it has been already well studied and has many tools to reduce its occurrence, such as aeration of the flow. Erosion by the impact of solids causes serious damage usually in the long term, but as the hydraulic structures built in the past show signs of detriment, solutions must be taken to avoid dam safety issues. Nevertheless, both processes can occur in concomitance, enhancing the erosion damage.

Further developments in this work may lead to suggestions to the Dam Safety Legislators to include the necessity of standardized erosion tests for concrete to be used in hydraulic surfaces of spillways and stilling basins. This could certify minimum conditions to guarantee a long term well-functioning of a hydraulic structure. The next steps will include testing different concrete compositions, also varying different rotation speeds, solids concentrations and types, as they depend on the basin characteristics where a structure is built.

5. Acknowledgements

We would like to thank for the support provided by FAPESP (São Paulo Research Foundation, Brazil) under the grants number 2000/03611-0, 2002/10348-0 e 2012/09843-8, essential to the development of this research, and also the support provided by CAPES (Coordination of Superior Level Staff Improvement) and school of Civil Engineering, Architecture and Urban Planning – Unicamp, under the 01-P-01879-2016. At last, we would also like to thank Gianandrea Vittorio Messa, researcher from Politecnico di Milano for his support under the mathematical approach.

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