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APPLICATIONS OF THE PARTICLE FINITE ELEMENT METHOD IN DAM ENGINEERING

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Summary. The paper presents the results of the application of the Particle Finite Element Method (PFEM) to the analysis of some of the more complex phenomena related to dam hydraulics: shock waves in spillways, aeration in bottom outlets, and erosion in the downstream river bed. Furthermore, the method has been applied to the study of the consequences of landslides in reservoirs: the wave generation, its propagation, and the affection to the dam.

1 INTRODUCTION

In the recent years, a great effort has been made in the International Center for Numerical Methods in Engineering in the development and implementation of the Particle Finite Element Method [1]. As a result, its application to a wide number of engineering problems is possible, such as fluid dynamics, fluid-structure-interaction, and erosion, among others [2]. CIMNE-Madrid group focuses in research into the field of dam safety, and has taken advantage of PFEM capabilities to analyze some of these phenomena. The paper briefly describes four examples of the application of PFEM to different problems related to dam hydraulics and dam safety: a) shock waves in spillways, b) aeration in bottom outlets, c) erosion, and d) landslides in reservoirs.

In our days, the most frequently used methodology for designing a hydraulic structure follows four steps: a) preliminary design based in experience and experimentally based manuals, b) laboratory tests campaign of this design to check its performance, c) modifications to the original design on the basis of the results of the tests, and d) construction of the final design.

Different numerical tools, some of them commercially available, have shown their capability to model most of the hydraulic problems to be considered in dams. Some of them use Eulerian formulations, and some others use a fully Lagrangian approach.

In spite of that, numerical modeling is rarely used in this process, unlike other kind of calculations, such as structural design, where numerical methods have displaced experimental tests almost completely.

Furthermore, there are still several challenges to be solved in the field of dam hydraulics. Some of the most relevant are related to the consideration of air-water interaction in bottom outlets and spillway chutes. This topic is very hard to analyze through physical testing due to scale effects and reliability of data acquisition, although it is of great importance in most structures subjected to supercritical flows. Numerical modeling seems to be an appropriate tool to assess this problem.

PFEM uses a Lagrangian approach combined with the resolution of the equations via the Finite Element Method (FEM). In order to do that, a finite element mesh has to be generated, which is typically updated every time step. With this strategy, the convection of the nodes can be reproduced accurately, while imposing Dirichlet conditions in a natural way. A detailed description of the method is not the objective of the paper, but the reader can find it in [1, 2] PFEM has been validated to reproduce some of the above mentioned hydraulic problems [3].

2 SHOCK WAVES IN SPILLWAY CHUTES: ITOIZ DAM CASE STUDY

PFEM has proven to be appropriate for the simulation of hydraulic problems in which the free surface is irregular, and greatly changes in shape during the transient solution. There are several examples in the literature, some of which have been used as benchmark problems, such as the typical dambreak example. The previous results [3] suggest that PFEM could be a useful tool in the hydraulic calculation of spillway chutes in which shock waves are expected.

Itoiz Dam is one of the most popular and recent structures constructed in Spain having a converging chute in its service spillway due to the lack of space in the downstream toe of the dam. The chute width varies from 53.75 m in the crest to 22.70 m at the entrance of the stilling basin. Figure 1a shows a picture of the dam, while figure 1b contains a view of the geometry of the numerical model. Some of the most relevant features of the spillway are included in Table 1.

Table 1: Characteristics of Itoiz Dam spillway

Maximum dam height	128 m
Spillway crest	4 bays; 12.50 m each
Design flood (10,000 years return period)	565 m^3/s

A pre-design of the spillway was developed before the construction, whose performance was tested in laboratory. The results showed that two shock waves appeared next to the walls, which became wider in the downstream direction, until they collided. They caused inadequate flow distribution at the end of the chute, with flow accumulation in the centre of the channel which penetrated in the stilling basin like a dart, favoring agitation in the latter. The inclination of the chute walls caused the overspill of a part of the flow.

On the basis of the results of these tests, the design was modified, so as to reduce the shock waves, as well as to improve the efficiency of the stilling basin. The curves which defined the chute walls were smoothed, and the length of the stilling basin was increased.

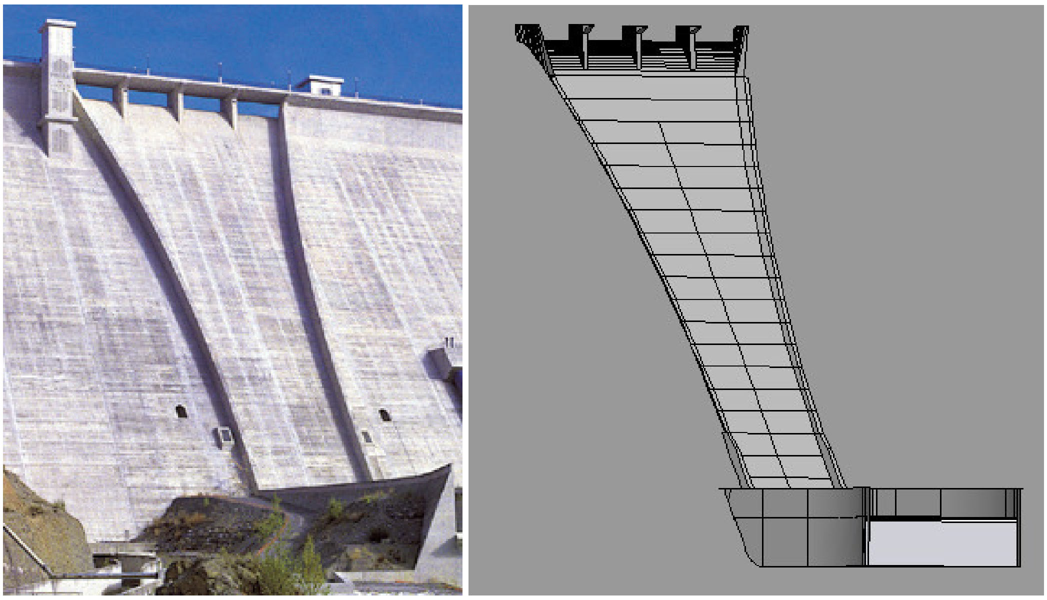

Figure 1: Itoiz Dam spillway. Left: downstream photo of the actual dam. Right: numerical model

The convergence of the chute walls still generated two shock waves next to the walls, but the flow distribution at the entrance of the stilling basin was more uniform. Overspill was avoided. The global behavior of the stilling basin was acceptable, with lower velocities at the entrance, and better energy dissipation.

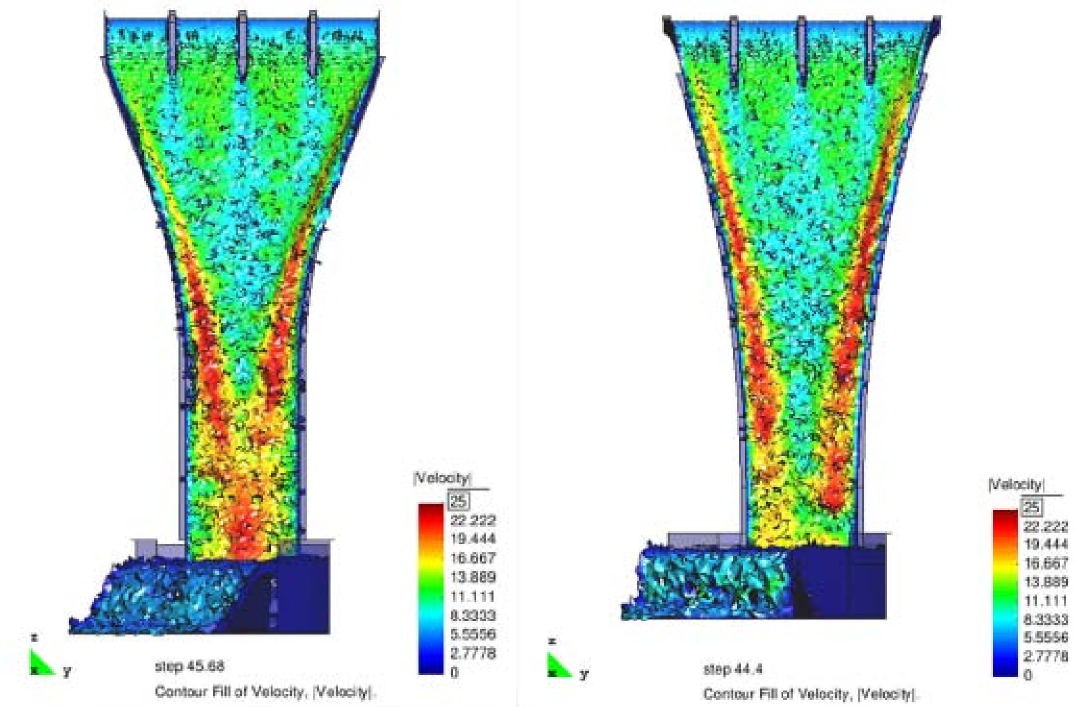

Figure 2: Itoiz Dam spillway. Left: original geometry. Shock waves collide at the end of the chute. Right: Final design. The shock waves remain, but they don't meet, thus flow distribution is better at the toe.

The aim of the numerical model was to reproduce the results of the laboratory tests, both for the original and final geometries. Figure 2 shows snapshots of the results of the numerical modeling, both for the original (left) and final (right) designs. Note that the above mentioned features of the spillway performance are reproduced.

3 AERATION IN BOTTOM OUTLETS

Bottom outlets are key elements to control the water surface elevation in reservoirs. Since the early twentieth century it has been found that an aeration system is necessary in the downstream side of the gate to achieve an appropriate performance of the structure. The system is typically placed downstream of the sealing device to prevent consequences due to the appearance of negative pressures. Otherwise, damages caused by cavitation and vibration are relatively frequent.

Due to the great difficulty to collect data or to study the phenomenon either in situ or in full scaled experimental facilities, the analysis has traditionally been carried out via laboratory tests in small-scale physical models. The results of these works have been used to develop empirical formulations for the calculation of the design air flow of the aeration system. Many authors have carried out this kind of studies, being the most commonly used the ones by Sharma [4], USACE [5] and Campell and Guyton [6]. However, the results of the different authors are divergent. Most of them analyze the situation in which a hydraulic jump is formed in the downstream conduit, but little information is available about free flow. Finally, most of them were developed from tests on rectangular conduits, which were the most popular in the last century. The design of the aeration system for a circular conduit (much more common nowadays) is usually made by means of the extrapolation of those criteria to the circular section. The great number of involved parameters and their wide variation make this methodology have its limitations.

In our work, PFEM has been used to assess this problem, in which the treatment of the interaction and mixing of two fluids (air and water) with very different physical characteristics is the greatest difficulty to be overcome.

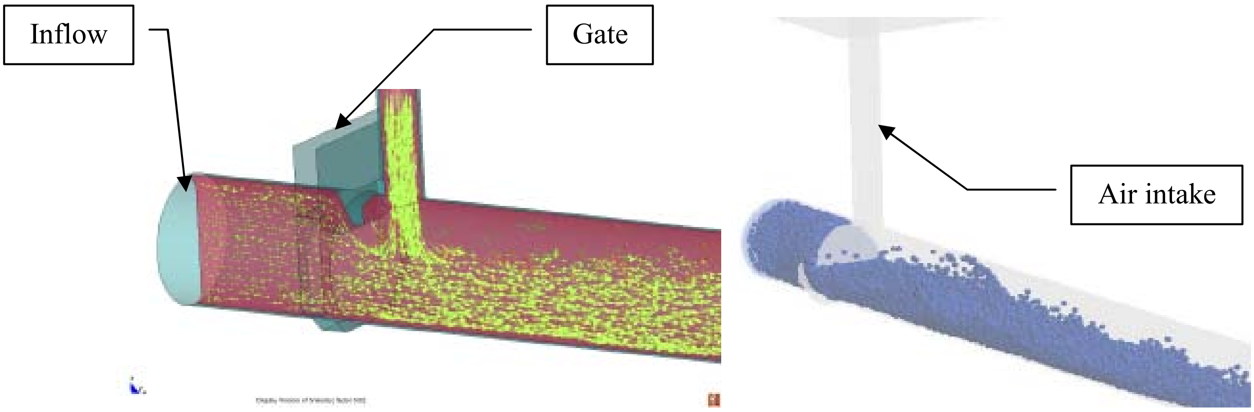

Figure 4: Two snapshots of one of the runs. Left: Vectors representing velocities on a longitudinal section, where it can be seen the air flow into the conduit. Right: Particles (nodes of the mesh) of the fluid layer (air layer has been turned off).

The method is being applied to verify the performance of the new flat-seat circular-section valves, whose design is being developed by the Sapanish company INHISA as an alternative to the traditional Bureau-Type. This work is being undertaken in the frame of VADIVAP project.

PFEM has turned out to be able to reproduce the velocity field both for the air and the water downstream the gate, as well as the interaction between both fluids. Figure 4 shows a snapshot of one of the calculations, in which it can be seen the air flowing through the air vent into the outlet.

Despite the air flow is the key variable, most of the authors have expressed their results in terms of the relation between β and the water Froude number, being β the ratio Q_a / Q_w, where Q_a is the air flow and Q_w the water flow.

Figure 5 shows the results obtained with PFEM, compared with those given by the experimental campaign and formulation developed by Sharma [4], which is the most commonly used. The latter represents a line joining the maximum air flow for every value of the Froude number. Note that the results of the laboratory experiments show an important dispersion from that line.

The numerical tests cover a small portion of the experimental campaign in free flow conditions, but the maximum values of β match Sharma's law as can be noted in figure 5.

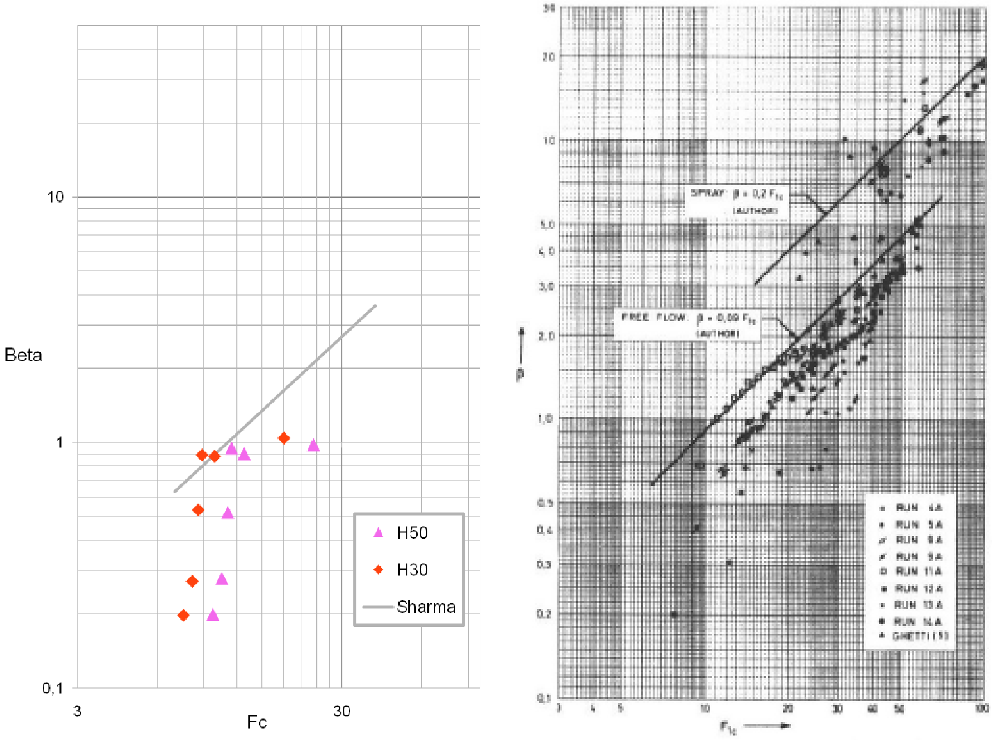

Figure 5: Left: numerical results for 30 m (diamonds) and 50 m (triangles) of upstream water pressure, in comparison with the expression by Sharma (line). Right: Original chart by Sharma, where it can be seen that his expression covers the maximums, as well as the dispersion of his results.

Once the model has been validated in that way, it is being used to run numerical tests to obtain conclusions about the design of the aeration system and to analyze the influence of every parameter in the air flow. It has been found that there are several variables which greatly affect the phenomenon, such as: a) shape of the conduit, b) diameter and length of the air intake, c) gate opening, d) upstream pressure, e) length of the conduit downstream of the gate, and f) hydraulic conditions in the downstream side (free flow/submerged flow) g) distance between gate and aeration conduit. The high number of involved parameters explains the difficulty of applying empirical formulation.

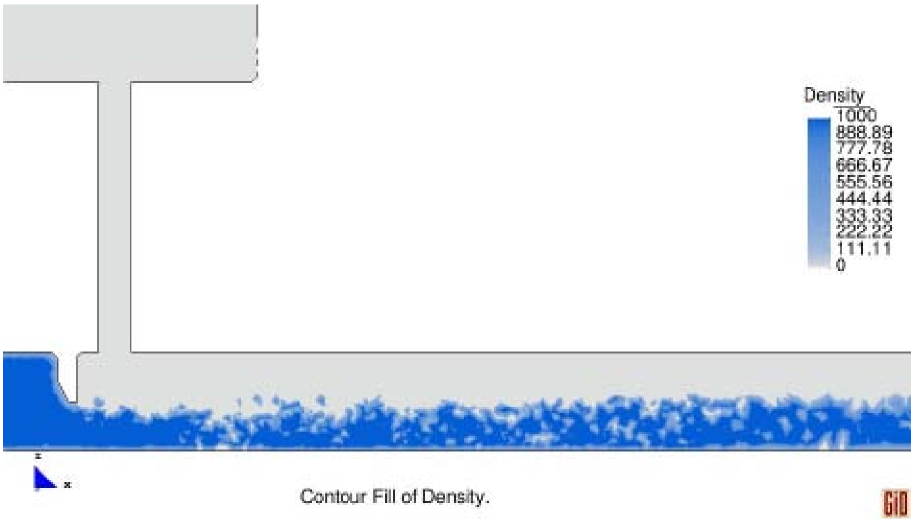

Figure 6: Mixture of air (grey) and water (blue) in the conduit (longitudinal cross section).

3 EROSION

Erosion is another important concern in spillways, especially in tailwater pool technology, as well as in other many fields of engineering, particularly in river hydraulics. A formulation for erosion analysis has been implemented in PFEM [7].

The erosion model is based on the frictional work at the surface originated by the shear stress in the fluid. The resulting erosion model resembles Archard law [8, 9] typically used for modeling abrasive wear in surfaces under frictional contact conditions. The algorithm for modeling erosion at the fluid bed can be summarized as follows:

1. Computation of the resultant tangential stress induced by the fluid motion in every point of the bed surface.
2. Computation of the frictional work originated by the tangential stress.
3. The onset of erosion at a bed point occurs when the frictional work exceeds a critical threshold value defined empirically according with the properties of the bed material.
4. When the critical threshold is exceeded, the node is detached from the bed region and it is allowed to move within the fluid flow, i.e. it becomes a fluid node (but it conserves its density).
5. Sediment deposition can be modeled by an inverse process. Hence, a suspended node adjacent to the bed surface is assigned to the bed domain when its velocity decreases below a threshold value.

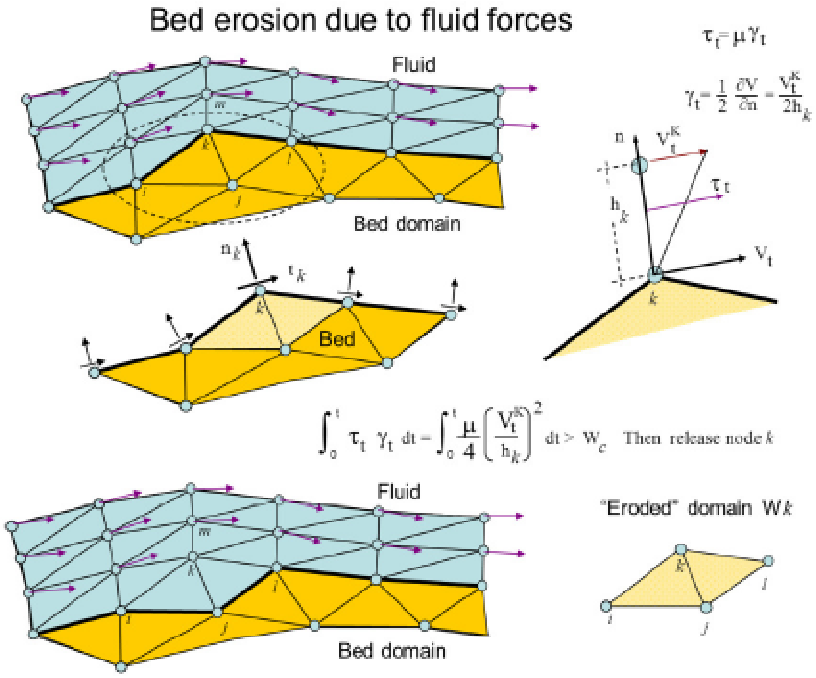

Figure 6: Modeling of bed erosion with the PFEM

Figure 7 shows some images of the application of PFEM to the study of erosion downstream the sky jump spillway of Barriga Dam (Spain).

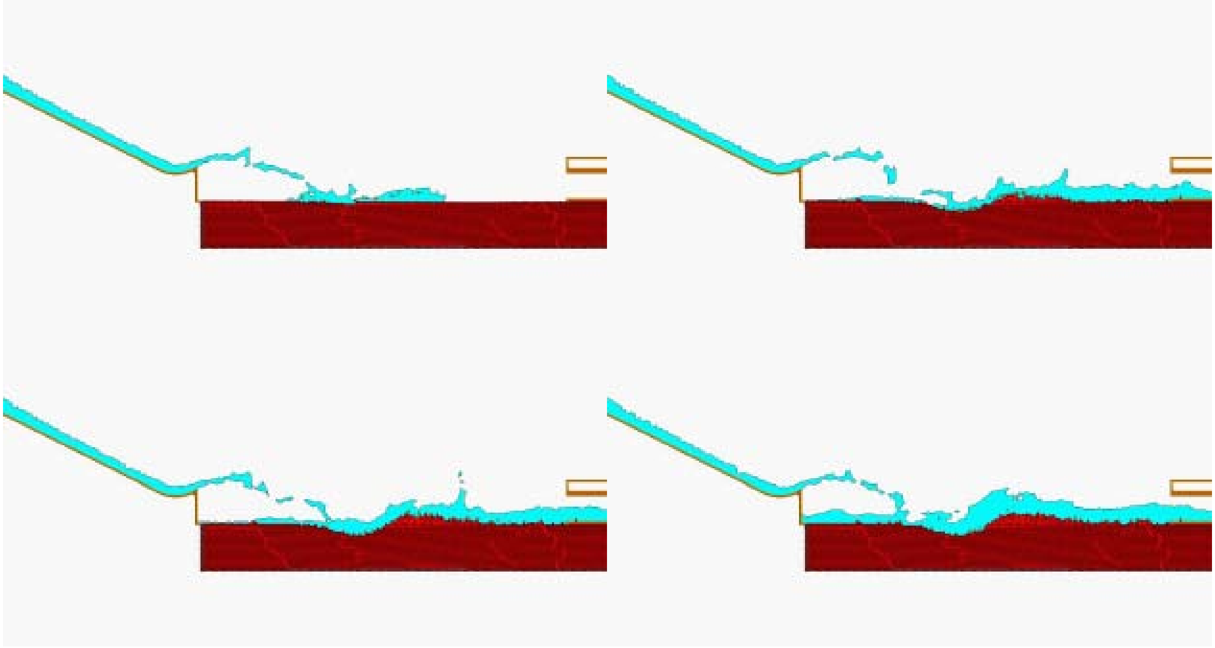

Figure 7. Modeling of bed erosion in the downstream area of Barriga Dam spillway with the PFEM.

The model reproduces the behavior of the laboratory tests carried out for this spillway [10], in which the flow undermined an area near the impact, whereas a part of the dragged material was deposited immediately downstream.

The authors are working in the development of practical criteria to establish the proper relation between the geotechnical information commonly used to characterize the river bed (granulometry, porosity, cohesion, etc.) and the parameters of the numerical model: a) erosion parameter and b) minimum velocity threshold.

4 LANDSLIDES IN RESERVOIRS

The analysis of the consequences of landslides in reservoirs is another application not directly related to dam hydraulics, but to dam safety. PFEM is particularly suited for modeling landslides, their impact into the still water in the reservoir, the wave generation, its propagation, and its affection to the dam as well as other structures sited in the shores.

Landslides in reservoirs have caused several dambreaks in history, as well as a large number of casualties. Although the frequency of occurrence of landslides is low, they are the third most important natural hazard in terms of casualties, after earthquakes and floods.

Landslides in reservoirs have a special interest, because variations in the water surface elevation (particularly rapid drawdowns) can foster their occurrence. The presence of a reservoir for a long time make the material in the slopes turn saturated, thus increasing their pore pressure and reducing effective stress. This unstabilization is partially compensated by the raise of total stress provoked by the hydrostatic pressure of the water in the reservoir. A rapid drawdown eliminates this stabilization in a lapse which in general is too short to allow the pore pressure to dissipate, thus increasing the probability of occurrence of a landslide.

PFEM has been validated for its application in the simulation of the interaction between landslides and a still mass of water, which can be a reservoir, a bay or a lake [11]. Various benchmark tests have been carried out, in which the falling mass has been considered either as a rigid solid or as a viscous fluid with a high density.

Figure 8 shows the results of the simulation of the experiment carried out by Sælevik [12]. It consists of a group of prismatic boxes accelerated into a mass of water in a rectangular channel. Three sensors measured the evolution of the water surface elevation.

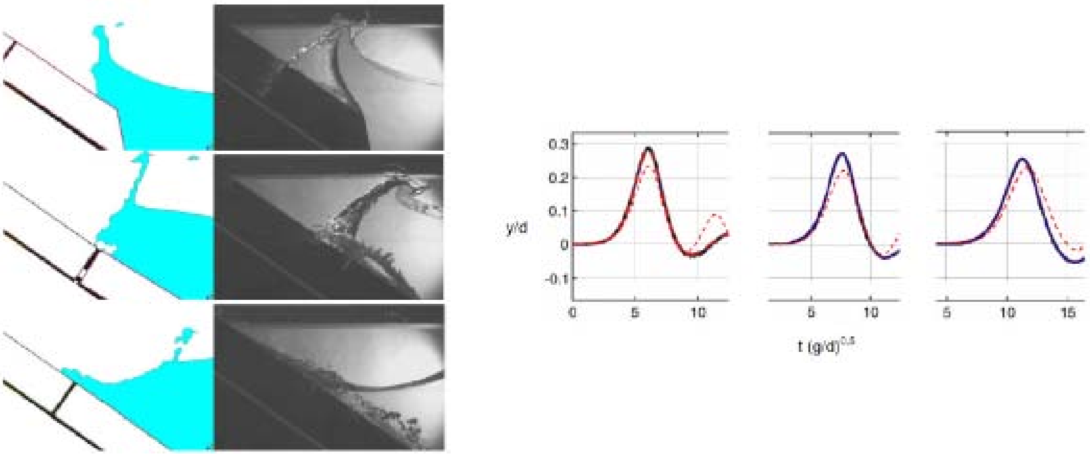

Figure 8. Modeling of the experiment by Sælevik et al [12] with the PFEM. Left: Comparative snapshots between numerical and experimental tests in the wave generation stage. Right: Comparison of the evolution of the water surface elevation in the sensors (dotted line represents the results by PFEM, whereas solid line shows the experimental results).

The model has been applied to the analysis of the Lituya Bay landslide, which is one of the most famous and well documented accidents of this kind. The landslide was originated by an earthquake and mobilized 90 million tons of rocks that fell on the bay originating a large wave that reached a height on the opposed slope of 524 m.

Figure 9 shows images of the simulation of the landslide with PFEM. The sliding mass has been modeled as a continuum with a prescribed shear modulus.

No frictional effect between the sliding mass and the underneath soil has been considered. Also the analysis has not taken into account the erosion and dragging of soil material induced by the landslide mass during motion.

PFEM results have been compared in terms of the maximum run-up in both northern and southern shores of the bay. In the first, the maximum run-up obtained with PFEM was 551 m (see figures 10 and 11), which is 5% higher than the value of 524 m. observed experimental by [13]. The maximum height location differs in 300 mts from the observed value [13]. In the southern shore the maximum water height observed was 208 mts, while the PFEM result (not shown here) was 195 m (6% error).

More information on the PFEM solutions of this example can be found in [11].

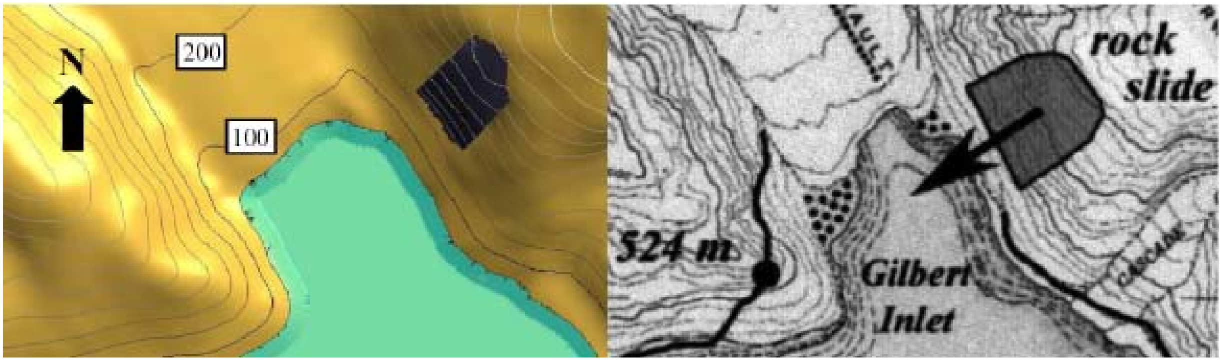

Figure 9. Lituya Bay landslide. Left: Geometry for the simulation. Right: Landslide direction and maximum run-up [11,13]

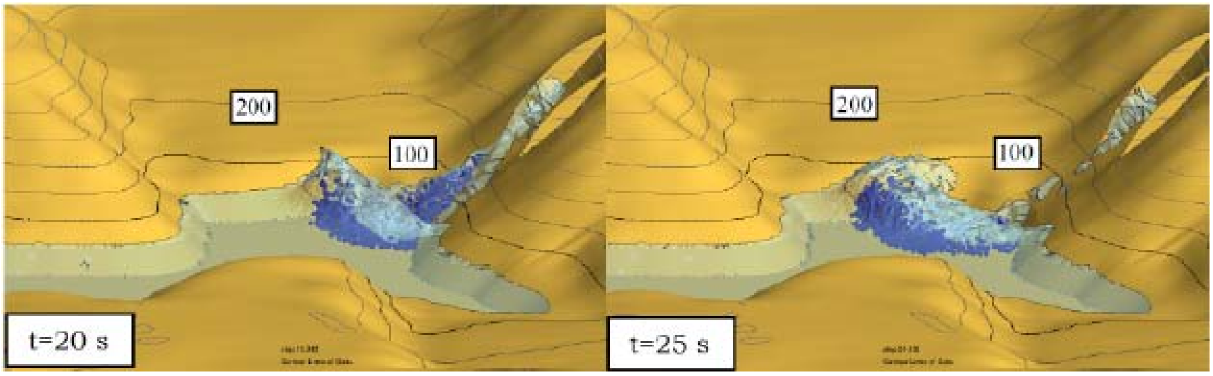

Figure 10. Simulation of Lituya Bay landslide with the PFEM. Wave generation stage.

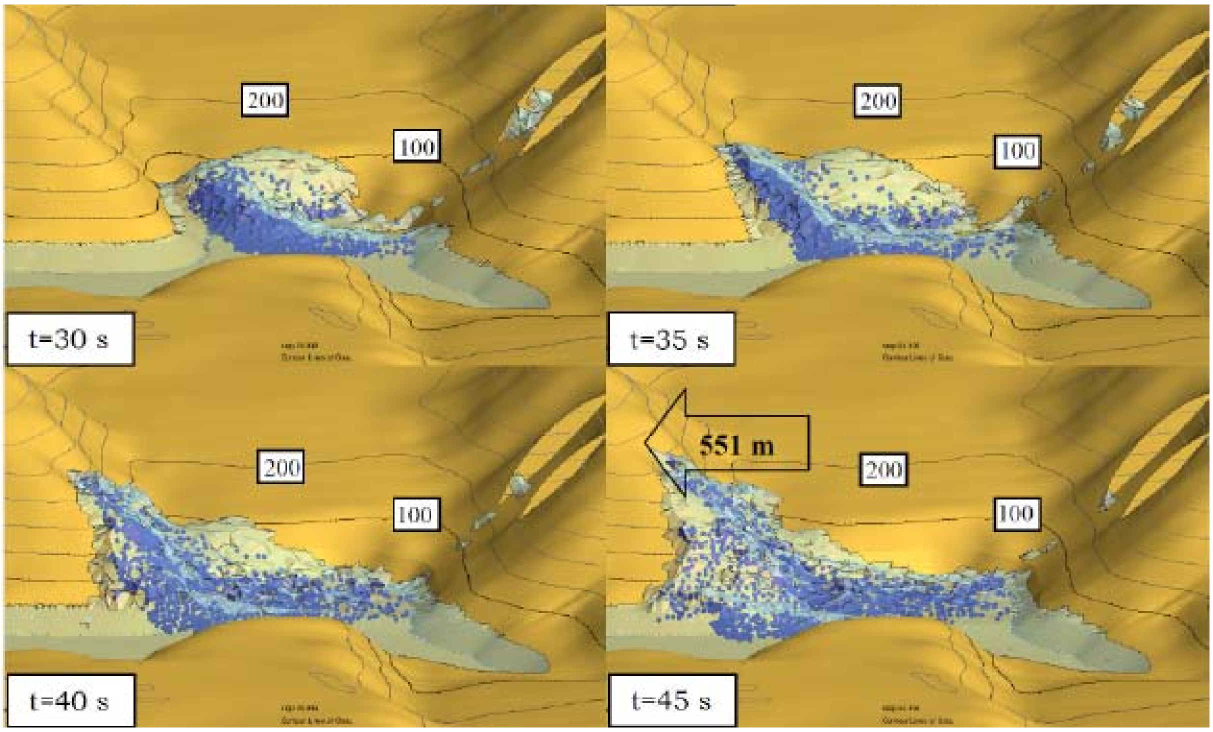

Figure 11. Simulation of Lituya Bay landslide with the PFEM. Wave propagation and maximum run-up in the northern shore.

5 CONCLUSIONS

PFEM has been applied to the simulation of different important phenomena related to dam hydraulics and dam safety. It has been found that is application can be useful both in the design stage, as a complement to experimental tests, and in the analysis of dam safety in front of landslides.

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