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Hydraulic 2D Model of Landslide Generated Wave –Cases of Chehalis Lake and Chambon Lake

Hydraulic 2D Model of Landslide Generated Wave – Cases of Chehalis Lake and Chambon Lake

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***Abstract*— In 2015, a landslide began to fall above Chambon Lake in France. This event reminds us that this phenomenon stands as one of the main risks for dam safety. Risks associated to generation and propagation of landslide-induced impulse waves in reservoirs might have dramatic consequences around the lake shores, for the dam itself, and also downstream as the Vajont catastrophic event showed in 1963. Recent research and permanent improvement of models have provided better risk evaluation tools by linking geology and hydraulic physics.**

Since 1998, EDF has been using Telemac to model landslide-induced waves. The first work was a comparison between numerical and physical models for the Billan landslide above Grand'Maison Lake. The landslide was defined as a hydrograph with very high flow.

In 2010, EDF started using Telemac in a different way to model landslide entering into a lake: a landslide is now represented by a dynamic vertical deformation of the bathymetry. This approach used Chehalis Lake landslide as validation case: in 2007, a landslide of 3 000 000 m^3 occurred in Chehalis Lake with a wave run-up going up to 40 meter high. Run-up leaves were collected all around the lake.

This way to model landslide-induced impulse waves gives good results and can be apply in safety management. However we have to keep in mind that numerical results only provide orders of magnitude as uncertainties inherent to landslide forecast (velocity, volume ...) remain high.

In 2015, this approach was applied to evaluate risks of "Berche" landslide at Chambon Lake with good confidence in the results.

I. Introduction

Landslides in reservoirs and lakes are a major potential problem for dam safety. Waves induced by landslides can cause [1]:

- damage to shoreline structures and boats,
- overtopping of dams by waves with resulting damages and downstream flooding,
- failure of dams,
- upstream flooding due to river blockages,
- loss of usage of the water body due to the final position of slide material.

Interest to study landslide is evident in terms of security.

In 2007, a 3 000 000 m^3 landslide occurred in Chehalis Lake, a natural lake near Vancouver in Canada. The maximum run-up height of the wave induced by the landslide reached about 40 meters. Damages were limited as it occurred in winter when the two campsites located on the lake sides were closed.

Electricité de France (EDF) was interested to test the efficiency of tools used to model landslide in reservoir. Chehalis landslide was a good opportunity to test this efficiency since a lot of information about the Chehalis landslide itself, topography (bathymetry) and run-up (wave marks: trash lines, tree scars…) were collected. EDF studied the wave induced by the landslide in the lake, its generation and its propagation. Two different methods were tested: empirical equations from Heller's studies [2] and [3], and a 2D model with TELEMAC-2D.

In 2015, "Berche" landslide began to move above Chambon Reservoir in the Alps. Tests done with Chehalis Lake Landslide allowed EDF to manage risks induced by Berche Landslide with good confidence using both methods Heller's empirical equations and TELEMAC-2D

II. General Methodology

A. Heller's study

The main topic of this article is the use of TELEMAC-2D to model wave induced by landslides. But, most of the time, before building a complex model, it can be useful to know the order of magnitude of wave that can be induced by a landslide.

Here is a short summary of Heller's work [3]. It follows works of Fritz [4] and Zweifel [5]. A lot of experiments were made on a unique channel. Fritz and Zweifel carried out 223 runs and Heller added 211 runs. From results of these 3 works, Heller provided empirical equations which allow predicting the wave height considering all relevant parameters of the landslide at impact on water surface.

Heller determined a set of governing parameters that allow calculating wave near field characteristics: slide impact velocity V_s, slide thickness s, bulk slide volume $\forall_s$, bulk slide porosity n, slide density ρ_s, slide width b, slide impact angle α, still water depth h, gravitational acceleration g and water density ρ_w.

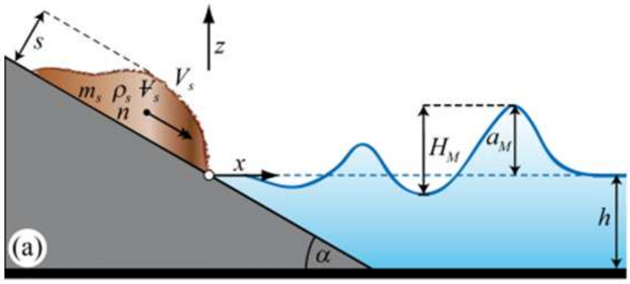

Figure 1. *Wave generation governing parameters*

From these parameters, Heller calculated 3 dimensionless numbers:

F	:	Froude number	$F = \frac{V_s}{(g*h)^{\frac{1}{2}}}$	(1)
S	:	Relative slide thickness	$S = \frac{s}{h}$	(2)
M	:	Relative slide mass	$M = \frac{V_s*\rho_s}{\rho_w*b*h^2}$	(3)

From these 3 dimensionless numbers and the governing parameter α, Heller defined another dimensionless number: *Impulse product parameter* P.

$$P = F * S^{0.5} * M^{0.25} * \left(cos\left(\frac{6\alpha}{7}\right)\right)^{0.5} \quad (4)$$

From this impulse product parameter, Heller determined empirical equations to calculate near field characteristics and wave characteristics on a given point of the propagation zone in a channel ("2D") or in a basin ("3D"). Water height maximal value H_m (5), or at a point in a channel ("2D") *H(x)* (6) or in a basin ("3D") *H(r,γ)* (7) and run-up wave height (8) are given by equations below:

$$H_m = \left(\frac{5}{9} * P^{\frac{4}{5}} * h\right) \quad (5)$$

$$H(x) = \left(\frac{3}{4}\right) * \left(P * X^{\frac{-1}{3}}\right)^{\frac{4}{5}} * h \text{ with } X = \frac{x}{h} \quad (6)$$

$$H(r,\gamma) = \frac{3}{2} * P^{\frac{4}{5}} * \left(\cos\left(\frac{2*\gamma}{3}\right)\right)^2 * \left(\frac{r}{h}\right)^{\frac{-2}{3}} * h \quad (7)$$

$$R = 1.25 * \left(\frac{H}{h}\right)^{\frac{5}{4}} * \left(\frac{H}{L}\right)^{\frac{-3}{20}} * \left(\frac{90°}{\beta}\right)^{\frac{1}{5}} * h \quad (8)$$

Other equations such as wave celerity or wave length are detailed in Heller's study.

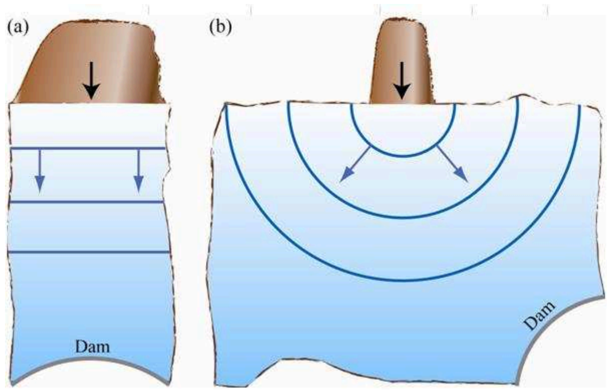

Figure 2. *"2D" (a) and "3D" (b) configuration*

B. TELEMAC-2D

When wave and run-up heights induce risks for population or dam, a TELEMAC-2D model can be implemented to have a better assessment of wave height by taking into account effect due to topography (island, complex shore shape, reflection effects…).

TELEMAC-2D cannot model a real landslide entering a lake. Therefore, 3 ways to simulate a landslide were tested on Chehalis Lake case:

1. The landslide is replaced by a hydrograph,
2. The landslide is replaced by a dynamic vertical deformation of bathymetry,
3. The landslide is replaced by a block of water in the area from where landslide begun.

The first hypothesis is a natural input for the software but landslide behaviour after impact and effect of a "shock" cannot be simulated. The third hypothesis is interesting but many parameters such as density cannot be taken into account and there are not many possibilities to adapt initial conditions.

Therefore the second hypothesis is deemed the best way to simulate the landslide and the induced wave. But it is not the easiest way to use TELEMAC-2D. Subroutine Corfon.f can be used to modify bathymetry, but this subroutine is only called at the first time step. The use of an application programming interface (API) would be useful but such a tool did not exist in 2010. Therefore a program using a loop was created modifying corfon.f and calling TELEMAC-2D for only few time step. Two time step are defined:

- Time step of TELEMAC-2D,
- Time step of the loop (modifying corfon.f therefore moving the landslide).

Another difficulty had to be overcome: when option "computation continued" is used, corfon.f is called only if the geometry was not recorded in the previous computation file. And when corfon.f is called, it is adapted to sediment transport calculation (Sisyphe), keeping surface elevation and adapting water height, whereas we need the opposite. Therefore TELEMAC-2D have to record only water heights and velocities but no geometry and no water surface elevation.

The landslide shape under water can have an impact on waves and wave reflexion. Therefore 3 ways of underwater landslide behaviour were tested:

1. Landslide stopping (constant shape): The simplest way of modelling the landslide is to let it move at constant speed without distortion and stop it at the deepest point of the lake;
2. Landslide vanishing: When the landslide reaches the bottom of the lake, it continues underground until it vanishes totally. It is as if the landslide is disintegrated when it touches the bottom of the lake (there is no conservation of landslide's volume);
3. Landslide scattering: When the landslide has totally entered water, its thickness decreases and its width increases, conserving the total volume of the landslide.

The third hypothesis gave the best results and is always used for new cases (Berche case).

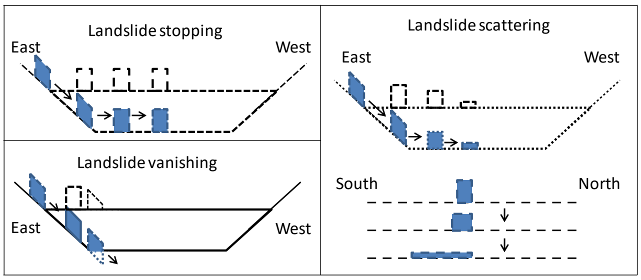

Figure 3. *Different ways to model landslide progression underwater*

When bathymetric deformation is used to model a landslide, the landslide kinetic energy is transferred to the water body by potential energy (elevation) and the initial water volume moving at impact is equal to the landslide volume.

When a real landslide occurs, depending on Froude number of the landslide, the initial water volume moving at impact can be much bigger than the landslide volume (up to 8 times [4]) and wave generation is due to different phenomena:

1. Physical displacement of water by the landslide,
2. Viscous drag and pressure drag (not modelled by TELEMAC-2D).

Therefore 2 verifications are needed before using TELEMAC-2D: the initial water volume moving should be similar to the landslide volume and the predominant force at impact should be the physical displacement. The first condition is obtained when Froude number is below 2 and the second condition when wave celerity is higher than landslide celerity, therefore when Froude number is not significantly higher than 1.

These conditions can seem restrictive but when the lake depth is between 30 and 40 m, landslides with a velocity up to 20 m.s^{-1} can be modeled and when the lake depth is around 100 m, landslides with a velocity up to 30 m.s^{-1} can be modeled.

III. CHEHALIS LAKE CASE

A. Model

The lake

Chehalis is located in the North-East of Vancouver in British Columbia, Canada. Chehalis Lake's main axis is South-North. On this axis, the lake is 8.2-km long. On the East-West axis, the lake is around 1-km long. There is a 450-m wide neck dividing the lake in two parts:

- North part, 2.8-km long (where the landslide occurred),
- South part, 5.4-km long.

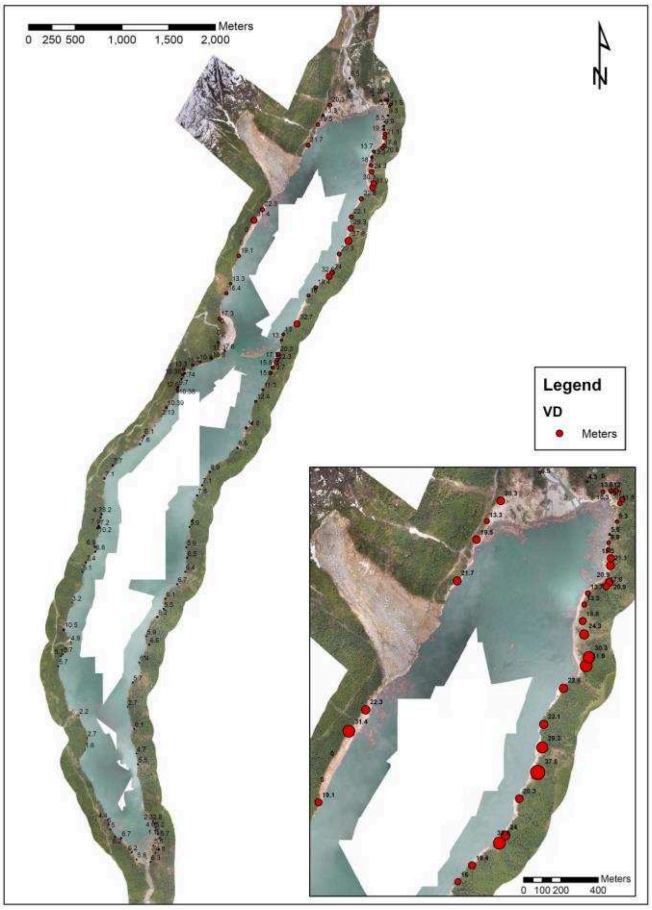

Figure 4. *Chehalis Lake and run-up recorded*

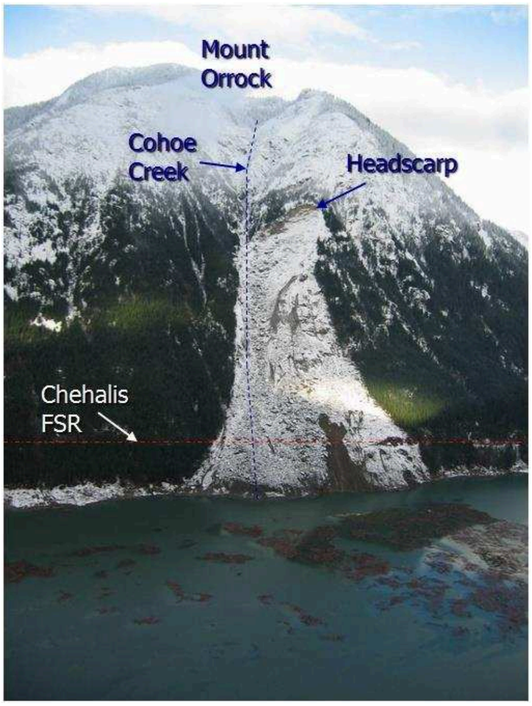

Figure 5. *Chehalis Lake landslide*

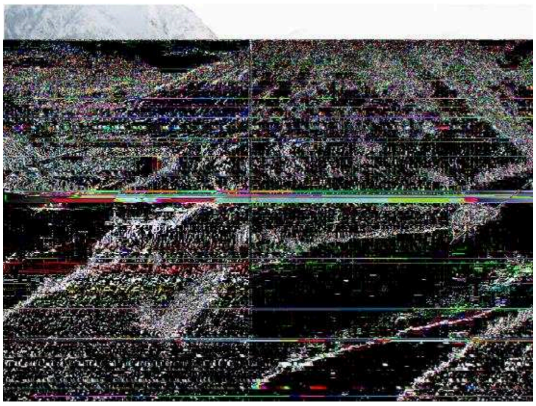

Figure 6. *Chehalis Lake and landslide*

The landslide

The landslide occurred on December 4th, 2007. Around 3 000 000 m^3 of rockslide fell into the north part of Chehalis Lake. The wave induced by the landslide uprooted many trees on shores creating many woody debris. It occurred during a storm flood event that masks any possible surge wave signature in Chehalis River.

Velocity of the landslide was estimated around 20 $m.s^{-1}$.

Topography / bathymetry

In June 2009, a bathymetric and side scan sonar survey was conducted to assist in evaluation of the lakebed conditions at Chehalis Lake. The objectives were to generate data sets which could be used to model the wave, examine the lake bed features generated in the proximity of the failure, develop volume estimates as well as look for evidence of prior failure events.

On top of this bathymetric survey, topographic data of slide area and shores were obtained by LIDAR

Equation and scheme used

In 2010, simulations were done with V5P9 of TELEMAC-2D. Using Boussinesq equations seemed naturally more adapted to the present problem since it is a wave. But the first tests led to very long computation times or errors due to tidal flats.

Therefore the choice was to use shallow water equations with finite volume (in the version V5P9 of TELEMAC-2D used, the finite elements code uses the method of characteristics in its calculations and this method did not work well on a resting lake or on tidal flats).

Mesh

4 mesh sizes were used depending on location:

- In the north part of the lake (near the landslide)
  - 15 m in the centre and
  - 5 m on shores and in the impact area
- In south part of the lake (south of the neck),
  - 25 m in the centre
  - 15 m on shores.

B. Results

Many simulations were done to test a lot of hypothesis: different ways to simulate the landslide, underwater landslide behaviour, shallow water or Boussinesq…

Here is presented the simulation corresponding to the best recorded run-up all around shorelines: with a bathymetric landslide scattering, using shallow water equations with finite volume scheme, a good correlation between simulation results and recorded run-up were found. Results were analysed area by area.

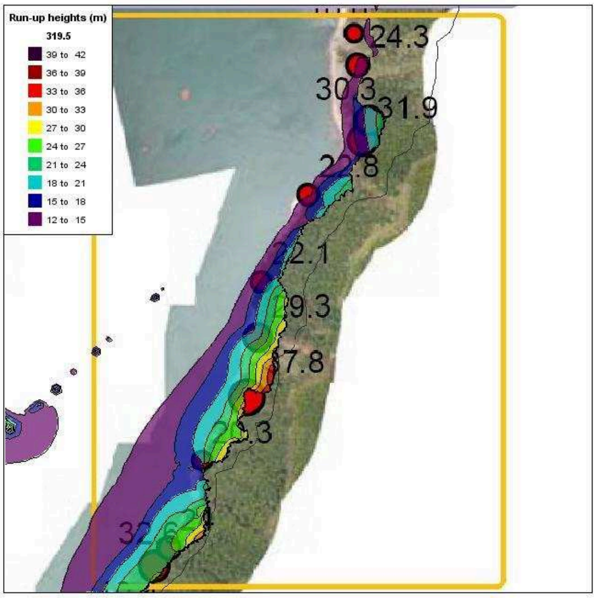

Figure 7. *Simulated run-up facing landslide*

Calculated and observed run-up heights on the shore facing the landslide were similar. The south part of this area gave really good results, but the north part seemed a little under estimated. Maximum calculated run-up height was 38 m for a 40 m observed run-up.

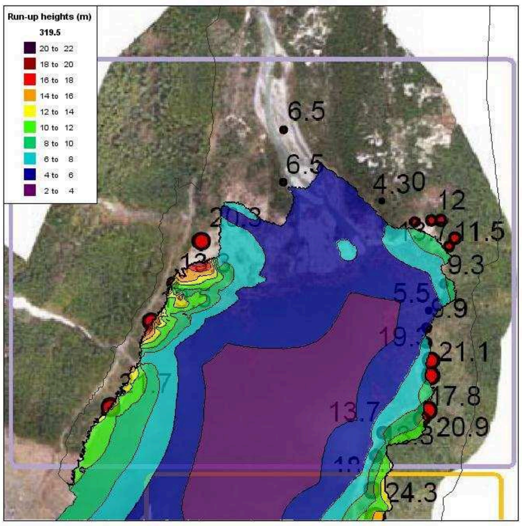

Figure 8. *Simulated run-up in North part of the lake*

In the north part of the lake, the east shore results seemed a little bit under estimated and the west shore results good.

Near the landslide impact, results were really close to observed run-up heights, but maxima of calculated run-up heights were located a little bit more south than maxima of observed run-up heights

In the south part of the lake, average, minimum and maximum run-up heights were good, but calculated run-up heights decrease from north to south a little bit quicker than observed run-up heights.

C. *Feedback*

This case gave a good confidence in the numerical method implemented. Comparison of results from TELEMAC-2D, Heller equations and run-up recorded showed a good correlation between results of the 2 methods and reality. Therefore it was concluded that these methods can be used for risk assessment (if conditions on Froude number are fulfilled for TELEMAC-2D).

IV. BERCHE CASE

In 2015, Berche landslide began to move above Chambon Lake. Geotechnical studies concluded that the landslide should remain with low velocity, but 2 scenarios could not be totally excluded:

1. Fall of 50 000 m^3 at 20 $m.s^{-1}$ into the lake,
2. Fall of 150 000 m^3 at 10 $m.s^{-1}$ into the lake.

First estimations of run-up heights on shores and at the dam were done with Heller's equations. But to have better confidence in results and take into account particular shape of the lake, a TELEMAC-2D model was developed to simulate both scenarios.

A. *Chambon Lake*

Chambon Lake is located between Grenoble and Briançon in the French Alps. Chambon Lake's main axis is East-West. On this axis, the lake is 3-km long. On the South North axis, the lake width varies between 250 m and 1km with an average of 400 m. Just like Cheahlis Lake, there is a 250m wide neck dividing the lake in two parts (the dam and the landslide are in different parts). Depth at impact area is around 34 m.

B. *Model*

Software version and equations

Between 2010 and 2015, TELEMAC-2D improved a lot. For this case, version V7P1 of the software was used. Boussinesq equations could be used without difficulties.

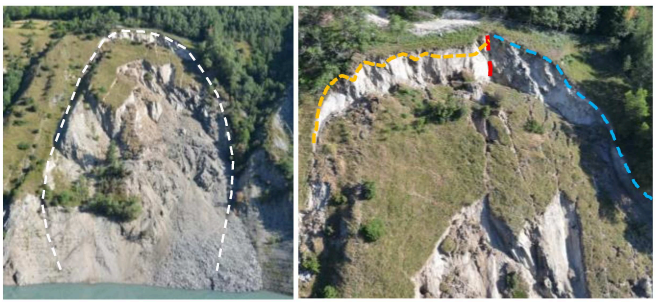

Figure 9. *Berche landslide*

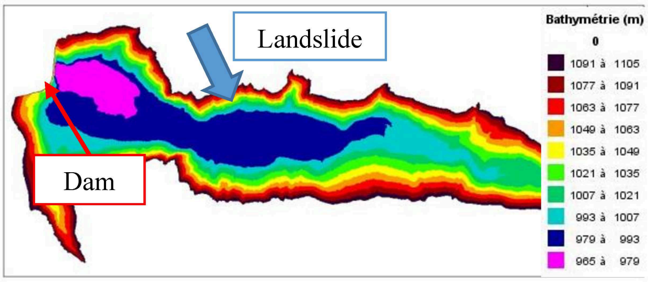

Figure 10. *Chambon Lake topography and bathymetry (French reference altitudes)*

Topography / bathymetry

A lot of information about bathymetry was available because lake sedimentation is monitored.

A LIDAR survey was undertaken during summer 2015.

Mesh

2 mesh sizes were used depending on location:

- 2 m in impact area and on shoreline,
- 5 m everywhere else.

Landslide shape and underwater behaviour

Taking into account Chehalis Lake feedbacks, a landslide scattering underwater was studied and its shape was chosen to maximise energy transfer between landslide and water.

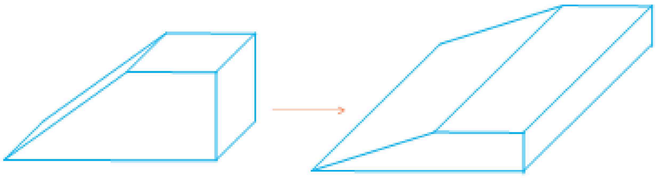

Figure 11. *Landslide shape in model and underwater behaviour (scattering)*

C. *Results*

Both scenarios were simulated.

Water depths at impact area are around 34 m. The first tests for scenario 1 yielded a wave celerity between 18 and 21 $m.s^{-1}$ for a landslide velocity of 20 $m.s^{-1}$ (Froude number of the landslide around 1). These results were used for risk assessment, therefore, to avoid any risk on security, a safety factor was applied to all run-up heights of scenario 1.

This factor was chosen by comparison between Heller's equation and TELEMAC-2D first results. Both methods gave similar wave heights (around 8 m), but TELEMAC-2D gave for this scenario lower wave length (lower energy transfer) and lower run-up heights facing the landslide (12 m vs. 16 m).

For each scenario results were studied on shores facing the landslide and at the dam.

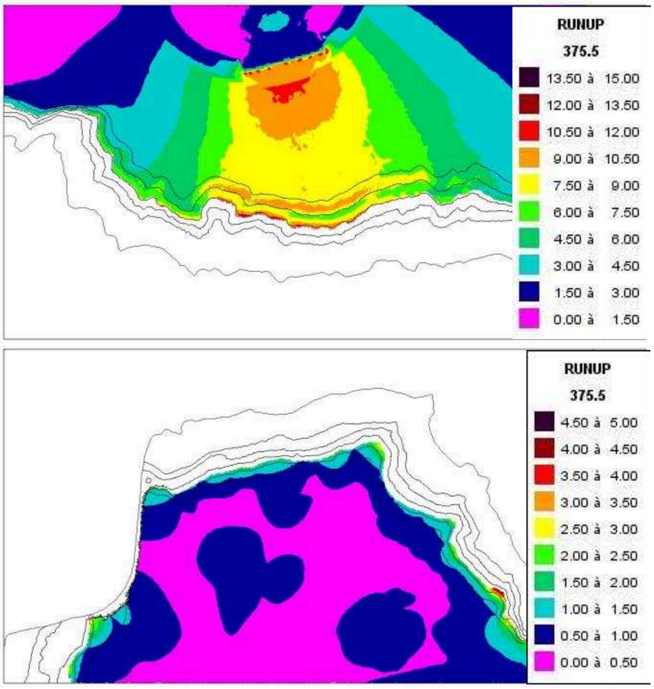

Figure 12. *Run-up heights (m) facing the landslide and around the dam for scenario 1*

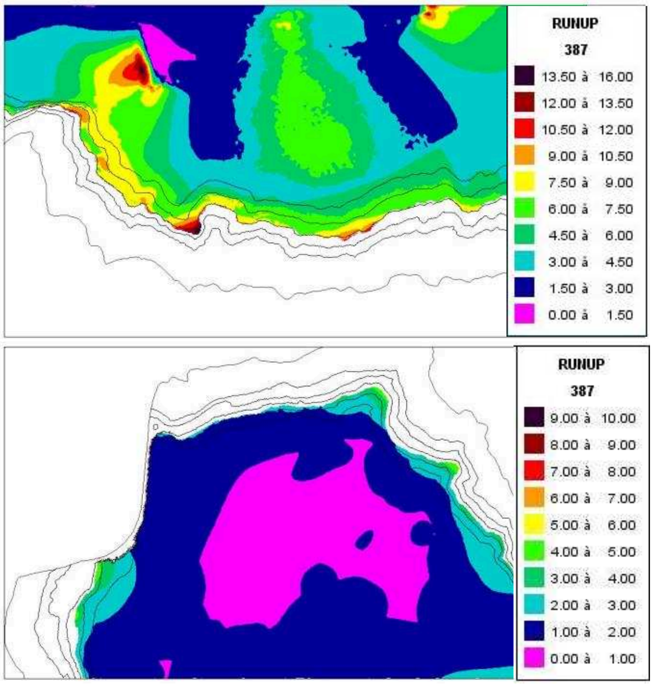

Figure 13. *Run-up heights (m) facing the landslide and around the dam for scenario 2*

These simulations allowed to manage risks all around the lake. The water level of the lake was adjusted during all studies depending on the knowledge about the landslide and risk induced.

Around the dam, it showed that there was no risk of overtopping and no risk of dam breaking

Facing the landslide, a road was built to allow car traffic from one side of the lake to the other (the landslide forced to close the tunnel that was used for traffic before). Risk assessment with TELEMAC-2D modelling allowed to have a safety road construction site.

V. CONCLUSION

Nowadays, thanks to Heller's equations, EDF can manage a landslide crisis with a good confidence in risk assessment. But a n additional safety factor is most of the time needed since this method does not take into account lake shape particularities.

Thanks to TELEMAC-2D modelling, with time, it is possible to take into account lake shape particularities and try to lower the safety factor used with Heller's method if Froude number of the landslide is not higher than 1.

The program implemented to model landslides should be improved by the use of the API. If another study must be carried out on this subject, the program will be rewritten with the API.

Special cases still remain such as landslide with high Froude number or really narrow lakes where wave induced by landslide cannot be fully generated before reaching opposite shore. For these special cases, TELEMAC-3D, Smoothed particles hydraulic (SPH) modelling or scale model should be used.

ACKNOWLEDGEMENT

I would like to thank geologists and Chambon dam operators who help us to have the best risk assessment and Denis Aelbrecht for help and control of these studies.

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