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Comparison of sediment transport formulae during a flood wave in the river: an application of Telemac teaching

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***Abstract*— For twenty years, the state pays attention to the risks of landslides: they could create a natural dam that would obstruct the bed of a river in the Alpine valley, creating a reservoir upstream. Originally, the assumption was that the accumulation of water would eventually cause a dam failure, creating a wave of destructive flooding and widespread, could happen. More recently, studies have shown that this scenario was not realistic: in fact, the water flow is gradually eroding the dam, creating intermittent flows downstream. In 2008, the CNR (Compagnie Nationale du Rhone [7]) conducted different tests on a physical model. The overall objective of our work is the study of some of these tests and comparing the experimental results of the CNR and our morphodynamics simulation of the river bed evolution. We make comparisons between different sediment transport formulations (Rickenmann [4], Einstein-Brown [1], Grass [2], other ...) based on the study of Recking [3] to see their influence on the erosion evolution of the river bed.**

I. INTRODUCTION

The Telemac chain of code is use since several years to teach the numerical approach in a project. The project (propose to the student) is during 10 weeks in the second year of the engineering school ENSE[3]. The student work only a half day a week on the subject. The idea of this practical lecture is to teach to them how conduct a project with a numerical approach.

During the two last years, we propose to our student a comparison between numerical simulation with Telemac and data from a physical model. The experimental took place at the CNR in Lyon and the model represent a study on a possible creation of a natural dam.

The study site is located in the department of Isere. Since several years, the State gives a very detailed attention to these risks of falls of ground: they could create a natural dam which would block the bed of Romanche, creating a water reserve to the upstream. With the origin, the assumption was that the accumulation of water would end up causing the rupture of the dam, thus creating a wave of destroying immersion; more recently, studies showed that this scenario was not realistic: in fact, the dam would be eroded gradually, creating intermittent overflow rates in the downstream part of the valley.

These modifications led to the following formulation of the subject of this workshop of engineering: “Study of progressive erosion and sedimentary transport on the top of the natural dam of Séchilienne”.

In 2008, CNR (National Company of the Rhone) carried out various tests on a small-scale model of Séchilienne, in particular two tests numbered 17 and 21 (see [7]).

The objective general of our work is the study of test 21 and the comparison between the results and the data of CNR obtained with their model. We will carry out comparisons between various existing formulas of erosion and the data.

II. LOCALIZATION AND PRESENTATION

Séchilienne is a commune of Isere, localized at 30 kilometers in the south-east of Grenoble, on the road connecting Grenoble and Briançon. It belongs to the canton of Vizille and is located in the valley of the Romanche river.

Séchilienne is known for its active zone of landslide located on the Southern slope of right bank of the valley of the Romanche, at the southern end of the mountain chain of Belledonne (see Fig. 1).

This site, called “Ruins of Séchilienne”, knew many falls of blocks, in particular during years 1726, 1762, 1794, 1833 and 1906. The scree cone of the Ruins is visible from the secondary road, which serves Bourg d’Oisans.

Figure 1. Localisation of the Ruins of Séchilienne.

III. PRESENTATION OF THE STUDY

A. *Presentation of former studies*

As indicated in the introduction, the scenarios considered up to now were very pessimistic. At the time of a rainy event of strong intensity, an important landslide of the mountain would lead to the complete obstruction of the valley and the creation of a dam of several tens meters. That would lead to the formation of a lake of approximately 20 million m^3 to the upstream and the road would be cut. According to former studies, this dam will resist at the rising waters due to flooding and would be broken only when passing the peak of the hydrograph, i.e. at the most critical moment. This rupture would involve an overflow rate with the downstream, forming a wave of immersion which would reach the cities and industrial facilities located downstream from the dam. All these scenarios were deduced from digital models. On these various conclusions, several parades were installing. Many measuring apparatus were also installed in order to monitor closely the evolution of the phenomenon (contours exact of the zone of landslide, kinematics and movement of the zone…). These measurements make it possible to generate alarms in real time.

B. *General presentation of the study of CNR*

These data were use by CNR, which enabled it to make a more thorough study of this landslide through the construction of a small-scale physical model. The purpose of this model, on the scale 1/60e, was to study the speed of erosion of a dam by overflow of water of Romanche and to provide complementary data (flow in downstream, flow upstream, dimension of water on the level of reserve, quantity of transported materials …)

This scientific tool made it possible to model a very complicated physical process that the mathematical models could not entirely represent.

Several scenarios were considered according to the characteristics below:

- The height of the dam formed by the landslide of the 3 million m^3;
- The materials (size, nature) constituting the dam;
- Flow of Romanche;
- Test of a second material constituting the dan different from the first testing;
- Tests relating to a 18 m height dam and to a second landslide falling into water reserve formed by a first landslide of 6 m height.

This study by the CNR on this reduced model gives the behavior of the dam formed in bottom of valley of Romanche. The principal conclusions are as follows:

- A 6 m height dam, corresponding to the landslide of a volume of 3 million cubic meters (able to occur in the 10 next years) does not present a risk of brutal rupture because of a progressive erosion. Moreover, a simultaneous hundred-year flood would increase the downstream flow only of 10%.
- A second landslide falling into water reserve formed by a first landslide does not present a real risk, neither for the downstream, nor for the upstream.
- A long term landslide (in 50 years) forming a 18 m height dam for a volume from 5 to 6 million cubic meters would present a more important risk for the downstream with an increase of the flow in the case of a hundred-year flood, in the order of 20%.

C. *Presentation of our study*

Thanks to the data of CNR [7], we could recover the bathymetry of Romanche. We tried to set up a digital model which will make it possible to have the results of simulation to compare with thus obtained on the small-scale physical model. We had to model the different flood that might occur, the various transformations undergone by the bottom of the river (erosion, "un-paving" ...). This will calculate the over-flow in each case and to allow predictions on new models. We have two tests on the site of Séchilienne made by CNR: test 17 which was treated last year and testing 21, we will fully address this year. Both tests were carried out for a dam of 6 m above the bed of the Romanche. The same size of material was used for both tests. The results of last year on over-rates are consistent with the observations of the CNR, so we considered that the hydraulic model was correct. We have therefore chosen to focus primarily on modeling the erosion of the river bottom.

1) Test 17: During test 17, the landslide occurs out flood of the Romanche River, forming a dam in the Romanche valley. The flow of Romanche gradually fills the reserve created by the dam and flows on this and then a flood occurs later. In this scenario, the passage of a hundred-year flood which was studied. The students of last year already modeled this entire test.

We initially tried to improve modeling the un-paving and erosion by using zones polygonal rather than rectangular (what was used previously). Then, we modeled erosion thanks to various formulas to try to take into account the phenomenon observed by CNR.

2) Test 21: During test 21, the landslide occurs for one period of the flood. In the first time, we thought that the test of CNR consisted in making fall the landslide at a given time at the maximum of the flood. However, after having looked at the provided documents more attentively, we realized that CNR used same bathymetry as in test 17.

In this case, the landslide is established in the model (what corresponds to the bathymetry of case 17), then a constant flow (corresponding to the maximum of flood) is introduced very quickly into the model. In this scenario, it is the maximum flow of the hundred-year flood which was studied. We thus modeled this scenario, by using various formulas of erosion as for test 17 (because we have same granulometry). We could thus compare our results with those of CNR. Bathymetry being identical to the preceding case, the study of this test especially allowed us to model erosion more easily.

IV. STANDARD MODELING FOR THIS PROJECT

The system TELEMAC is a whole of software of numerical simulation applied to the flows on free face, at sea or in river, in two or three dimensions.

The applicability goes from the local study of impact of the construction of works (bridges, ears, mole…) until the calculation of the current due to the waves or tides while passing by the reproduction of the flood, rupture of dams and the transport of sediments.

All the software of the system uses powerful algorithms based on the finite element method. The field of calculation is discretized with not structured grids using triangular elements, which makes it possible in particular to refine the grid in the zones of particular interest. System TELEMAC proposes a complete data processing sequence with software of simulation, "preprocessors" and "post-processors".

The pre and post-processors are the elements of the chain which make it possible to prepare and manage a calculation, to display the results. These tools are common to all the modules of calculation, which ensures the homogeneity of the unit.

After having traced contours external and the interior lines of the field, it is necessary to define the size of the mesh. We choose here to create constant meshes. During the project, we tested several sizes of grids: 20m, 10m, 5m, 2m in the aim of evaluating the influence of the grid in calculations. We could observe that the precision of calculation increased when the mesh decreased. However, the computing times then were increased considerably. We thus found a compromise by choosing for the majority of the cases the grid of 10m.

For our study, the border upstream is with flow imposed and the border downstream on imposed height. For the side borders, they correspond to the banks and are thus regarded as solid walls.

Fig. 2 shows the hydrograph of the hundred-year flood used by CNR and that which we used in our simulations. After having controlled the result, we use Blue Kenue to treat the data so extracting information to be analyzed and compare with the results of CNR. Thus, we could extract from the profiles height of water and bathymetry at various moments with the same sections transversely as those used by CNR. Fig. 3 represents an example of evolution of the bottom in function of time on a transversely given section obtained with Blue Kenue.

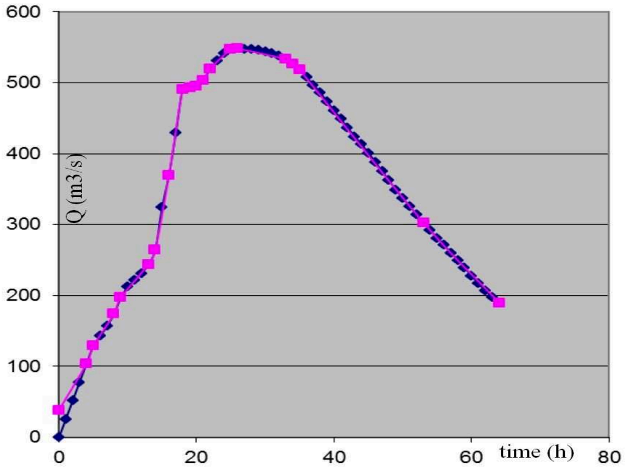

Figure 2. Hydrographs of CNR (purple) and of our study (pink) for the hundred-year flood (m^3/s) over time (h).

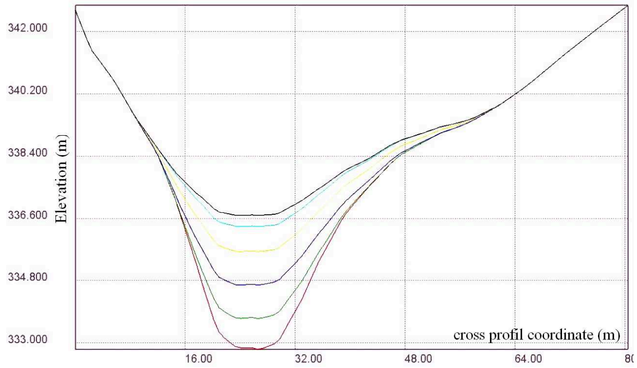

Figure 3. Erosion of the bottom of section 16 during the passage of the hundred-year flood (m^3/s) over time (h).

V. MODELING EROSION

Sediment transport can be considered as a matter production, which will be moved by the river and then sediment again: it is also called transit sediment or sediment transport. This is a complex phenomenon involving a large number of meteorological, hydrological, geological parameters, etc.

There are two types of moving materials:

- The bed load, for materials of large size, which corresponds to a transport on the bed in shifts.
- Suspension, that is to say, the finer sediment transport by the flow.

This is increased by the force of floods, the slope of the river bed and the narrowness of the channel. There are two main phases in the sediment transport: the phase of erosion and the deposition phase. For our study we only studied the phenomenon of erosion because it is the cause of the over-flow downstream (see [5] and [6]).

In our project, we are dealing with fluvial erosion, and more precisely to regressive erosion, observed by the CNR in the various tests. Regressive erosion is a mechanism for widening stream that comes after the lowering of the bed downstream. It begins with the digging at baseline also called fixed point before heading upstream (the base level of a river corresponds to the lowest level at which a river can erode bed.).

Regressive erosion is a mechanism for digging of rivers that comes after the lowering of the bed downstream. It begins with downstream at the basic level also called fixed point before rising towards upstream (the basic level of a river corresponds to the lowest level to which a river can erode bed.). This type of erosion is much faster than the traditional erosion which, it, acts in the downward direction.

This phenomenon occurs when the slope is higher than the slope of balance. This increase in slope led to an increase in the erosive power of the river: the transport capacity becomes higher than the contributions, this difference involving an erosion of the bed and banks.

Erosion is propagated then upstream to restore the initial slope of balance. In our case, the landslide is done on only one side of Romanche, which generates a nonsymmetrical deposit. An angular part called "breach" or "gap" by CNR is formed, and it is on this level that the erosion occurs mainly, which digs the dam starting from this point.

Many formulas are proposed to model solid transport by bed load in the rivers. They use various variables, in particular data concerning the granulometry, the width of the bed, the hydraulic diameter and the slope. In this case, it was not found yet of sedimentary formula of sediment transport and erosion compatible with the bathymetry (strong slope).

Within the framework of our study with the Sisyphe code, we used several different formulas, in order to compare the numerical results with the data and to find the most adapted one:

- The formula of Bijker is normally used in the cases of bed load and suspension. It is made of two components: bed load, which is entirely empirical, and suspension, which takes as a starting point the preceding component, and which is drawn from the theory of Einstein.
- The formula of Rickenmann (see [4]) which makes it possible to obtain the bed load starting from the liquid flow of the river.
- Einstein-Brown formula [1].
- Grass formula [2]. It is build by using the morpho-dynamic equation of Exner.
- Empirical formula.

In addition to these theoretical formulas, we tried to propose our own formula in order to represent erosion. We tried various simple formulas, by choosing relations of proportionality between erosion and the flow per linear meter, since the flow is one of the principal parameters influencing erosion. We thus programmed relations of the form:

$$E = Aq^n \tag{1}$$

where A is a constant and n varying from 1 to 3. E represents the sea bed evolution at each time step. For n=3, erosion observed was really too strong, even with low values of A. Finally, we chose A=1×10–7 and n=1, which we integrated in a standard file FORTRAN for our simulations only with Telemac2d module (without the coupling with Sisyphe module.

In our study cases, we chose to look at the evolution of the bed on 3 profiles, corresponding to profiles 15, 16 and 17 of the study of CNR (see Fig. 4).

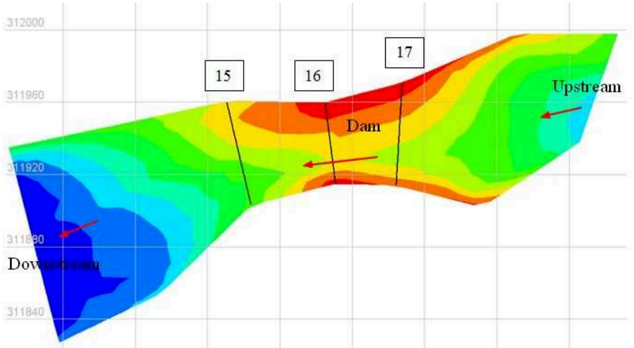

Figure 4. Simulation domain with the position of the Dam and the profiles 15, 16 and 17.

VI. RESULTS

A. *Comparison with test 17 data (hundred-year flood)*

For this modeling, the tests are made during three days of real time in order to make entirely the hydrograph hundred-year flood. We did not model the "un-paving" (abrupt setbacks of part of the dam) observed by CNR, because we observe some divergence of our results compared to the observations on the small-scale model. On the grid of 10m, we need approximately 18 hours to carry out the simulation on a PC. All the profiles show for the results are taken looking in the upstream direction. The profiles of CNR's data are truncated to facilitate the comparison.

1) Profile 15: with Bijker (see Fig. 6), until t = 2h, we see that our curves are smoothed in contrast to those of the CNR (see Fig. 5). However, the numerical values coincide. For the curves representing the time above 17h, there is too much erosion, the theoretical result moves away significantly from the experimental result.

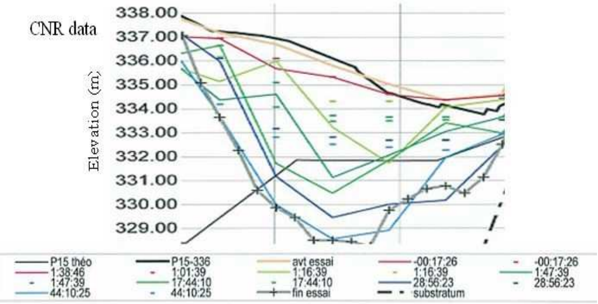

Figure 5. Test Case 17: profile 15 data of the CNR.

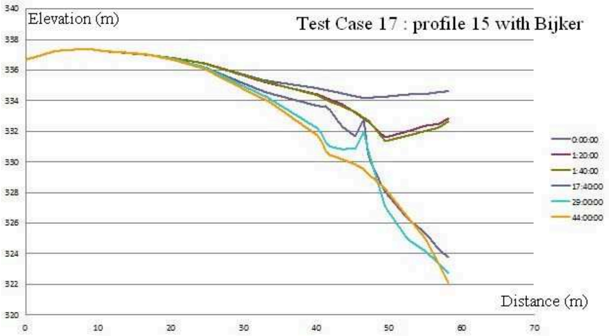

Figure 6. Test Case 17: profile 15 simulated with Bijker formulae.

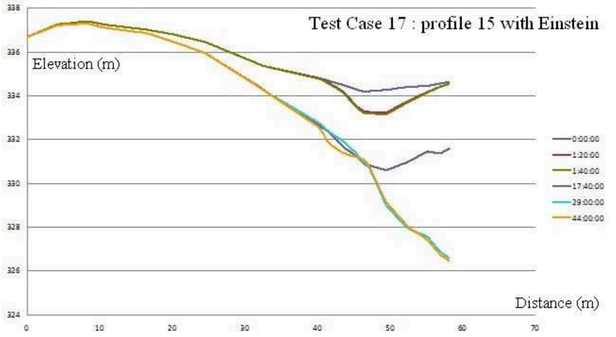

Figure 7. Test Case 17: profile 15 simulated with Einstein formulae.

With Einstein formula (see Fig. 7), we obtain similar results to those obtained for Bijker, except that the results are good up to t = 5h40. There is still a significant erosion of the profiles at the final time.

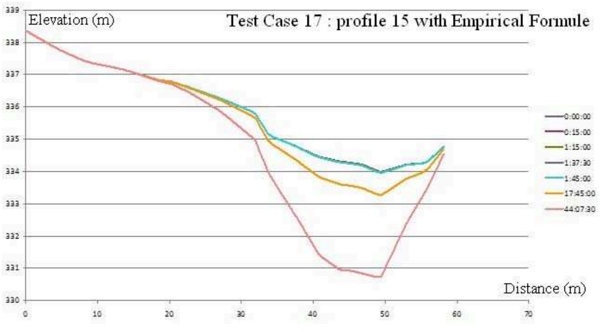

Figure 8. Test Case 17: profile 15 simulated with Empirical formulae.

With the empirical formulae (see Fig. 8), the shapes of the curves are quite consistent with those of the CNR, but erosion is not large enough.

2) *Profile 16*: With Bijker (see Fig. 10), the results for short times are not very good (see fig. 9): the shape is moderate and the erosion is not large enough. However, the profile obtained for the curve t = 18h is closer to the data, but the following simulations are incorrect (the erosion is too great).

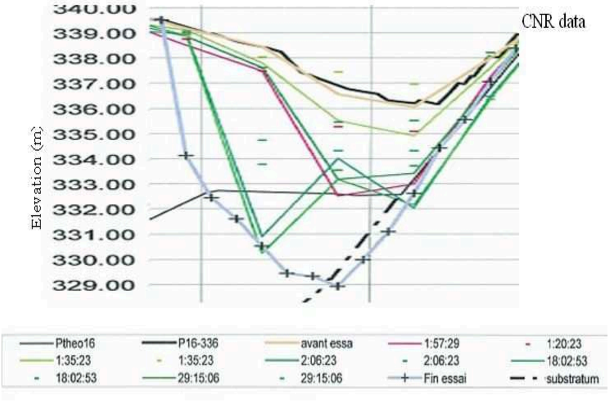

Figure 9. Test Case 17: profile 16 data of the CNR.

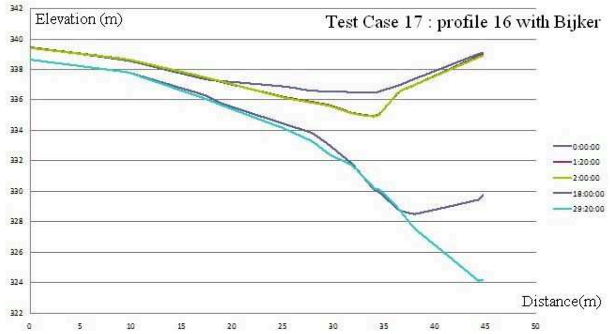

Figure 10. Test Case 17: profile 16 simulated with Bijker formulae.

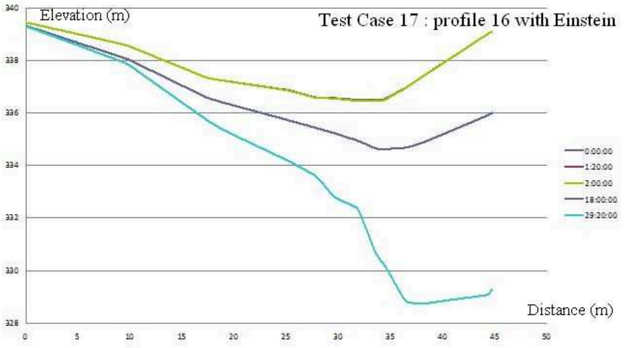

Figure 11. Test Case 17: profile 16 simulated with Einstein formulae.

With Einstein (see Fig.11), the results at short times are not correct. On the other hand at very long times (t = 29h), the behavior and the values are correct.

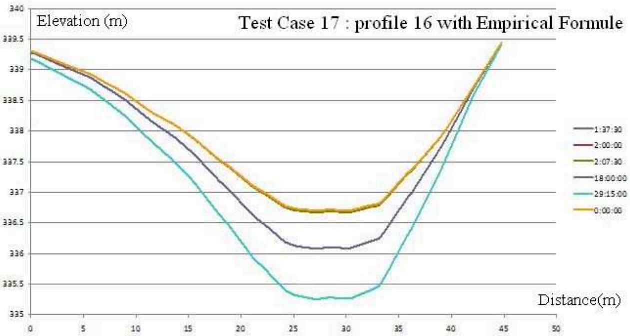

Figure 12. Test Case 17: profile 16 simulated with Empirical formulae.

With the empirical formula (see Fig.12), the behavior is correct for the all times, but on the other hand the erosion is for each time step too weak.

3) Profile 17: with Bijker (see Fig. 14), the behavior is quite correct. In contrast the values of erosion are not very good at long times (about one meter gap between simulate and experimental test (see Fig. 13)).

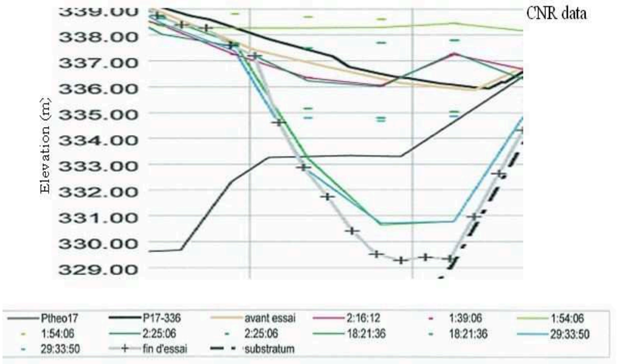

Figure 13. Test Case 17: profile 16 data of the CNR.

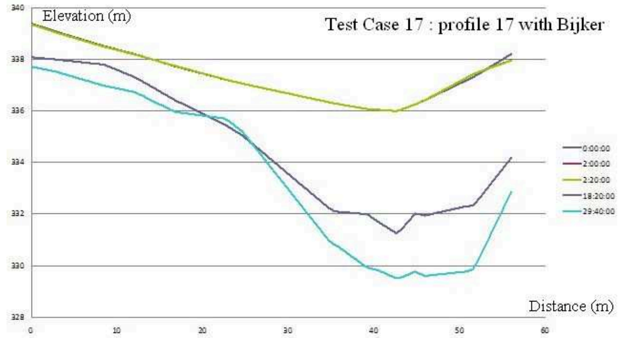

Figure 14. Test Case 17: profile 17 simulated with Bijker formulae.

With Einstein (see Fig. 15), the curves at short times are incoherent because we observe identical profile from t = 2h to t=18h. On the other hand, the shape of the last curve is good, but erosion is too weak. With the empirical formula (see Fig. 16): The results are wrong. The shape is correct but the erosion is quasi non-existent.

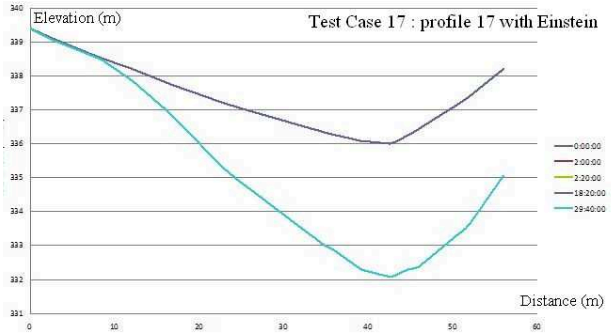

Figure 15 Test Case 17: profile 17 simulated with Einstein formulae

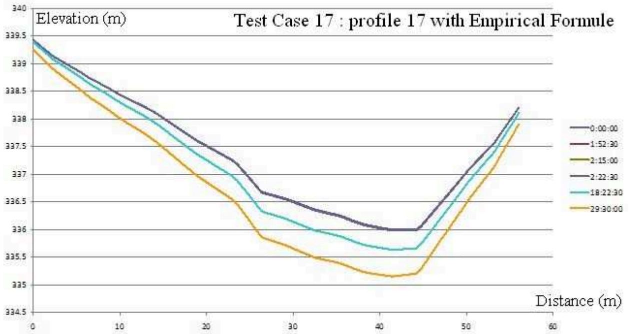

Figure 16 Test Case 17: profile 17 simulated with Empirical formulae

B. *Comparison with test 21 data (ten-year flood)*

For this modeling, the tests are made during 15h to simulate the maximum of the ten-year flood (Q = 300m^3/s). We either did not model the "un-paving" observed by CNR. On the grid of 10m, we need approximately 6 hours to carry out the simulation on a PC.

1) Profile 15: with Bijker (see Fig. 17), the results are good for very short times. On the other hand, it seems according to the figure of CNR that an "un-paving" occurs after 30mn so our results after thi time are wrong because of the gap create by the "un-paving" on the river bed. With a translation of our curves, the shape seems to be correct.

With Einstein (see Fig. 17), the depths of erosion are correct along the entire simulation in time. On the other hand, the digging of the channel is done over a width much more reduced than in the results of CNR. That can be due to that the "un-paving" occurred after 30mn changes the shape of the breach in the dam.

With Grass formula (see Fig. 17): There still, the phenomenon of "un-paving" is not modeled, which distorts interpretation. If not, the profiles are overall good, with a broader channel which corresponds well to the results provided by CNR.

1) Profile 16: with Bijker (see Fig. 18), the depths of erosion are not good. But temporal data of the CNR are missing on their graph, so the interpretations are less easy. The shape is relatively correct but the erosion is too weak (only 2m in 15 hours).

With Einstein (see Fig. 18), the shapes and the values are good. But, we observe on the profile of CNR at t = 11h40 an increase of the river bed elevation, which can correspond to a deposit of sediment which is difficult to simulate.

With Grass model (see Fig. 18), the results are not very realistic. Erosion is progressive but does not correspond at all to the results observed on the small-scale model.

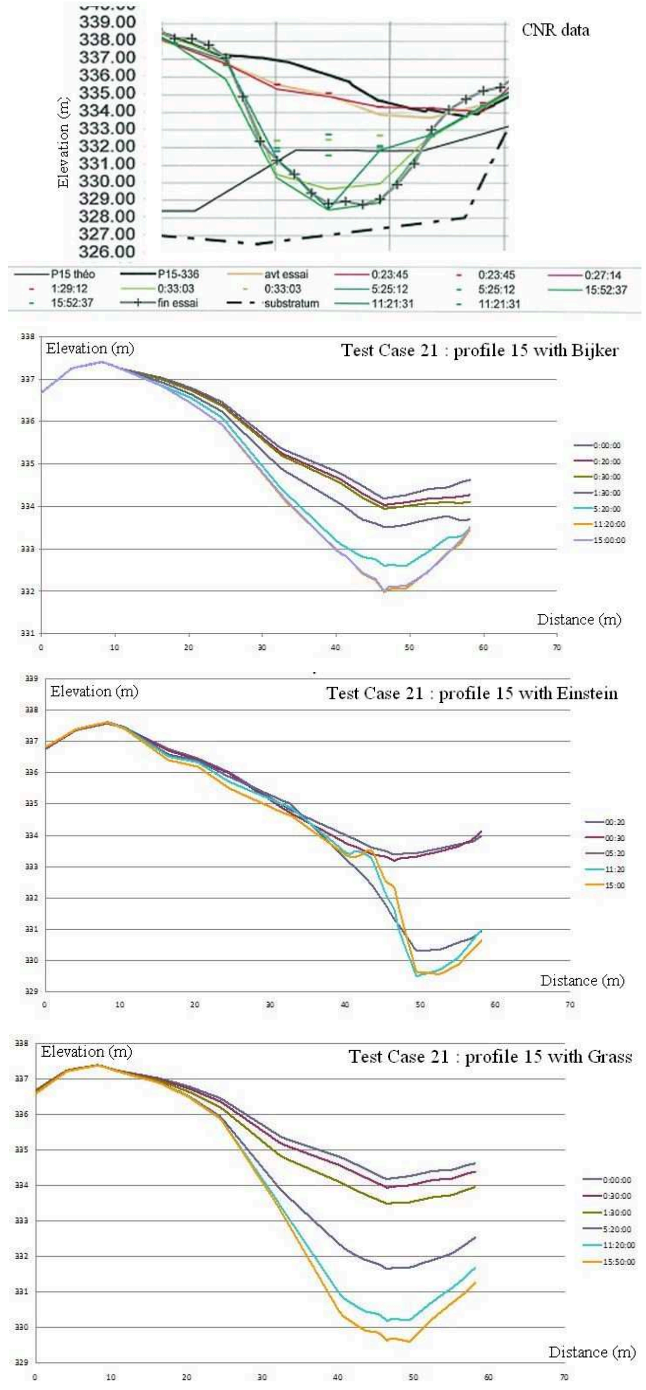

Figure 17. Test Case 21: profile 15, the CNR data and simulated data with Bijker, Einstein and Grass formulae.

3) Profile 17: with Bijker and Grass models, erosion is nonexistent in this part upstream of the dam, which is in clear disagreement with experimental data from the CNR. With Einstein, there is an erosion that has generally the same shape as the experimental profiles, but the values are not very good (too much erosion before $t = 6$h and not enough after).

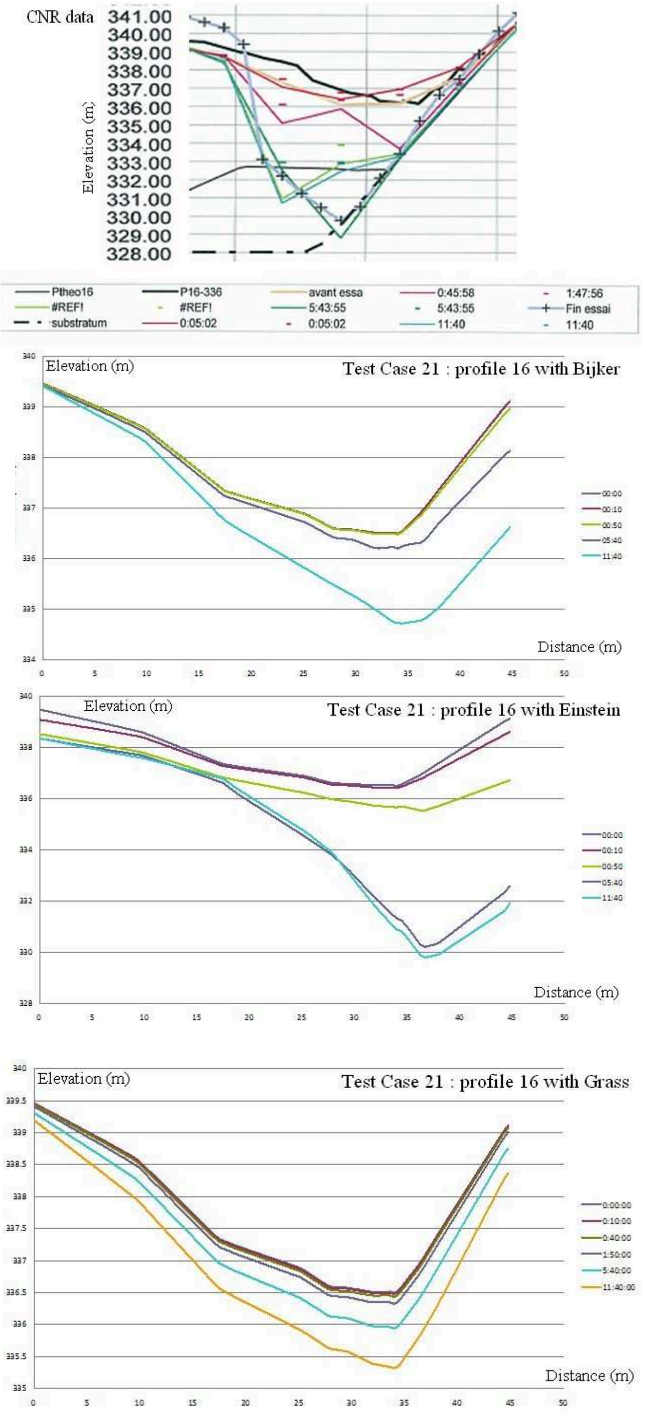

Figure 18. Test Case 21: profile 15, the CNR data and simulated data with Bijker, Einstein and Grass formulae.

VII. CONCLUSIONS

This project of Workshop of Engineering on the topic of the Ruins of Séchilienne allowed us to extend our knowledge as regards numerical modeling of flow in river and to control the bases of the software Matisse, Telemac and Bluekenue. We are now able, starting from data of bathymetry of a river bed and hydrological data, to model a floof and to extract from the results information necessary to their good comprehension.

This study was the occasion for us to measure the difficulty in following objectives: many data-processing problems forced us to reorganize the aim to achieve. In addition, of new elements of comprehension reached us during the project and led us to adapt our study.

For test 17, the simulation which approaches more the tests carried out by CNR is the one using the formula of Bijker. In addition, the phenomenon of “un-paving” is not taken into account in our study, which can explain why erosions obtained numerically are often too weak. Our empirical formulae seem correct but remain to be improved. It would be necessary to continue to make evolve/move the coefficients to obtain erosion a little more important and to better follow the results of CNR.

For test 21, the simulation which approaches more of the tests carried out by CNR is the one using the formula of Einstein.

We decided this year to look further into the modeling of erosion; we hope that our results will make it possible to make progress for the study in the future projects of Workshop of Engineering. Modeling must still be improved, in particular with the “un-paving” phenomenon.

ACKNOWLEDGEMENT

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