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Pairing riverbanks instability and fluvial hydraulics for the prediction of risk zones on a river undergoing dam break flooding

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ABSTRACT: The safe operation of dams requires a good assessment and understanding of the involved risks of their failure. The direct consequences are usually considered to be limited to the maximum flooding zone created downstream. However, considering the magnitude of the dam-break flows, the riverbed could undergo deep changes. The simulation of the evolution of river reaches resulting from such catastrophic events is performed by coupling the hydraulic and sediment transport numerical model GSTARS with a slope stability model that is based on the Bishop's simplified method, which we recently developed. This paper presents a novel methodology for the delimitation of the veritable safety zone along river banks by taking into consideration not only the flood risks but also the possible induced landslides. Validation tests are performed on specific reaches of the Outaouais River (Quebec).

1 INTRODUCTION

Dams, especially those of significant height and large reservoirs' capacity were always subject in Quebec to careful inspection, monitoring and management. However, some recent events (such as Lake Beloeil, Chicoutimi River, Ha! Ha! River, Quebec, Canada) are a clear reminder that dam failures, piping failure breaches, and overtopping due to insufficient spillway capacity during large outflows are quite possible. Precipitation-runoff floods and dam failure floods result in an unusual rapid water surface elevation, and high velocity outflow through the downstream river. The inundation of river banks may cause significant erosions, important landslides and creates potentially unstable embankments, as those observed in the aftermath of the Saguenay floods in 1996. As the main goal is the protection of life and property, it is difficult to restrict the hazard potential to the only inundation zone, without considering the final extension of the larger damaged area. This wider zone may include areas with elevation higher than the maximum water level reached by the flood. The delineation of the evacuation zone of the population should be therefore extended.

The simulation of dam-break floods are essentially carried out using numerical models with fixed bed assumption (except MIKE 21 and TELEMAC models). The bathymetry and the topography of the river valley are then considered invariant and the erosion of river bed and river banks with sediment depositions are all neglected. However, the river beds and their banks are movable and sometimes unstable. Under these conditions, can one really assume that the forecasted impact and damage generated in the downstream river valley by a possible dam failure would be limited to the only consequences of the rise of waters?

The problem addressed in this paper is the definition of risk zones that are potentially at risk during a dam break by taking globally into account the maximal water level, sediment transport at the river bed and eventual induced landslides. Unlike inundation studies, our approach to the problem is based on a careful analysis of the geotechnical and topographical characteristics of the floodable zone and its neighbourhood. Such analysis allows an accurate characterisation of the erodible zones and zones of reduced stability. The solution method requires a further analysis of the flood flow in order to evaluate the potential of soil wrenching and local transport and also requires a stability analysis of river banks to identify the zones of potential landslides and include them in the risk zones.

The proposed solution uses advanced knowledge of the hydraulic and geotechnical aspects of the problem and their combination is fundamental for the comprehension of the processes involved and for the methods used to achieve the analysis. The methodology suggested in the sequel outlines our approach to the problem. To accurately study the evolution of the river bed and river banks under the impact of a dam-break flood wave, it is necessary to implement an incremental procedure and include to the hydraulic simulations the riverbanks analyses and the latest modifications of the bathymetry. It is therefore necessary to take into account the new bathymetry at the next time step and continue the hydraulic calculation. The details of the calculation scheme are explained in the following sections. This procedure is applied to a reach of several kilometres of Outaouais River upstream of Notre-Dame-du- Nord (Quebec).

2 METHODOLOGY

The phenomenon of erosion and landslide are complex processes because they depend on several characteristics such as geological, geotechnical and hydraulic conditions and involve various parameters which are seldom considered simultaneously. Moreover, the lack of the fundamental knowledge of the phenomena could hinder its realistic simulation. The complete gathering of the field data and detailed numerical modeling of the phenomena require considerable resources, especially if one is interested in studying a long reach of the river valley.

The large outflows associated with the dam-break flood wave can cause in various zones significant modifications to several sections of a river. The average slope of the bank profiles of these sections, in equilibrium before the failure, can exceed the angle of repose of the talus slope following erosion resulting from the rupture.

The adopted approach is based on a sediment transport model, able to evaluate the evolution of the river's sections under the effects of erosion, coupled with a slope stability calculation model for the river banks. The stability of the banks can be assessed at any time of the dam failure hydrograph. The valuable information regarding the erosion and bank stability is therefore available for all the sections of the river. The approach is based on a combination of two models GSTARS (river erosion) and BISHOP (slope stability), which will be presented in the following sections. After a short description of the models coupling, the algorithm for the simulations will be discussed in more details.

2.1 GSTARS model

The Generalized Stream Tube model for Alluvial River Simulation (GSTARS, Yang et al., 1998) is a one-dimensional hydraulic and sediment transport model for use in natural rivers and manmade canals. The model was developed by the U.S. Bureau of Reclamation.

The sediment transport calculations are carried out after the evaluation for each flow, of the backwater curve obtained using a one dimensional model along the river reach being studied. This hydraulic model allows the computation of quasi-steady flows for which the discharge hydrographs are approximated by bursts of constant discharge. The hydraulic computations allow therefore the use of conceptual stream tubes along the whole river reach while adapting locally to the existing conditions at some sections. A sediment routing and transport calculations are then performed for each stream and sediment size fractions. GSTARS offers various formulae of sediment transport depending on the existing soil conditions and sediment types of the section along the reach. For each section, GSTARS takes into account the balance of the volumes of bed sediment erosion and deposition. This allows the detection of the sections which may undergo erosion or global accretion.

One of the features that GSTARS offers is the capability of varying and adjusting the form of the section. In the event of total erosion, GSTARS will not systematically deepen the section to remove the necessary volume. Other adjustments can also be achieved by widening the cross section. The choice of deepening or widening of the section is commanded by the minimization of the total stream power of the reach.

2.2 BISHOP model

The BISHOP model was developed in order to carry out and automate the stability analyses of river banks. This model, which is subsequently coupled to the model GSTARS, is capable of taking into account the groundwater level distribution and the hydrostatic pressure of water in the river. Landslides calculation with the BISHOP model are based on circular slip surfaces

Program BISHOP determines a safety factor evaluating the potential risk of a landslide a long the river bank using the Bishop's simplified method (Phillipponnat and Hubert, 1997). For each river bank (two banks per hydraulic section), this model determines automatically the slip-circle having the minimal safety factor. It is thus possible to determine the length of retreat of the edge of the bank following a landslide. This allows the calculation the setback length of the edge of the river bank after a landslide. The setback length is subtracted from the edge position of the river bank determined by GSTARS. In this regard, the maximum extent of the soil erosion-landslide is determined at every moment and after the flooding, which allows the delineation of the safety zone as a preventive approach in the event of dam break.

2.3 *Coupling GSTARS/BISHOP*

The model GSTARS is launched by setting the conditions before the dam-break and using the flood's hydrograph. One of the results files of GSTARS describes the time dependent evolution of the sections. Several possibilities of data processing can be considered.

It is possible to transfer the characteristics of the sections and water levels at regular intervals to the BISHOP model in order to test the stability of the river banks during the flood event. This approach allows the monitoring of the evolution of the river banks stability and the assessment of the onset of bank instability which require an intervention of the civil authorities.

In the event of bank failure, the new geometry of the sections will be taken into account and the numerical simulations are carried out for the next time step using GSTARS. The transfer can also be only applied to the conditions after the passage of dam failure hydrograph. The assessment of stability in this case should be rather perceived for long-term.

2.4 *Flow chart of calculations*

The flowchart depicted in fig.1 explains the various logical steps leading to the predictions. The first step is the input of the hydraulic and geotechnical data (stratigraphy, cracking formation on the slope top, talus actual height and natural angle of river banks), which are supplemented by the test results carried out on some collected samples (granulometry, liquid limits and plasticity limits, cohesion and critical shear stress). An assessment of the state of natural stability is obtained.

In the second step, we consider successively the various possible scenarios of dam failure for which the following procedures will be reiterated. Analyses of hydraulic calculations specific to each scenario and to each zone being studied provide the evolution of the flow, the water level and velocity speeds and therefore the evolution in time of the shear stresses that are applied to the river bed.

In our approach, we simulate step by step the time evolution of the river reach subjected to the potential dam-break flow. We take into account simultaneously the hydraulic and geotechnical aspects and their coupling. Indeed, each section of this river reach undergoes changes caused not only by the river hydraulics, mainly sediment erosion and deposition but also by the possible landslides which eventually change the river bank profiles. Both mechanisms develop in parallel.

The initial hydraulic and geotechnical characteristics are first defined and then will be used for testing the slope stability for various sections that are representative of the river reach before the dam-break. The hydraulic and sediment transport model GSTARS determines the flow characteristics and the erosion potential of the bed for each time step. In the absence of erosion, the analysis is advanced for the next time step. If the erosion occurs, at least around one river bank, the new sections representing the bed at the end of the time step are tested for the stability of their slopes. Stability is evaluated for drained conditions for the first potential profile slide and with none drained conditions afterwards. The Bishop's simplified method is adopted for the analysis of stability and the search for the location of the centre of the slip-circles is automated. In the absence of rupture for all the sections, the simulation is advanced to the next time step. If there is rupture, the profiles representing the unstable slopes are modified based on a distribution rule of the mass wasting deposits of the unstable talus of the section being studied and the calculation are carried on (for the next time step) using the hydraulic-sediment transport model. The simulation is ended by a long-term stability analysis using the river sections obtained after the passage of the dam failure hydrograph.

Using this approach, we can draw a map delineating the zones of ultimate limits of instability, i.e. by extending the zone of instability which may develop in the long term, even when the condition are back to normal.

Although this methodology is based on recent and reliable models which are in routinely improved, when analyzing the results it is always important to bear in mind the inherent random aspects that are specific to the geotechnical characteristics and the fact that the solid transport laws are essentially valid in a steady state regime. Their extension to unsteady flood flow regimes is not straightforward.

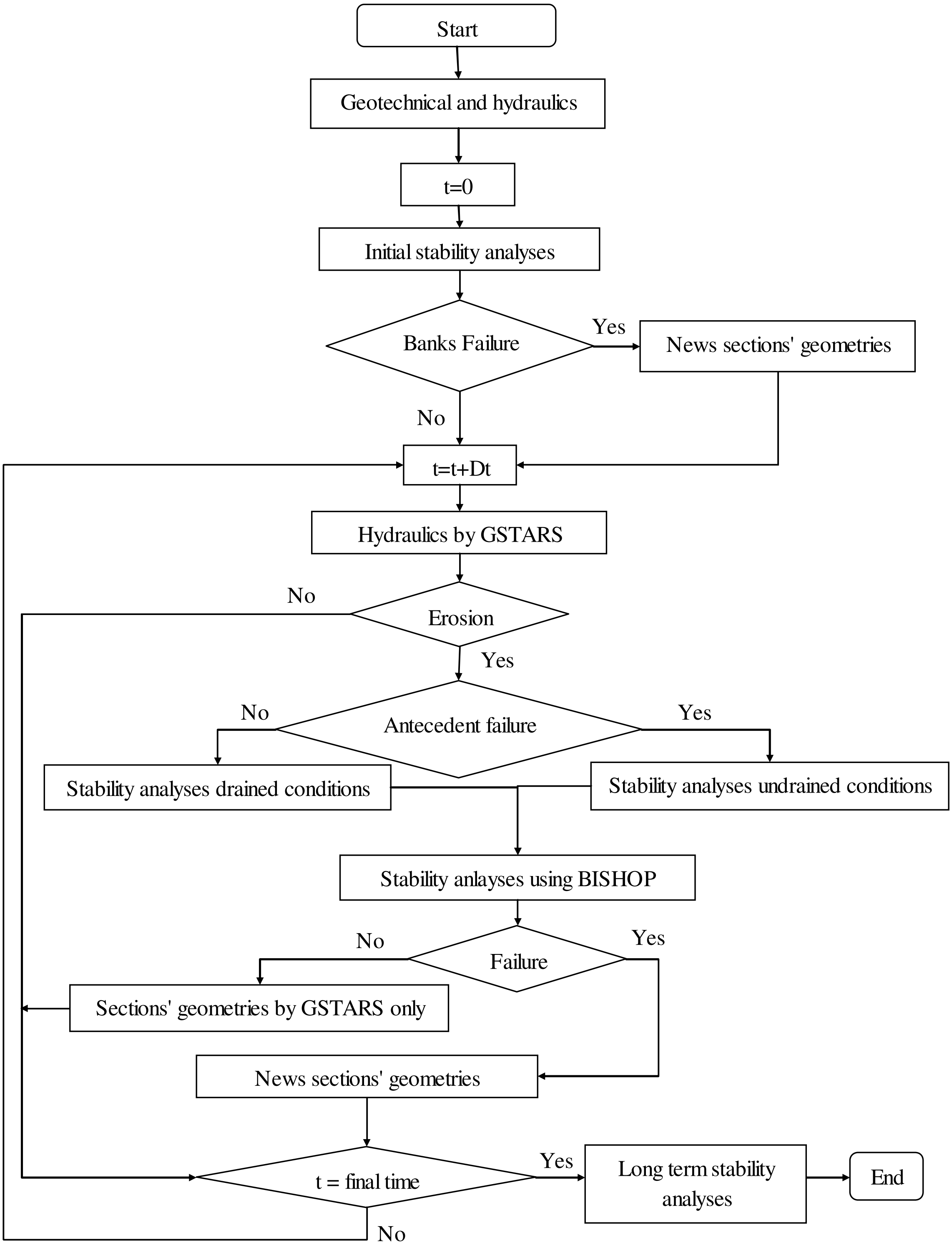

Fig.1. Detailed analysis methodology.

2.5 *Definition phase of risk zones:*

Once the simulations are completed, the cumulative results obtained using this approach allows a cartographic characterization of the risk zones, which may be unstable according to the prescribed conditions and assumptions. The risk zones can be drawn on a digital map representing the river reach being studied. A legend representing the setbacks and depicting the position, color and line thickness along the initial river bank edges allows a better visualization of the risk zones.

3 APPLICATION TO THE OUTAOUAIS RIVER REACH

A river reach located between the Dam "Première Chute" and lake "Témiscamingue" was selected as a demonstration site for the proposed approach. The presence of cohesive sediments along the river and the steepness of slopes of the local banks make this location an ideal study site.

3.1 Site description

The reservoir "Première Chute" is the last constructed dam on the "Outaouais supérieure" before the river mouth discharge in the "Lake Témiscamingue". Approximately seven kilometres separate the dam from the northern entry of the "lake Témiscamingue" by the Outaouais River. Just after the dam exit, where the flow is westward, the river undergoes an elbow change in direction towards the north then returns along a gradual curve to the south-west direction. At the exit of the dam, the river bed is broad and one notices the presence of an island made up primarily of rock and debris. Afterwards, the river narrows gradually and then remains almost of constant width until the bridge "Notre-Dame du Nord" at 3.3 kilometres. Finally it widens towards the "lake Témiscamingue" at the junction of "la Pointe Miller". On most parts of the reach, the river banks are high, abrupt and susceptible to erosion.

The data characterizing the river banks is collected from several sources. Two technical reports were published by Hydro-Quebec: St-Arnaud (1981) and Lalonde el al. (1981). Thibault (2000) summarized the data available by compiling information obtained from Hydro-Quebec and the Transport Department. Aerial photographs were used to carry out a photo-interpretation of the studied reach. Geotechnical drillings were also carried out in the area. Observations and field studies on the ground were conducted to assess the vegetation cover, the height and the angle of the slopes. Soil samples were collected and used for geotechnical measurements and analysis. To validate and update these data, a field visit to the study area was organized by researchers from École Polytechnique (Quebec) and the Laval University (Quebec) between the 4 and September 8, 2000. During this period, comprehensive information was collected regarding the geometry of the river banks, the active erosion zones, the recent slips and landslides. Soil samples of were collected for further analysis and the bathymetry of the river was updated and completed. Finally, several technical reports regarding landslides were consulted during a visit to the city hall of the municipality of "Notre-Dame-du-Nord". A first compilation of this data will be presented in the next section.

3.1.1 Characteristics of the soil of the river banks

The area of the river being crosses a zone of clay deposits that were formed after the retreat of the glaciers. The major parts of the river banks therefore consist of clay with sand layers at the surface (0.5 to 1.5 m) in several locations. Drillings show the presence of a layer of granular soil of several meters of thickness beneath the layer of clay. The height of the talus slopes decreases towards downstream. Several elements control the river course or limit the bank and bed erosion. For instance, an increase in the width of the river downstream the bridge would be caused by the proximity of a rock base under the western abutment of the bridge. The deviation of the river at 1500 m upstream of the bridge could be explained by the presence of a bottom rock base at a lower depth under the sand point of the left bank. The observed clay is varved and characterized by the alternation of dark layers (very argillaceous) and pale layers (fairly silted). Table 1 presents a summary of results obtained from laboratory and field tests. The low values of the shear stress strength show that clay is sensitive to remolding, but not low enough to produce quick clay flow. However, erosion at the talus toe is more obvious on most parts of the river.

Table 1. Geotechnical data

Parameters		Results	
Granulometry (< 2 μm)	Clay layer	80% to 90%	
	Silt layer	35%	
Moisture content (W)	Clay layer	60% (<I_l)	
	Silt layer	25% to 35% (~ I_l)	
Vane test Nilcon	Undrained cohesion (Cu)	Near the surface	90 kPa
		6.5 m	45 kPa
		> 6.5 m	Increase by 2 to 3 kPa/m
	Remold undrained cohesion Cur	2 to 4 kPa for 6 m of depth	
Swedish fall cone test	Remold undrained cohesion Cur	4 to 12 kPa	

3.1.2 River bank topography

The height of the river banks decreases in the downstream from 25 m, near the power station, to reach 5 m at the mouth of Lake Témiscamingue. The average slopes are about 20 to 25 degrees. Only the right bank area, close to the old camp-site, presents an almost vertical slope (see Figure 6). The depth of the thalweg and the angles of the river banks were determined.

The banks do not go downwards with a mild slope into the river. There is often a terrace of approximately 1 m. After this terrace, the banks ascent up according to the average slope. Breaks on the slope can be observed in the cases of former circular slip surfaces.

Observations regarding the height and the average slope angles were made for many sections of the Outaouais River, for both sides of the river banks. It is noticed that in general, the right bank is higher than the left bank, the river having crossed a tilted plateau and going downward the South-East. Moreover, the steep angles observed towards the right bank lake are probably due to the erosive action of the wind generated waves by the winds on the lake.

3.1.3 Normal hydraulics conditions

The hydraulics turbines at the hydroelectric power plant of “Première Chute” need a maximum flow rate of 630 m³/s and the maximum capacity of the spillway is 3033 m³/s. The maximum flow rate at the site will never exceed 3663 m³/s. The water level of “Lake Témiscamingue” influences the downstream reach of the river. This water level (maximum of 179 m) depends on the flow rate and the lake management.

3.1.4 Dam break’s hydraulic conditions

The scenario used for this application corresponds to the cascading failure of the upstream dams of ‘‘Rapide des Quinze’’ and ‘‘Rapide des Iles’’ causing the dam break of “Première Chute”. Fig.2 illustrates the dam break hydrograph at “Première Chute” with a maximum of 9780 m³/s.

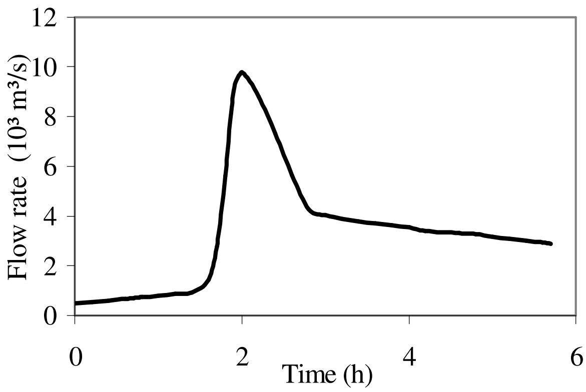

Fig.2. Dam break flood hydrograph at ‘‘Première Chute’’.

3.2 Results

Fig.3 shows the evolution of river bottom at a typical section (section 46) during the passage of the dam break flood. After 8 hours, the average erosion stabilized around 0.5 m.

Fig.4 illustrates the right bank retreat evolution at the same section. As long as the safety factor is greater than 1, the retreat is nil and it starts after 3 hours to stabilize around 4.25 m after 8 hours.

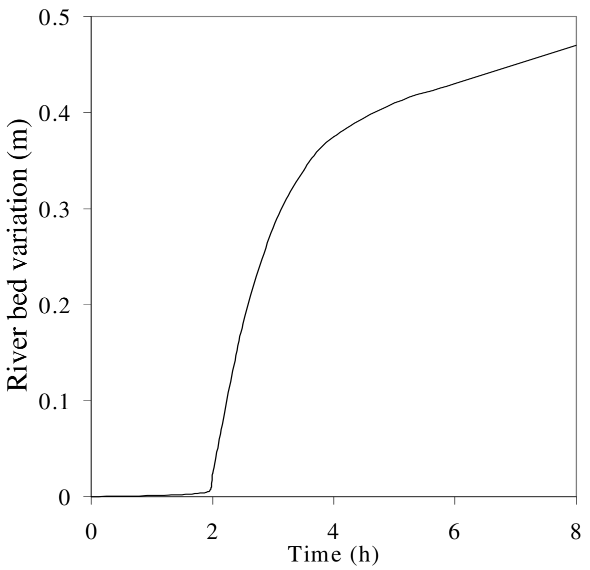

Fig.3. River bed Variation at section 46 during the dam break flood.

This methodology allows the monitoring of the safety factor of all the hydraulics sections along the River-banks. Fig.5 shows an example.

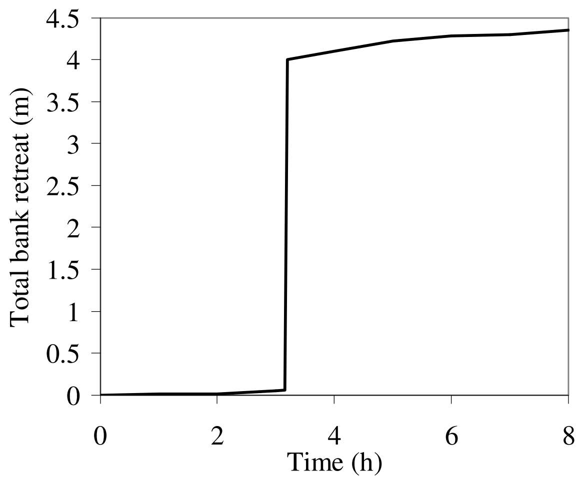

Fig. 4. Right bank retreat evolution at section 46 during the dam break flood.

3.2.1 Definition of risk zones:

A map of the risk zone is presented in fig.6 (exaggerated graphically by ten folds). The zone the most potentially affected would be out located at the right bank at the mouth outlet of the river into the lake. Setbacks reaching 80 m are predicted, but this are is unpopulated. Around the bridge of Notre-Dame-du-Nord, setbacks ranging from 6 to 8 m are predicted at the left river bank. Setbacks could reach over 10 to 12 m at the right bank. This river bank, from the power station until the bridge, is affected extensively and could present retreats ranging from 15 to 17 m at several locations.

4 CONCLUSIONS

In a dam break flood event, most rivers undergo important inundations. The limits of the potentially inundated area define actually the risk zones. The security of the habitants of those zones and the properties are the present preoccupations in the emergency plans conducted by the dam proprietors and the cities.

However, in some cases, the dangerous zone may be larger than the inundated one which is established under a fix topography hypothesis. The erosions and dam breaks induced landslides may extend significantly the risk zones.

The proposed methodology in this article allows the delimitation of the veritable safety zone along river banks by taking into consideration not only the flood risks but also the induced landslides. Indeed , each section of the river reach is subject to changes caused by the river hydraulics via the associated erosion or sediment deposition and also undergoes profile changes caused by possible landslides. This methodology produces on every riverbank a limit of potential impact.

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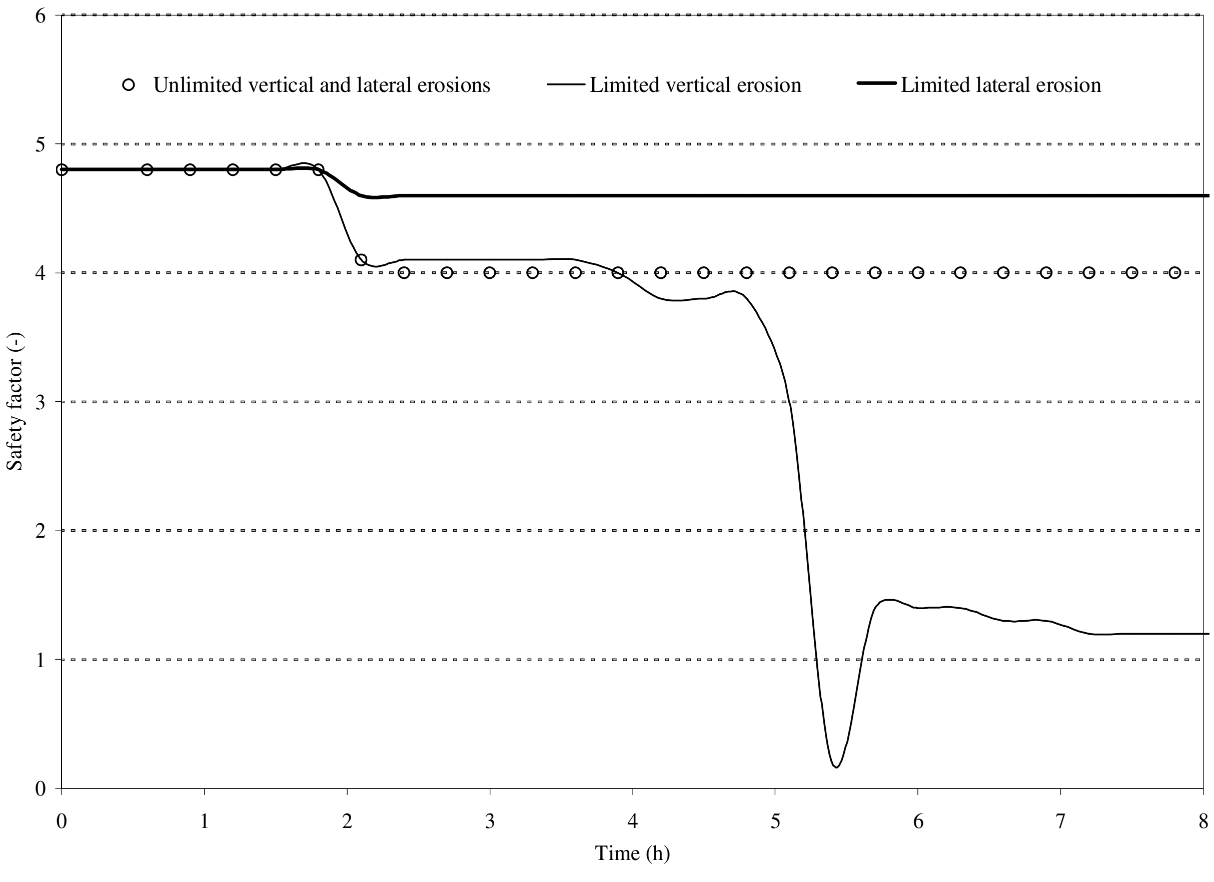

Fig.5. Comparison of the evolution of the safety factor of a bank for 3 scenarios: unlimited vertical and lateral erosions, limited vertical erosion and limited lateral erosion.

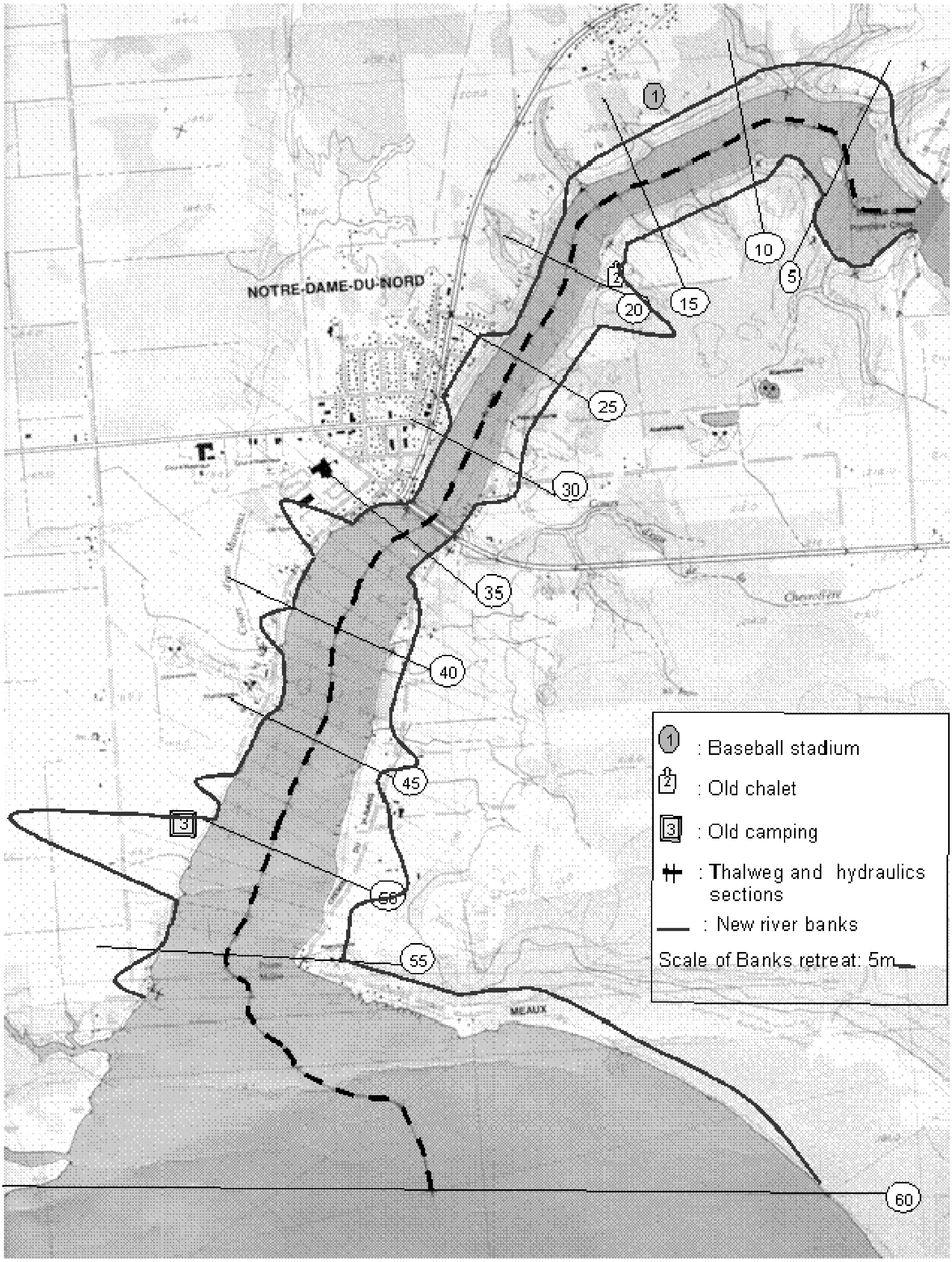

Fig.6. Riverbanks retreats after dam break occurrence (retreats are 10 times exaggerated)