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Nardi, Laura; Rinaldi, Massimo

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Modelling riverbank retreat by combining reach-scale hydraulic models with bank-scale erosion and stability analyses

L. Nardi & M. Rinaldi
Dept. of Civil and Environmental Engineering, University of Florence, Italy

ABSTRACT: In recent years many progresses have been made in understanding and modelling bank erosion processes, but an accurate quantification of shear stresses exerted by the flow on the bank area, and consequently of the fluvial erosion rate continues to be a challenging issue. The objective of the present research is to test different methods to evaluate the rate of riverbank retreat. The first step of the research consisted in data collection, which included field surveys along a study reach of the Cecina River. Different hydraulic models have been selected in order to calculate the flow parameters involved in the quantification of erosion rates, with an attempt to test new methods for the estimation of near-bank shear stresses, and subsequently to link them to bank erosion models. Specifically, we have employed a method recently developed by Kean & Smith (2006) to determine the form drag exerted on small-scale topographic bank features and thus to quantify the near-bank flow field. Mass failure analyses have been carried out applying the Bank Stability and Toe Erosion Model (BSTEM) on the eroded profiles obtained from the fluvial erosion analysis. Results and comparisons of the different methods are discussed.

Keywords: Riverbank retreat, Fluvial erosion, Near-bank shear stress, Bank stability

1 INTRODUCTION

Riverbank retreat is a key mechanism in river morphodynamics, and its quantification requires a combination of bank stability methods, typically applied at the bank-profile scale, with hydrodynamic models to obtain the flow parameters necessary to estimate fluvial erosion. Several progresses have been done during the last years in modelling bank failures at the scale of single bank profiles (see for example Rinaldi & Casagli, 1999; Simon et al., 2000; Abernethy & Rutherfurd, 2000; Rinaldi et al., 2004; Pollen & Simon, 2005; Darby et al., 2007; Pollen & Simon, 2008). At the same time, several progresses have been achieved in the field of hydrodynamic modelling, as demonstrated by the increasing diffusion of a wide range of commercial softwares (i.e. RIVER2D, TELEMAC 2D, FaSTMECH, SSIIM, DELFT3D, CCHE3D, TRIVAST among others). However, few attempts have been done to link bank stability with hydrodynamic flow conditions at the reach scale. Recent works of Rinaldi et al. (2008) and Luppi et al. (2009) have provided examples of hydrodynamic reach-scale modelling combined with bank stability modelling at bank-profile scale. However, the following limitations of this modelling system can be remarked: (1) the extremely time intensive computation effort for some components (i.e. hydrodynamic and groundwater flow modelling) do not encourage its use for more extensive applications; (2) near-bank shear stress remains the most critical component to characterize, since direct measurements and numerical modelling are both difficult.

The general aim of our research is to explore other possible modelling methods more suitable for a combined bank stability analysis at the reach scale and attempting to address the previous limitations, with particular focus on the inclusion of near-bank shear stresses. In this paper, the general structure of the modelling methods, and some example of application of different models along a study case are presented and discussed.

2 STUDY AREA

The study case (Figure1 and Figure 2) is located in the middle–lower part of the Cecina basin

(Central Tuscany, Italy) where detailed GIS analysis on multi-temporal series of maps and aerial photos have shown the highest rates of river-bank retreat, with 2.7-3.8 m/year over the period 1994-2004. The catchment has an area of about 905 km^2, and the river has a total length of about 79 km. The middle and lower parts of the catchment are dominated by hilly slopes constituted by erodible fluvio-lacustrine and marine sediments, and the river is sinuous and locally meandering.

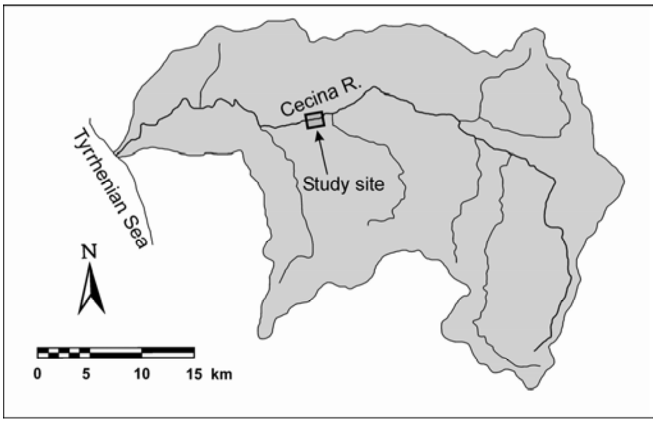

Figure 1 Cecina basin and location of the study reach

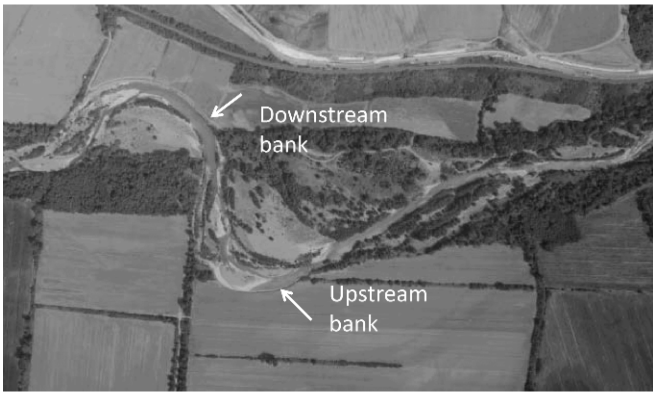

Figure 2. 2006 aerial photograph showing the study reach and monitored bank (aerial photograph reproduced by permission of Provincia di Pisa).

The eroding banks within the study reach have vertical extension ranging from 2.0 to 3.8 m. Although the lateral bank stratigraphy is quite variable and includes several sedimentary layers (gravel, sand, sandy silt, massive silt or silt and clay), the banks can be described as being composed of a cohesive upper portion overlying a gravel toe.

3 METHODS

The research has been carried out according to the following steps: (a) data collection; (b) hydrodynamic modelling; (c) numerical implementation of the Kean & Smith (2006a, b) model; (d) fluvial erosion; (e) bank stability.

Data collection included a detailed topographic survey obtained by a differential GPS, grain size distributions of bank materials, measures of the critical shear stress for cohesive materials by the use of the CSM (Cohesive Strength Meter) (Vardy et al. 2007), and measures of the small scale bank roughness at 5-cm intervals on representative reaches of two eroding banks, as required by the Kean and Smith model.

Hydrodynamic modelling included the use of two different types of numerical simulations: 1D model (HEC-RAS 4.0), and River 2D, a two dimensional depth averaged finite element hydrodynamic model developed by the University of Alberta.

The Kean & Smith model for determination of form drag for regular and irregular sequences of topographic bank features was implemented in MatLab environment. The roughness elements are modelled as Gaussian-shaped features. The form drag on an individual roughness element is determined using the drag coefficient of the individual element and a reference velocity that includes the effects of roughness elements further upstream. In order to define the near-bank flow field, an outer velocity at the boundary of the bank region, where the flow is not affected by the roughness elements on the bank, is required. The outer velocities have been therefore calculated throughout the two hydrodynamic models. Both simulations have been performed in steady state conditions, for different discharges, from 45 m^3/s up to 671.2 m^3/s (return period of 15 years).

Near bank shear stress has been obtained by applying different methods (see Flow chart in Figure 3), as follows:

1 Since the study case is characterized by the presence of a meander, results of the mean shear stress obtained by HEC-RAS have been modified according to Soil Conservation Service diagram (1977) to account for the effect of curvature. Afterwards, the near-bank shear stresses have been obtained by applying the Simons and Senturk (1977) distribution.
2 Simulations performed by River2D directly provided shear stresses along the bank profiles for the different simulated discharges.
3 Hydraulic models provided input data (values of the flow depth and velocities within the region of the flow unaffected by bank roughness, i.e. the outer boundary layer) required by the Kean and Smith model. Different values of near bank shear stresses have been obtained by the model starting from both HEC-RAS and River2D simulations.

Regarding fluvial erosion, an excess shear stress formula (1) (Partheniades, 1965, Arulanandan et al., 1980) has been applied to quantify the rate of fluvial erosion (ε):

$$\varepsilon = k_d(\tau - \tau_c)^a \quad (1)$$

where ε (m s^{-1}) is the fluvial erosion rate per unit time and unit bank area, τ (Pa) is the boundary shear stress applied by the flow, k_d (m^3 Ns^{-1}) and τ_c (Pa) are erodibility parameters (erodibility coefficient, k_d, and critical shear stress, τ_c) and a (dimensionless) is an empirically derived exponent, generally assumed to equal 1.0.

Finally, bank stability analysis was carried out by applying the USDA-ARS Bank-Stability and Toe-Erosion Model (BSTEM). The model was originally developed by Simon et al. (2000), then extended to account for the main effects of vegetation (Pollen and Simon, 2005) and extensively applied to various studies (e.g. Cancienne et al., 2008).

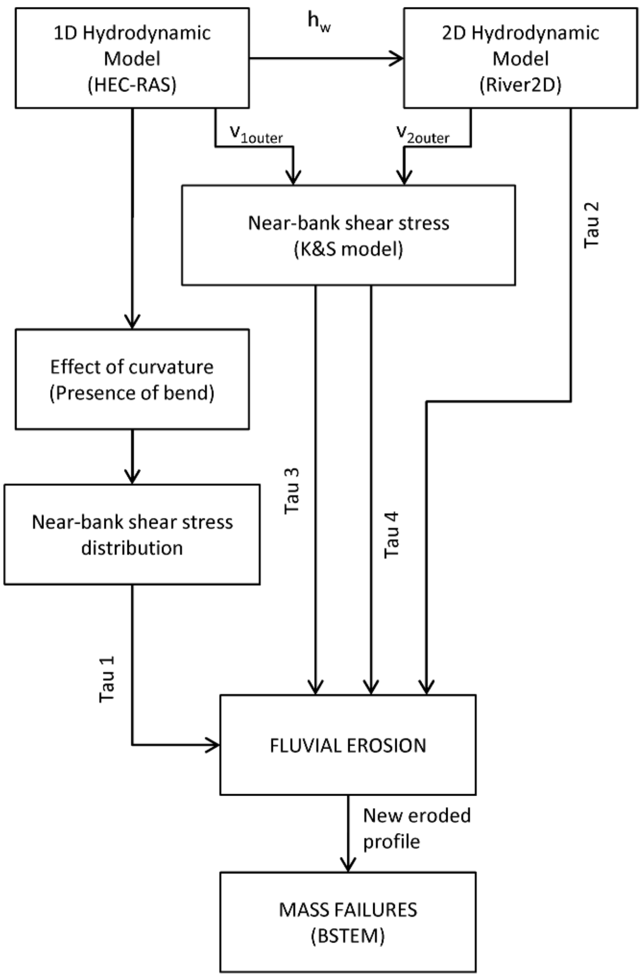

Figure 3 Summary of tested models. h_w is the downstream water surface elevation obtained by the 1D model and used as boundary condition for River2D mdel; Tau 1 is the near bank shear stress obtained by applying formulas from literature (Simons and Senturk, 1977); Tau 2 is the shear stress calculated by River2D; v_{1outer} and v_{2outer} are the velocities obtained respectively by the 1D and 2D hydraulic model at a distance where bank roughness does not produce any effect on the flow ; Tau 3 and Tau 4 are the near bank shear stresses obtained by Kean and Smith model (K&S) starting with v_{1outer} and v_{2outer} , respectively.

Although BSTEM also includes the computation of fluvial erosion rates, this model was used here only for bank stability analyses. One of the main reason of this choice is that BSTEM does not allow the user to specify shear stress as input data. BSTEM calculates the factor of safety (FS) for planar and cantilever failures in multi-layer riverbanks by using the following limit equilibrium methods: horizontal layers (Simon et al., 2000), vertical slices with tension crack (Morgenstern and Price, 1965), and cantilever failures (Thorne and Tovey, 1981).

The analyses have been carried out on the eroded profiles obtained from the steady flow simulations, assuming a duration of 3 hours and using discharges contained within the cross sections. Bank profiles are described with 23 points, which are the maximum number of coordinates allowed by the model. Below the water table, pore water pressure calculations are based on hydrostatic pressure distribution. The same formula was used to estimate the negative pore water pressure (matric suction) above the water table. Failure plane angle corresponding to the minimum value of the factor of safety is calculated.

4 APPLICATION AND RESULTS

Bank retreat analyses have been focused on two representative riverbanks along the reach: although both of the banks are composed of different layers (Figure 4), they have been schematically represented as composite banks, with a lower gravel layer and an upper cohesive layer. Bank parameters required by the models are reported in Table 1.

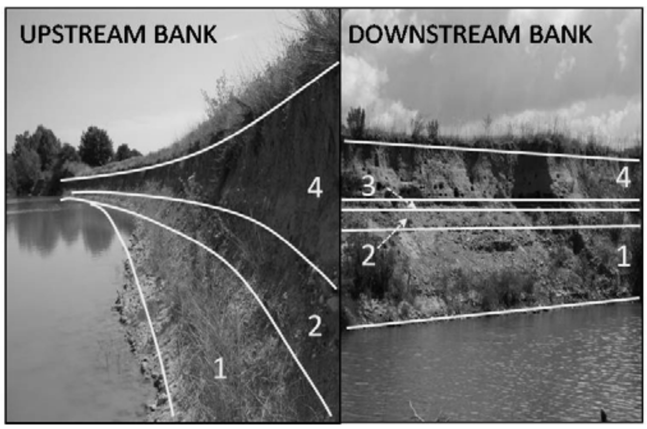

Figure 4 Upstream and downstream banks. Boundaries between the different layers of the banks are marked by lines. Numbers in the photos represent different materials: (1) Coarse gravel/ cobbles and sand; (2) Fine gravel and sand; (3) Sand; (4) Sandy silt

In particular, for the cohesive material, critical shear stresses (τ_c) have been measured by the cohesive strength meter (CSM), while erodibility coefficients k_d (both for granular and cohesive material), critical shear stresses for the gravel layer (for which direct measures are not available), and geotechnical parameters for the cohesive layer (ϕ', c', and ϕ^b) derive from previous researches (Rinaldi et al., 2008, and Luppi et al., 2009) carried out on a bank with similar characteristics.

Table 1 Parameters used for the bank erosion modelling at the upstream and downstream bank, both for cohesive (C) and gravel (G) layer. τ_c is the critical shear stress; k_d, the erodibility coefficient; D_{50} the mean grain size; ϕ' the effective friction angle; c' the effective cohesion; ϕ^b the matric suction angle; γ_s the saturated unit weight; σ and H are the streamwise length scale and the protrusion height of the element roughness, respectively.

Bank	Upstream		Downstream	
Layer	C	G	C	G
τ_c [Pa]	1.25	8.1	1.58	8.1
k_d [m^3/Ns]	4.97E-06	6.14E-06	4.97E-06	6.14E-06
D_{50} [mm]	0.038	6.7	0.038	10.9
ϕ' [deg]	35.9	36	35.9	36
c' [kPa]	3.9	0	3.9	0
ϕ^b [deg]	25.5	15	25.5	15
γ_s [kN/m^3]	20.2	20	20.2	20
σ [m]	0.9915	0.2804	0.9915	2.94
H [m]	0.1621	0.0745	0.1621	0.75

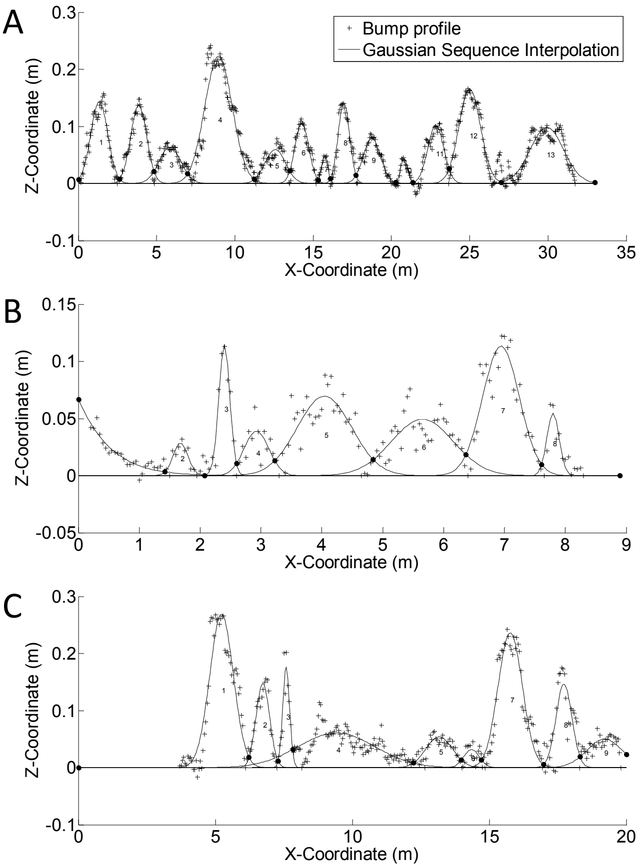

Figure 5 Measurements and Gaussian fit of the topographic elements for the characterization of the small-scale bank roughness at: (A) cohesive layer of the upstream bank; (B) gravel layer of the upstream bank; (C) gravel layer of the downstream bank.

Geotechnical parameters for the gravel layer are those provided by BSTEM for that type of material.

A series of measurements of the amplitude of the topographic elements with 5-cm intervals, respectively along the cohesive layer of the upstream bank, and along the gravel layer of both (upstream and downstream) banks have been first carried out. The characteristic parameters of the Gaussian shapes (Figure 5) which describe the roughness elements on the banks (protrusion height, H; streamwise length scale, σ; and spacing between crests, λ) have been determined from these measurements. The same parameters of the upstream bank have been assumed for the cohesive layer of the downstream bank, since no measures were available there.

Near bank shear stresses have been determined for the two selected riverbanks. Analyses have been carried out up to the maximum value of discharges contained within the cross sections, that is 302.3 m^3/s (2 years return period) for the upstream bank, and 432.6 m^3/s (4 years return period) for the downstream bank.

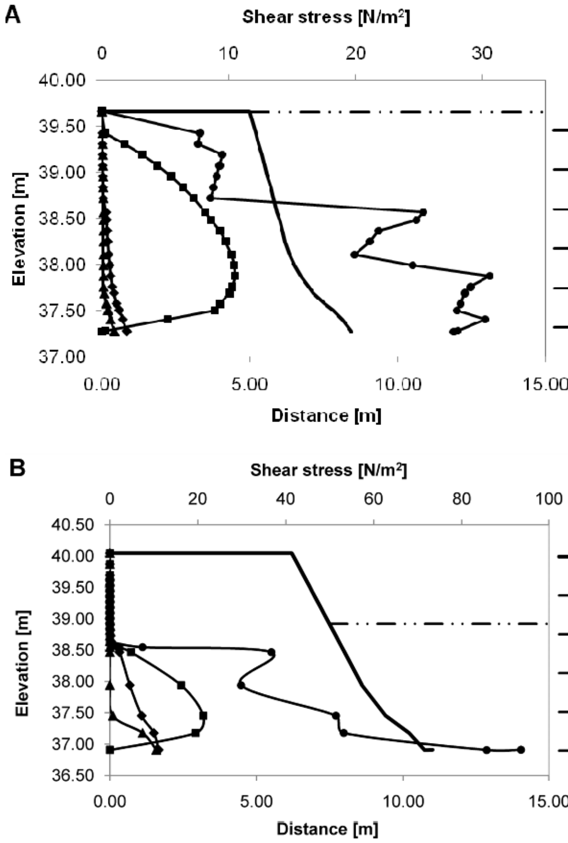

Figure 6 Value of near bank shear stress obtained by applying different methods on the upstream (A) and downstream (B) bank. BP is the bank profile; WSE is the water surface elevation obtained by River2D model; Tau 1 is obtained by applying the Simons and Senturk (1977) distribution of shear stress to the results of the 1D model; Tau 2 is derived directly from the River2D model; Tau 3 and Tau 4 are the near bank shear stresses obtained by the Kean and Smith model starting with velocities in the region where the flow is not affected by the presence of the roughnesses calculated with HEC-RAS or River2D.

In Figure 6 values of near-bank shear stresses, obtained by applying different methods for the discharge with a return period of 2 years, are plotted along the upstream and downstream bank profiles.

Shear stresses on the downstream bank are higher than for the upstream bank. In particular, values of shear stresses on both banks, directly or indirectly resulting from the River2D model (Tau 2 and Tau 4), are significantly lower than the shear stresses obtained from the 1D model (Tau 1 and Tau 3); the same results for the other simulated discharges, and values of maximum retreat are a direct consequence. In fact, Table 1 shows that the highest rates of erosion, obtained by the steady flow simulation with duration of 3 hours, occur on the downstream bank, by applying the Kean and Smith model coupled with the HecRas outputs.

The shear stresses calculated at the upstream bank with all the methods used are always lower than the critical shear stresses, therefore no fluvial erosion is predicted. Moreover, the distribution of the shear stresses Tau 3 (Figure 6) is not as regular as the distributions of the shear stresses resulting from the other models. Irregularities of Tau 3 are observed where variations in the Gaussian parameters or in the outer velocities exist. The outer velocities have been selected for each point of the bank profile at a distance of 1.8 m from the bank. Since both the 1D and 2D model provide depth averaged flow parameters, a logarithmic velocity profile has been applied in order to obtain the velocity at each node.

The shear stresses obtained with the different methods are used to quantify the rate of fluvial erosion by the application of the excess shear stress formula (1) (Partheniades, 1965; Arulanandan et al., 1980).

Table 2 provides results of maximum lateral retreat at the upstream and downstream bank after 3 hours of steady flow, for discharge contained within the cross sections.

The highest values of lateral retreat have been obtained at the downstream bank by coupling the Kean and Smith model with the 1D hydraulic model.

It is interesting to notice that, unlike results obtained using monodimensional models, values of retreat obtained by River2D do not increase with discharge. This is due to the complex relationship between flow discharge and bank shear stress induced by the presence of the bends, which induces a shifting of the main flow along a chute channel in the central part of the cross section during high flows, thereby causing a reduction in near-bank shear stresses. Same findings are reported in Rinaldi et al. (2008), although the research was carried out at a different reach along the Cecina river and a different hydrodynamic model (DELFT3D) was applied.

Table 2 Maximum lateral retreat obtained on the upstream (A) and downstream (B) banks by applying different methods. S&S: Simons and Senturk (1977) distribution; HR: HecRas model; R2D: River2D; K&S: Kean and Smith (2006) model.

BankA	Max lateral retreat [m]					
Model	45 [m^3/s]	110 [m^3/s]	148.7 [m^3/s]	302.3 [m^3/s]		
S&S	0.00	0.22	0.17	0.35		
R2D	0.00	0.00	0.00	0.00		
HR+ K&S	0.09	1.52	1.56	1.47		
R2D + K&S	0.00	0.00	0.00	0.00		
BankB	Max lateral retreat [m]					
Model	45 [m^3/s]	110 [m^3/s]	148.7 [m^3/s]	302.3 [m^3/s]	380.1 [m^3/s]	432.6 [m^3/s]
S&S	0.00	0.44	0.61	0.87	1.19	1.32
R2D	0.00	1.16	0.81	0.16	0.14	1.10
HR + K&S	0.00	1.74	2.52	5.14	5.75	5.87
R2D + K&S	0.00	0.45	0.46	0.20	0.23	0.46

Table 2 highlights the importance of selecting the appropriate model to predict the rate of lateral retreat. In fact, values provided by different combinations of models can even differ by one order of magnitude.

4.1 *Example of application*

Due to the limitations of the monodimensional modelling and to the presence of a meander along the study reach, an example of application has been carried out on results derived from the Kean and Smith model based on outer velocities estimated by River2D. The application has been carried out on the downstream bank and using a discharge of 110 m^3/s with a total duration of 15 hours. The presence of a tension crack with depth of 0.5 m is included in the bank stability analyses.

The evolution of the bank profile can be summarized in 4 steps (Figure 7). Step 0 represents the initial condition, before the occurrence of fluvial erosion. Bank stability analysis provides a safety factor (FS) higher than 1.0 (FS=5.71), therefore the initial configuration is stable.

The profile corresponding to step 1 represents the eroded profile obtained by applying the excess shear stress formula. The steady flow duration has been set to 3 hours. Although a scour occurred at the toe of the bank, bank stability analysis shows that the bank is still stable (FS=2.78).

After 15 hours (Step 2), fluvial undercutting reaches high values and it causes bank failure (FS=0.97). After the failure, the final bank profile, correspondent to Step 3, is again stable with a factor of safety equal to 1.93.

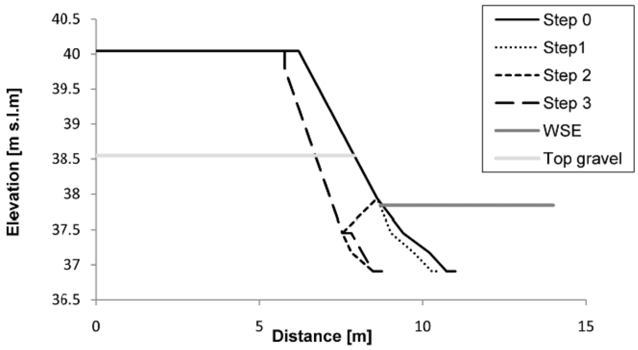

Figure 7 Downstream bank profile evolution.

5 CONCLUSIONS

In the present research numerical simulations have been carried out in order to test methods for modelling riverbank retreat at the reach scale. The efforts have been mainly focused on the calculation of near-bank shear stress, that is a key parameter in modelling fluvial erosion processes. Specifically, we have combined 1D and 2D hydrodynamic models with the method developed by Kean & Smith (2006) to determine the form drag exerted on small-scale topographic banks.

Bank stability analyses have been carried out on the eroded profiles by simulating cantilever and planar failures, and taking into account for the effects of confining pressures, pore water pressure on the saturated and unsaturated zones, and the presence of tension cracks. An example of application of coupling different models have been presented. Since results from the 1D hydraulic model have been considered to be not sufficiently adequate for the objective of the research, the two dimensional depth averaged model, River2D, has been applied in order to obtain the hydraulic parameters required by the near bank shear stress model proposed by Kean and Smith. The procedure here proposed, consisting in the combination of different selected models to simulate the key processes involved in bank retreat, appears to be suitable for larger applications to bank stability problems.

In future research, more efforts should be focused on the characterization of the gravel material. In fact, in situ tests to measure the critical shear stresses are not available for this type of materials, although it is frequently present in composite banks.

Moreover, monitored data of riverbank retreat associated to some flow events are necessary in order to assess the reliability of modelling results.

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