Sensitivity Analysis of the Effective Parameters with Respect to Cantilever Type Failure in Composite Riverbanks

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ABSTRACT

In composite river banks consist of a cohesionless material overlaid by a cohesive layer of material, bank erosion occurs by fluvial entrainment of material from the lower, cohesionless bank at a much higher rate than material from the upper, cohesive bank. This leads to undermining which in turn produces cantilevers of cohesive material. Upper bank retreat takes place predominantly by the failure of these cantilevers. The Kordan River in Iran is one example of a riverbank which is experiencing excessive erosion and bank retreat through cantilever type failure. In this research, to clarify the importance of the various parameters affecting the stability of composite riverbanks, the impacts of independent parameters affecting the stability of cantilever banks are evaluated in a series of model sensitivity analyses using a new model of riverbank stability analysis. Sensitivity analysis of the effective parameters in stability of banks against cantilever type failure, is carried out in this research for the most probable type of cantilever bank failure, i.e. shear-type failure. The results show that care should be taken when estimating the values of cantilever block height, block width, tension crack depth, block material cohesion, and the block material unit weight as the factor of safety is more sensitive to the variation of these factors. Conversely, a cruder estimation of the soil internal friction angle, matric suction angle, flow depth, and ground water level, may still provide a reasonable degree of accuracy in the bank stability analysis.

INTRODUCTION

Bank retreat is also a key process in fluvial dynamics, affecting a wide range of physical, ecological, and socioeconomic issues in the fluvial environment (Rinaldi and

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Darby, 2008). The significance of bank retreat is reinforced by studies of the contribution of bank-derived sediments to catchment sediment budgets, which have found that bank-derived materials may constitute a large fraction of total sediment yield (Simon and Darby, 2002).

In order to apply bank stability models, estimating the value of the controlling parameters that represent the various factors that affect the stability of cantilever banks is necessary. These factors include (i) the block profile (typically represented using the block height and block width); (ii) the geotechnical characteristics of the block materials (cohesion, friction angle, and density of the soil material); (iii) stream flow characteristics (e.g., water surface elevation and groundwater table elevation) that control the hydrological status (in particular the pore water pressure distribution) of the riverbanks. The degree to which the values of these parameters can be determined accurately varies according to whether they can be estimated either via direct field or laboratory measurements (though even in this case the magnitudes of the associated measurement errors will still vary) or by some other indirect means (e.g., through the use of models to estimate bank pore water pressures, tension crack depths, and the failure plane angle). The varying extents to which these controlling factors can be parameterized accurately suggests that each parameter may exert a varying influence in terms of generating uncertainty in the analysis of bank stability, but this aspect has not yet been considered in previous studies. The extent to which parameter uncertainties affect the reliability of cantilever block stability modelling therefore remains unknown.

In composite river banks consist of a cohesionless material overlaid by a cohesive layer of material, bank erosion occurs by fluvial entrainment of material from the lower, cohesionless bank at a much higher rate than material from the upper, cohesive bank. This leads to undermining which in turn produces cantilevers of cohesive material. Upper bank retreat takes place predominantly by the failure of these cantilevers. The Kordan River in Iran is an example of a riverbank which is experiencing excessive erosion and bank retreat of this nature. The study area for this research is a meander downstream of the Kordan river, part of the Shour River Basin, Iran.

The aim of this paper is therefore to identify the implications of uncertainty associated with parameterizing the factors that affect the stability of cantilever riverbanks by conducting a series of model sensitivity analyses. The results are used to provide guidelines for parameterizing bank stability models that are based on the shear type failure mechanism. In the following sections, the bank stability model used in this research, and the associated sensitivity tests are introduced.

MODELLING CANTILEVER RIVERBANK STABILITY

The factor of safety for shear-type cantilever failure is computed, since this mechanism becomes important when the basal fluvial erosion is taken into account. Cantilever analysis is restricted to the shear-type failure (Thorne and Tovey, 1981), which is the most common type observed along the simulated bank, with the factor of safety expressed by a new complete equation as (Figure 1):

$$FS = \frac{C'L + S\tan\phi^b + \left(F_{cp}\cos\theta - U_W - H_{tw}\right)\tan\phi'}{W - F_{cp}\sin\theta} \tag{1}$$

where L is the vertical length of the cantilever block (m), C' is the total cohesion of the cantilever block (kPa), ϕ' is the effective internal friction angle of block material (degrees), ϕ^b is the angle expressing the rate of strength increase relating to the negative pore water pressure (degrees), S is the force produced by matric suction on the unsaturated part of the failure surface (kN/m), H_{tw} is the hydrostatic force exerted by any water present in the tension crack on a unit width of the failure block (kN/m), U_W is the hydrostatic uplift force on the saturated portion of the failure surface (kN/m), F_{cp} is the hydrostatic confining force due to external water level (kN/m), θ is the angle between the direction of the resultant of the hydrostatic confining pressure and a normal to the failure plane (degrees), and W is the weight of the cantilever block (kN/m).

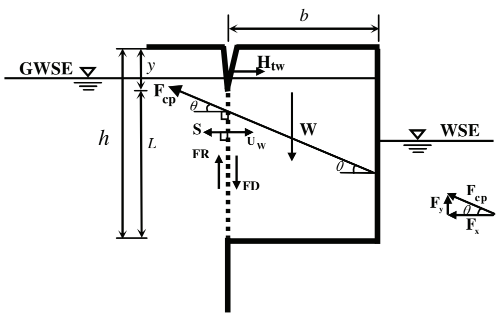

Figure 1. The bank geometry and forces exerted on the incipient failure block.

Any model is an idealization of reality and so it is helpful to briefly summarize the main limitations of the bank stability analysis. First, other types of cantilever failure (beam and tension) are not taken into consideration in the stability analysis. Second, our simulations do not account for the potential deposition of basal gravel or failed material derived from mass failures of the cohesive layer, the latter being assumed to be completely and instantaneously removed by the flow.

SENSITIVITY TESTS FOR PARAMETERS AFFECTING CANTILEVER RIVERBANK STABILITY

The key aim of this paper is to identify the implications, vis a vis the reliability of model estimates of cantilever block stability with respect to shear type failures, of uncertainties associated with the parameterization of the model input factors.

To determine the impacts of the independent parameters on bank stability, the effects of the parameters on the factor of safety (FS) are evaluated in a series of model sensitivity analyses, following the approach adopted by Van de Wiel and Darby (2007) (cited in Samadi et al., 2009). In this approach, a real cantilever block located in Kordan River (hereafter referred to as the reference block, Table 1) has been selected to provide a factor of safety representing marginal stability conditions (FS=1.088), so that an opportunity exists for variations in the parameter values to either stabilize or destabilize the block (Samadi et al., 2009). In these sensitivity tests, the range over which each parameter was varied (Table 2) was selected as follows:

(i) The reference block height (3.7 m) was varied, in the range from 1.2 to 5.0 m. These limits were arbitrarily selected, but they are sufficiently wide to encompass a wide range of riverbanks that are likely to experience the shear type failures that are the subject of the current analysis.

(ii) The tension crack depth range was selected on the basis that the maximum depth of the tension crack is half the bank height (Thorne and Abt, 1993). Based on the reference block height of 3.7 m, this gives an overall range of 0.0 to 1.85 m for this parameter.

(iii) The reference block width (0.64 m) was varied, in the range from 0.05 to 1.3 m. These limits were arbitrarily selected, but they are sufficiently wide to encompass a wide range of riverbanks that are likely to experience the shear type failures that are the subject of the current analysis.

(iv) Geotechnical parameter values (bank material cohesion, unit weight, and friction angle) were initially defined according to the range of values reported in Darby's (2005) bank material database, but with the parameter ranges extended by a factor of ±25% to ensure that the sensitivity tests conservatively encompass a wide range of natural riverbank material types.

Table 1. Properties of the reference cantilever block used in the simulations[a].

	Variable	Value
Input variables	Block height (m)	3.7
	Tension crack depth (m)	0.9
	Block width (m)	0.64
	Flow depth (m)	1.5
	Groundwater level (m)	1.5
	Bank material cohesion (kPa)	17.0
	Soil unit weight (kN/m^3)	18.0
	Friction angle (^{o})	34
	Matric suction angle (^{o})	18
Failure variables	Factor of safety (-)	**1.088**
	Slope of incipient failure plane (^{o})	90

[a] Note: Values of tension crack depth, river flow depth, groundwater table, and the matric suction angle were not measured, so their values were instead selected to ensure that the reference block's stability is marginal (i.e., to give FS=1.088).

Table 2. Range of parameter values used in the sensitivity analyses together with estimates of the uncertainty typically involved in estimating each parameter (cited in Samadi et al., 2009), and summary of the sensitivity analysis results indicating the significance of parameter uncertainty in affecting the reliability of simulated factors of safety[a].

Bank property	Range	Uncertainty due to measurement error (%)	Uncertainty due to inherent natural variability (%)	Parameter value range needed to induce a 15% change in factor of safety (%)	Effect of parameter uncertainty on reliability of bank stability estimate
Block height (m)	1.2 - 5.0	2.0	± 72	-24.6 to +35.1	Highly Significant
Tension crack depth (m)	0.0 - 1.85	n/a	± 72	-43.3 to +43.3	Highly Significant
Block width (m)	0.05 - 1.30	2.0	± 72	-12.5 to +18.8	Highly Significant
Bank material cohesion (kPa)	0.0 – 41.0	< 1	± 220	-14.7 to +15.9	Highly Significant
Soil unit weight(kN/m^3)	10.5 – 24.0	1.0	± 26	-13.3 to +18.9	Significant
Friction angle (^{o})	9.5 - 50	13.0	± 40	-73.5 to +47.1	Insignificant
Matric suction angle (^{o})	10 - 26	n/a	± 48	Not known but >> ± 48% [b]	Insignificant
Groundwater level (m)	0.0 - 4.0	1.0	± 25 (assumed)	-57.3 to +38.0	Insignificant
Flow depth (m)	0.0 - 4.0	1.0	Negligible	-100.0 to +166.7	Insignificant

[a] Note that the typical parameterization uncertainty is here taken as the largest of the two sources of uncertainty (measurement error and natural variability). [b] Since the range of simulated factor of safety induced by a wide variation in matric suction angles is so small (−2.4% to +2.7%, see Figure 3D for details), matric suction must have an insignificant impact on predictive reliability.

(v) According to Rinaldi and Casagli (1999), the magnitude of ϕ^b ranges from 10° to 26°, so this was the range used herein.
(vi) Based on the reference block height, we assumed that both the water level in the river and the groundwater level change from their lowest level (zero relative to the river bed) to the bankfull discharge level.

SENSITIVITY TEST RESULTS

In Figures 2–4, variations in factor of safety induced by varying the controlling parameters affecting cantilever block stability in the ranges stated in Table 2 are illustrated. In these diagrams, the range of parameter values that induce less than a ±15%

change in the simulated factor of safety (relative to the reference block) are highlighted by the grey-shaded areas. The ±15% change threshold is arbitrary, but is intended to represent a significant change in block stability relative to the reference block case. The shaded areas thus delineate the parameter variations (relative to the reference block) that have a relatively minor influence on the simulated factor of safety. Specifically, for those cases where the typical uncertainties for that parameter exceed the calculated ranges indicated on the diagrams, these parameter uncertainties induce large (where "large" is here defined by the ±15% threshold) uncertainties in the simulated factor of safety.

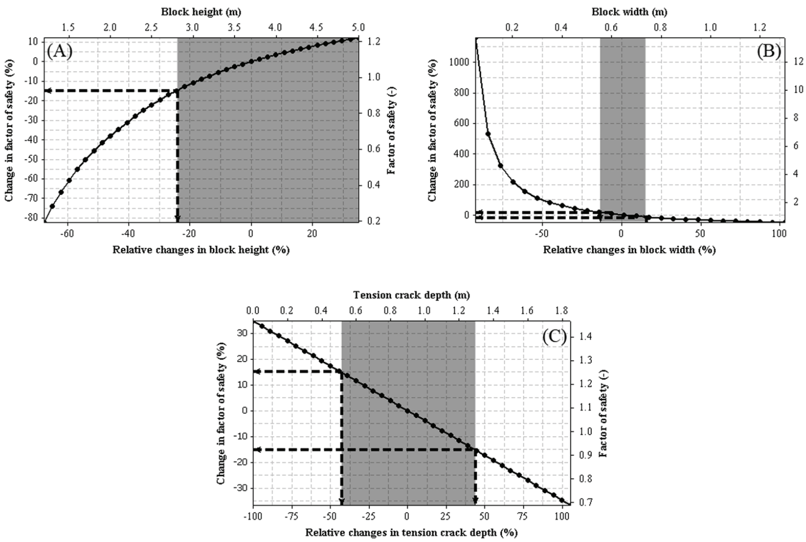

Figure 2. Simulated bank stability (factor of safety) as a function of variations in a range of bank geometry parameters. (A) Block height, (B) block width, and (C) tension crack depth for the reference block used in the sensitivity analyses (see Table 1 for definition of the reference block).

Bearing this in mind, Figure 2 illustrates the response curves obtained for the various bank geometry parameters, namely the block height (Figure 2A), block width (Figure 2B), and depth of tension crack (Figure 2C). The relationship between the parameter range (PR) and parameter uncertainty (PU) is used to determine the overall influence of parameter uncertainty on the reliability of the block stability modelling (cited in Samadi et al., 2009). This is achieved by defining four categories to describe a parameter's influence on reliability: (i) insignificant (PU<<PR), (ii) potentially significant (PU≈PR), (iii) significant (PU>PR), and (iv) highly significant (PU>>PR). In the specific case of the block height, this parameter is seen to have a highly significant impact on the reliability of the simulated factor of safety (Table 2). Similarly to the block height response curve, Figures 2B and 2C indicate that uncertainties in parameterizing the block width and tension crack depth are seen to have a highly significant impact on the reliability of simulated factor of safety (Table 2), at least for the case of the reference block investigated in this research. It can be seen that uncertainties in parameterizing the bank material cohesion and soil unit weight are seen to have a highly significant and significant impact on the reliability of simulated factor of safety, respectively (Figures 3A and 3C). However, the safety factor of the standard block is not very sensitive to the variation of the friction angle (Figure 3B), matric suction angle (Figure 3D), river flow depth (Figure 4A), and ground water table (Figure 4B), and the related uncertainty associated with error on estimating the amount of these parameters is not reasonable.

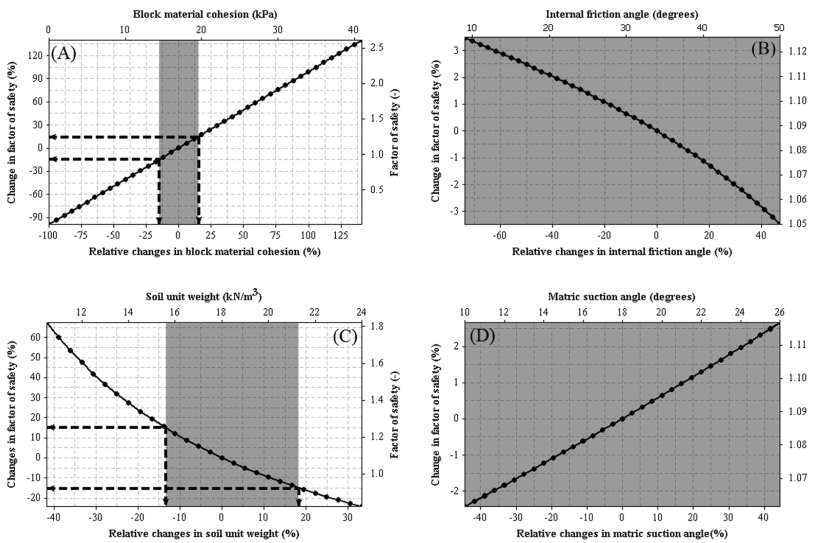

Figure 3. Simulated bank stability (factor of safety) as a function of variations in a range of geotechnical parameters. (A) Soil cohesion, (B) soil friction angle, (C) soil unit weight, and (D) matric suction angle.

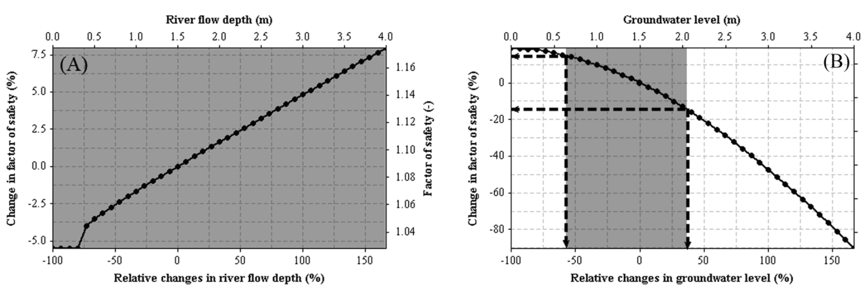

Figure 4. Simulated bank stability (factor of safety) as a function of variations in a range of hydrological parameters. (A) River water level, and (B) groundwater table.

CONCLUSION

In this research, the implications of uncertainly associated with several factors affecting the stability of cantilever banks with respect to shear-type failure are investigated by conducting a series of sensitivity analyses in this research. The sensitivity tests show the following results:

- The uncertainty associated with error on estimating the amount of cantilever block height, block width, tension crack depth, soil unit weight, and block material cohesion are quiet reasonable and the shape of all response curves is such that the factor of safety is more sensitive to changes in these parameters.
- In general, factor of safety is not very sensitive to the variation of the friction angle, matric suction angle, river flow depth, ground water table, and the related uncertainty associated with error on estimating the amount of these parameters is not reasonable. Hence, error on estimating the amount of the friction angle, matric suction angle, river flow depth, and ground water table has no significant uncertainty in factor of safety.

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