The effects of variability in bank material properties on riverbank stability: Goodwin Creek, Mississippi.

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Abstract

Bank erosion is an important area of research within fluvial geomorphology and is a land management problem of global significance. The Yazoo River Basin in Mississippi is one example of a system which is a victim of excessive erosion and bank instability. The properties of bank materials are important in controlling the stability of stream banks and past studies have found that these properties are often variable spatially. Through an investigation of bank material properties on a stretch of Goodwin Creek in the Yazoo Basin, Mississippi, this study focuses on: i) how and why effective bank material properties vary through different scales; ii) how this variation impacts on the outputs from a bank stability model; and iii) how best to appropriately represent this variability within a bank stability model.

The study demonstrates the importance that the variability of effective bank material properties has on bank stability: at both the micro-scale within a site, and at the meso-scale between sites in a reach. This variability was shown to have important implications for the usage of the Bank-Stability and Toe-Erosion Model (BSTEM), a deterministic bank stability model that currently uses a single value to describe each bank material property. As a result, a probabilistic representation of effective bank material strength parameters is recommended as a potential solution for any bank stability model that wishes to account for the important influence of the inherent variability of soil properties.

Keywords: bank erosion; bank stability model; model uncertainty; variability; probabilistic assessment of stability.

1. Introduction

Bank erosion is an important erosion process in alluvial streams and is a land management problem of global significance (ASCE, 1998a; 1998b). For example Simon et al. (1996) describe how in the loess area of the Midwest United States bank material can contribute as much as 80% of the total sediment eroded from incised channels. The Yazoo River Basin in Mississippi is one such example of a system which is a victim of excessive erosion and bank instability (DeCoursey, 1981).

The process off bank erosion is often associated with a channel response to incision through width adjustment. Conceptual models of bank retreat attempt to explain this response, describing how bank failure occurs when erosion of the bank toe and the channel bed adjacent to the bank have increased the height and the angle of the bank to the point that the gravitational forces exceed the shear strength of the bank material, resulting in mass failure (Osman and Thorne, 1988). Taking this conceptual model, the stability of river banks can therefore be considered to be controlled by a balance between the gravitational forces acting on the steepened bank, and the resisting forces controlled by the geotechnical strength of the in situ bank material. Given this threshold condition that determines bank stability, it is important to specifically quantify the driving and resisting forces in order to accurately define bank-stability thresholds.

The key component of the resisting force within this balance is the geotechnical strength of the bank material. Numerous studies have previously demonstrated the importance of soil strength in slope and bank stability. Lohnes and Handy (1968) described the importance of physical properties of the materials in their analysis of slope stability in loess and Thorne et al. (1981) used in situ tests of geotechnical properties to determine bank-stability conditions of incised streams in northern Mississippi. In more recent studies, Simon and Darby (1997), Simon et al. (2000), Rinaldi and Casgali (1999) and Darby et al. (2000), using many of the techniques described In Thorne *et al*. (1981), have all demonstrated how bank failures are triggered by changes in the geotechnical characteristics of the bank materials. This study aims to expand on this previous research and explore the variability in resisting forces that help to determine bank stability.

1.1 Bank stability analysis theory:

For the simple case of a planar failure of unit width and length, the driving (gravitational) force is given by:

$$S_d = W \sin \beta \tag{1}$$

where S_d is the driving force; W is the weight of the failure block and β is the angle of the failure plane (degrees). For saturated soils, bank resistance is represented by the revised Coulomb equation (Simon et al., 2000):

$$S_r = c' + (\sigma - \mu) \tan \phi' \tag{2}$$

where S_r is the shear strength of the bank material; c' is the effective cohesion (kPa); σ is the normal stress given by $\sigma = W \cos \beta$; μ is the pore-water pressure (kPa) and ϕ' is the effective friction angle (degrees). For un-saturated or partially saturated banks, due to the effect of negative pore-water pressures described by Simon et al. (2000), the equation derived by Fredlund et al., (1978) applies:

$$S_r = c' + (\sigma - \mu) \tan \phi' + (\mu_a - \mu_w) \tan \phi^b \tag{3}$$

where $(\mu_a - \mu_w)$ is the difference between the air pressure μ_a and the water pressure μ_w in the pores and represents the matric suction in the soil, which when summed with the inherent *effective* cohesion within the soil forms the total or *apparent* cohesion. ϕ^b describes the rate of increase in shear strength due to an increase in matric suction.

The ratio between the resisting (S_r) and driving (S_d) forces is expressed as a Factor of Safety (F_s), where a value greater than 1.0 indicates stability and where a value of 1.0 or less indicates imminent failure.

Building on previous work, Simon et al. (2000) addressed in detail the specific forces and processes controlling bank failures in incised channels and developed a bank stability algorithm for layered cohesive stream banks. This algorithm is for layered banks and is based on combining the Coulomb equation for saturated banks with the Fredlund et al. (1978) equation for unsaturated banks. The algorithm thus encompasses the influence of negative pore-water pressures on increasing bank strength, the influence of positive pore-water pressures in reducing bank strength and the supporting hydrostatic forces provided by in-channel flow, as well as accounting for the way that soil properties vary both vertically between layers and over time as moisture content changes. This algorithm became the initial version of the Bank Stability and Toe Erosion Model (BSTEM) developed at the USDA-ARS, National Sedimentation Laboratory

(Simon and Curini, 1998), an Excel based model that calculates the F_s for layered cohesive streambanks. The reader is referred to Simon et al. (2000) for further details on the derivation of the algorithm; the equation for the factor of safety is:

$$F_s = \frac{\sum c'_i L_i + (S_i \tan\phi_i^b) + [W_i \cos\beta - U_i + P_i \cos(\alpha - \beta)]\tan\phi'_i}{\sum W_i \sin\beta - P_i \sin(\alpha - \beta)} \tag{3}$$

where F_s is the Factor of Safety; c'_i is the *effective* cohesion of the material of the *i*th layer (kPa); L_i is the length of the failure plane incorporated within the *i*th layer (m); S_i is the force produced by matric suction on the unsaturated part of the failure surface (kN/m); ϕ_i^b is the rate of increase in shear strength due to matric suction in the material of the *i*th layer; W_i is the weight that the *i*th layer contributes to the failure block; β is the angle of the failure plane (°); U_i is the hydrostatic uplift force on the saturated portion of the failure surface (kN/m); P_i is the hydrostatic confining force due to external water level (kN/m); α is the original bank angle (°); and ϕ'_i is the friction angle of the material comprising the *i*th layer.

1.2 Uncertainty in bank stability analyses:

Young (1999) highlights that since the inherent uncertainty associated with modelling most environmental systems is often acknowledged, it is surprising that many models are completely deterministic in nature. In a similar application to riverbank stability, research surrounding slope stability has revealed that the heterogeneity of soils provides a major source of uncertainty in estimations of operational shear strengths within all slope design applications (El-Ramly et al., 2005), and is a well recognised issue within geotechnical research (Vanmarcke, 1977; Huang, 1983; El-Ramly et al., 2002; Duncan et al., 2003).

The case of bank erosion is no exception with the large number of influencing factors involved, and the variability within each of these factors, forming a significant level of uncertainty in the prediction of bank erosion rates (Bull, 1997). In particular the primary soil mechanics variables that control the resisting strength of river banks, including cohesion, friction angle and soil unit weight, have been found to be significantly inconsistent in several studies (Lohnes and Handy, 1968; Thorne et al., 1981; Simon, 1989; Simon and Darby, 1997). The uncertainty caused by this variability is currently recognised in the BSTEM in the form of a safety margin between Factor of Safety values of 1 and 1.3 within which banks should only be considered to be ‘conditionally stable’.

Thorne et al. (1981) originally represented this variability in geotechnical strength by calculating bank factor of safety for both the average and worst case ambient conditions during measurement. However, due to limited awareness of the important role of pore-water pressures on bank shear strength at the time there was no separation of *effective* cohesion and matric suction within their analysis. Therefore Thorne et al. (1981) were actually representing the variability in the measured *apparent* geotechnical parameters, largely controlled by pore-water pressure conditions at the time of measurement.

Darby and Thorne (1996a) also recognised the importance of variable bank material properties and attempted to provide a river bank probability of failure based on the range of soil properties present in the bank rather than the more traditional factor of safety based on a single value soil property. However, despite the useful nature of this probabilistic approach, as with the analysis performed by Thorne et al. (1981), this work was limited by its inability to distinguish measured *apparent* geotechnical parameters, caused by ambient moisture conditions, from actual *effective* geotechnical parameters.

Following a large body of research into the impact that matric suction has on the *apparent* shear strength of soils (Casagli et al., 1997, 1999; Simon and Curini, 1998; Simon et al., 2000), it is now possible to explore the true variability of *effective* soil strength parameters rather than that variation driven by soil moisture conditions. This study hopes to take advantage of this, and through an investigation of bank material properties on a stream in the Yazoo Basin, Mississippi, we focus on two issues; firstly, on how and why *effective* bank material properties vary spatially and secondly, on what impact this variability has on the output of a bank stability model.

2. Study Area, Instrumentation and Data Collection

The study area for this research is an intensively studied bendway section in the Goodwin Creek Experimental Watershed (Simon and Collison, 2002), north-central Mississippi [Figure 1]. Bank materials along Goodwin Creek consist of 1 to 2 meters of moderately cohesive brown clayey-silt of late Holocene age (LH) overlying approximately 1.50m of early Holocene grey, blocky silt of low cohesion lower permeability. These two units are separated by a thin layer (~10cm) containing manganese nodules and characterised by very low permeability. These materials overlie 1.00m of sand and 1.50m of packed sand gravel.

Figure 1

All of the data required to complete this study's aims was collected from the Goodwin Creek experimental bendway, during July and August 2005 and is based the around seven cross-sections spaced approximately 30m apart. Continuous measurements of pore-water pressures at five depths (0.30, 1.48, 2.00, 2.70 and 4.30m), surface-water stage and rainfall have been recorded at the site from November 1996, along with regular cross-section surveys following every major flow event (Simon and Darby, 1997; Simon and Curini, 1998; Simon et al., 2000).

A series of in situ shear strength measurements were taken using an Iowa Bore-hole Shear Tester (BST; Luttenegger and Hallberg, 1981). Samples for particle size, soil moisture and bulk unit weight were also taken on the outer banks of cross-sections A though G, with one cross-section (B) chosen to receive more intense measurement. In total 10 sets of measurements were taken at Cross-Section B: 5 in the upper, Late Holocene layer (LH - approximately 1.00m depth) and 5 in the lower, Early Holocene layer (EH - approximately 2.00m depth). For the remaining cross-sections the number of in situ shear strength measurements and associated particle size, soil moisture and unit weight measurements was reduced to just 2 at both the 1.00m and 2.00m depths.

2.1 Evaluation of effective geotechnical properties:

Friction angle and apparent cohesion values were obtained from the direct-shear measurements. However, since apparent cohesion is the sum of the effective cohesion (due to the soil skeleton) and cohesion caused by matric suction (ψ; negative pore-water pressures), as described above, it was necessary to account for the impact that moisture content has on generating cohesion. This was done by converting the apparent cohesion (c_a) values given by the direct shear measurements to effective cohesion (c') values using (Fredlund et al., 1978):

$$c_a = c' + (\psi)\tan\phi^b \qquad (4)$$

where ϕ^b is the rate of increase in shear strength due to matric suction.

The values for the parameter ϕ^b used within this study (9.98 in the LH layer and 19.8 in the EH layer) were derived in a similar manner to the value that Simon et al. (2000) derived for the LH unit at the same site. A series of BST tests were conducted in both the LH and EH units at the same depths as tensiometers around which the measurements were taken. The BST tests were performed over a wide range of soil-moisture conditions reached through artificially wetting the soil from a dry state. By plotting the measured apparent cohesion values against matric suction for each soil unit it was possible to evaluate the ϕ^b value for both the LH and EH layers. The ϕ^b value of 9.98 found for the LH layer correlates well with the value of 10.4 the Simon et al. (2000) found within the same layer while the value of 19.8 in the EH layer demonstrates that the value of 17.5 assumed by Simon et al. (2000)

for that layer was not unreasonable.

2.2 Generation of bank stability model test conditions:

To evaluate the effects of variability in measured effective geotechnical parameters on predicted bank stability, a synthetic test-bank condition was created based on a single surveyed bank profile and set of pore-water pressure measurements at various depths for an instance when the bank profile was at a near critical state ($F_s \approx 1$). The bank and instance chosen was Cross Section D on the 31st November 2004 at 0:00am. It is important to note at this point that the reason for choosing to isolate just one instant is that, as explained above, this study is not concerned with the impact of soil pore-water pressures, channel hydrostatic supporting forces and the effects of moisture content changes on geotechnical properties. These issues have been explored in earlier work by Simon et al. (2000), which the user is referred to. Instead, this study attempts to isolate the impact that the variation in *effective* cohesion, friction angle and unit weight properties have on predicted bank stability. In short, herein we attempt to quantify the uncertainty in bank stability estimation caused by variability of the *effective* geotechnical parameters rather than the variability of those *apparent* geotechnical parameters that are influenced by hydrological changes through time.

In order to assess how the variation in material properties influences the accuracy with which the BSTEM predicts bank failures, the necessary model input parameters for a series of past 'near critical state' instances were obtained from a combination of regularly updated cross-section surveys, historic pore-water pressure values from permanently installed tensiometers, and the *effective* bank material property values that were gathered for the intensively measured cross-section (B).

For further details on the data-collection procedure readers are referred to Parker (2005) a copy of which can be accessed through contact with the lead author.

3. Investigating the spatial variation of the geotechnical properties of a stream bank.

Table 1 and Figure 2 give details of the distributions of each of the geotechnical parameters in both the layers tested for the entire Goodwin Creek bendway. A visual examination of this data shows a significant level of variation within all of the parameters measured. This level of variability is strongly supported throughout the bank stability literature. For example, data published by Thorne et al. (1981) demonstrate similar variation throughout their measurements also taken within Yazoo Basin, Mississippi. This is due to variation in soil composition and properties from one location to another, even within homogenous layers.

El-Ramy et al. (2002) attribute this variability to factors such as variations in mineralogical composition, conditions during deposition, stress history, and physical and mechanical decomposition processes.

Also of note is the different frequency distribution shapes between the various geotechnical parameters. The friction angle values measured in both layers approximate a normal distribution, the effective cohesion values have a strong positive skew with a high concentration of values around zero, and the saturated unit weight distributions are erratic in both layers. These characteristic distribution shapes for effective cohesion and friction angle have been observed previously by other studies, notably the analysis of soil properties of slopes in Hong Kong by El-Ramly et al. (2005).

Table 1

Figure 2

Figure 3

Table 2

Figure 4

3.1 Micro- versus meso-scale variability:

Whilst it has been demonstrated that there is a significant amount of variation within the bank material properties of the Goodwin Creek bendway, it is not known at what scale this variation is present. Soil properties may vary at the micro-scale (within a single block of soil found at one cross-section bank) or at the meso-scale (between different blocks of soil found at separate locations). In order to compare the distribution of the geotechnical parameter values measured at a single cross-section (Cross-Section B) to the distribution of the average geotechnical parameter values from each of the cross-sections, exploratory data analysis in the form of boxplots has been performed [Figure 3].

Although by no means entirely consistent, a visual examination of these plots highlights a trend of wider distributions in the data obtained from all of the measured cross-sections than in the data measured just at cross-section B. However, it must be taken into account that the sample size for the data obtained from all of the measured cross-sections is slightly larger the data measured just at Cross-Section B, and this can impact on this particular method of viewing the spread of data (Coakes and Steed, 2001).

As well as comparing the variation of bank material properties within Cross-Section B to the variation of average bank material properties between cross-sections it is also possible to statistically examine the proportion of the total variation that is explained by the results being grouped into cross-sections using a one way analysis of variance (ANOVA) test [Table 2]. The results of this analysis is show that although neither layer's friction angle measurements are statistically significantly related to cross-section, there is a statistically significant relationship between cross-section and both the effective cohesion and saturated unit weight values for both layers. Also for all of the variables the eta-squared values are well above Cohen's (1988) guideline for independent variables having a large effect, suggesting that cross-section significantly influences bank soil properties.

The means plots of each parameter across the cross-section in Figure 4 support the results of the ANOVA test, demonstrating significant differences in some of the parameter values when compared across the cross-sections. Ideally any patterns in these geotechnical parameters across the cross-sections would be compared against geological survey data to find a cause for this variation. However, unfortunately the best available surveys for the Goodwin Creek catchment are crude in terms of both spatial resolution and accuracy making this impossible.

It would initially seem that the results of the above analysis are inconclusive, that the neither the variation within or between cross-sections was significantly greater than the other. However, this is not the case since these results are important in demonstrating that there is *both* a significant level of variation between sites, and also within them.

The micro-scale variability observed in this study is frequently observed in the literature. For example, Thorne et al. (1981) also found a large amount of within site variability in the Old Paleosol layer at the 'Tommy Florence' site on Johnson Creek, Mississippi, where apparent cohesion values ranged between 15.2 and 118.3 kPa. However, it is important to recognise that the variability observed in past studies like these may be partly due to variability in matric suction rather than the material properties themselves. Nevertheless, Mitchell and Soga (2005) support the idea of inherent variability of soil properties, describing how these variations in composition and texture can occur within distances as small as a few centimeters, whilst Bull (1997) goes further, describing how each of the primary soil properties described by Grissinger (1982): particle size, clay content, bulk density and ionic strength; vary over small spatial scales, impacting on interparticle strength. Further explanation of this small scale variability can be gained from Wood's (2001) description of the loess materials making up the Goodwin Creek bendway banks where she explains that the soils properties may be complex as a result of structurally controlled weathering and erosion processes such as desiccation cracking, tensile stresses and biological and chemical processes.

When considering the meso-scale, between cross-section variation, demonstrated by both the results of this study and also the variation present in other studies, such as the between site variation in Thorne et al.'s 1981 study and the between bend differences found by Simon and Darby (1997) it appears that there is a spatial control over bank material properties. DeCoursey (1981: 50) refers to this kind of variation in the banks from place to place as being a result of the:

…deposition pattern of ancient sediments and the re-working of bank and bed materials as the channel migrates back and forth through the valley.

Grissinger et al. (1982) concur, describing that the nature of the valley fill deposits in North Central Mississippi significantly influence the properties of streambank material.

4. Investigating how the observed variations in bank material properties impact the results of a bank stability model.

Before exploring the impact that the above observed variations in geotechnical parameter values have on the factor of safety values predicted by the BSTEM it is first necessary to observe the correlations between the input bank material properties [Figure 5]. This is crucial since, for example, maximum friction angle values are unlikely to occur in conjunction with maximum cohesion values and therefore it is necessary to restrict the values of input parameters to within reasonable boundaries of the general correlation found between the properties. Prediction intervals describing where any soil property measurement will fall 95% of the time have been imposed on the correlation plots, defining the boundaries that input parameter values can be drawn from. This ensures that the correlations between the geotechnical parameters are maintained during bank stability simulations.

Figure 5

Figure 6

A sensitivity analysis of the BSTEM to each of the geotechnical input parameters within the ranges observed at the Goodwin Creek bendway and allowed by the correlation relationships demonstrates that effective cohesion has the strongest control over bank factor of safety when all other factors are kept constant [Figure 6]. Within this sensitivity analysis each of the 3 geotechnical parameters of interest was varied from 0% (the minimum observed value that fitted within the parameter correlations) to 100% (the maximum observed value that fitted within parameter correlations). These increases were carried out in parallel in both modelled layers, maintaining the importance of stratigraphy in bank stability.

Increases in both effective cohesion and friction angle were found to increase the stability of the modelled bank while increases in saturated unit weight did the opposite, decreasing the factor of safety. These patterns are supported strongly by the literature which describes how the stability of streambanks increases with an increase in both soil shear strength parameters, since they increase the resisting forces to failure (Osman and Thorne, 1988a). The importance of cohesion in particular is re-iterated by Istanbulluoglu et al. (2005) who found that as soil cohesion of gully banks in Colorado increased, erosion slowed down. Past studies have also reported how an increase in the unit weight of the bank material increases the driving forces causing bank failure (Rinaldi and Casagli, 1999), although this increase in unit weight does also increase the frictional resistance resisting failure (Simon et al., 2000).

Based on the relationships observed in the above sensitivity analysis it is possible to explore the maximum and minimum factor of safety values that could be predicted by the BSTEM based on combinations of the effective geotechnical parameter measurements from just one bank profile cross-section. By exploring the potential range of factor of safety values, this study attempts to demonstrate how the results of deterministic models such as the BSTEM can be affected by the variability inherent to natural systems.

This type of analysis is alike to that carried out by Thorne et al. (1981) in which they found the average and 'worst case' bank conditions based on a range of measurements. Similarly, Simon and Hupp (1987) looked at 'ambient' and 'worst case' conditions in a consideration of critical bank heights on the North Fork Obion River, Tennesse. A key difference between these studies and the analysis in this study is that in their instance 'worst case' conditions are those where the bank is under saturated conditions, as might occur after prolonged rainfall. Since our study differentiates between the inherent, effective soil properties and those properties controlled by soil moisture conditions it is possible to examine the extreme conditions of stability generated by the range in effective bank material properties alone. To avoid confusion with the afore mentioned earlier 'ambient – worst case' work, within this study we shall refer to our extreme cases as those under most- and least- resistive effective geotechnical conditions.

Table 3 contains the input data used and the resultant most resistive, average (mean) and least resistive factor of safety values returned by the model. For this part of the analysis each of the runs was based upon the same bank profile and hydrological conditions, and used the range of values for each of the geotechnical values collected at cross-section B. Note that for all cases the range of values is restricted in order to preserve the natural correlation between the variables described above. As would be expected based on the results of the sensitivity analysis, these tables show that the model produces a significant range of possible factor of safety values in response to the range of bank material properties found at Cross-Section B. In reality though, it is important to recognise that whilst the extreme F_s values are theoretically possible, their chance of occurrence is extremely low, requiring specific unlikely combinations of geotechnical parameter values. The majority of combinations of geotechnical parameter values are in general likely to result in more conservative F_s values, making the most- and least- resistive cases unlikely but nevertheless still possible.

Table 3

Figure 7

One point to note in Table 3 is that the scope of F_s values caused by the variability of geotechnical parameter values crosses either side of the critical value of 1. In theory this implies that depending on which measurement is chosen to represent each parameter the bank may be predicted as both (conditionally) stable and unstable. In order to explore this effect further the F_s values generated as a result of the most and least resistant possible and mean effective geotechnical conditions were found for a further 9 events. The resultant ranges in predicted F_s values, along with whether a bank failure was observed, are displayed in Figure 7. As with the event in Table 3, for all 9 cases the scope of F_s values predicted crosses the point of unity between driving and resistive forces (F_s of 1). This means that depending on which geotechnical parameter values were taken, different conclusions could have been drawn on the stability of the river bank in question.

In terms of validating the success of the BSTEM in predicting failure events no definite conclusions can be drawn as it could be said that in each case the model both predicted the stability both correctly and incorrectly dependent on the input parameters chosen. Interestingly, this even applies to the events where the BSTEM predicted F_s values above the safety margin of 1.3, below which banks are considered 'conditionally stable'. As mentioned above, this is the means by which the BSTEM currently accounts for uncertainty in stability predictions caused by the variability of bank material properties. This is common with many conventional deterministic slope analyses which, rather than accounting for quantified uncertainty in an explicit manner, rely instead on conservative parameters to deal with uncertain conditions. El-Ramly et al. (2002) describe how past experience has shown that designs based on these conservative parameters are not always safe against failure. Figure 7 shows this to be true in the case of the BSTEM also, with a failure being observed during the event on the 11th April 2005 when the F_s value given under mean effective geotechnical parameter values is well above that conservative 'conditionally stable' level. Yet when considering the full range of geotechnical parameter values it is clear that failure could have been predicted by the BSTEM. It is clear that whilst the BSTEM may be effectual in determining bank F_s given the correct input parameters, its current approach for dealing with the uncertainty caused by variability in bank material properties is limited.

5. Probabalistic assessment of riverbank stability

El-Ramly et al. (2002) identify that in order to deal with uncertainty appropriately in slope analyses it is necessary to implement probability concepts. Probabilistic slope stability analysis was first developed in the 1970s and has now become well established in slope engineering literature (Huang, 1983), although El-Ramly et al. (2002) criticise its slow adoption into engineering practice. As described above, the riverbank stability model developed by Darby and Thorne (1996a) includes the option of providing a probability of failure rather than the deterministic factor of safety approach. The model works by substituting measured bank material probability distributions instead of the single valued soil property values used in factor of safety equations. Then by dividing each continuous bank material property distribution into discrete classes, it is possible to define a finite number of combinations of soil property values. Each of these discrete combinations is directly applied in the bank stability equations to determine the factor of safety for that combination. Then the probability of failure is obtained by calculating the proportion of all possible combinations of cohesion, friction angle and unit weight values that result in a factor of safety of less than 1 (Darby and Thorne, 1996b).

However, despite the attractiveness of the probabilistic approach taken by Darby and Thorne, the Darby and Thorne model algorithm itself is not recommended above that of the BSTEM since it is limited in its ability to account for the effects of pore-water pressure, which is a fundamental factor in determining conditions of instability (Rinaldi et al., 2004). Instead it is recommended that a means of representing bank stability in a probabilistic manner is developed for the BSTEM so that the variability of bank material properties demonstrated within this study can be appropriately accounted for.

Following the example set by those involved with slope engineering (Huang, 1983; El-Ramly et al., 2002; 2005) and by Darby and Thorne (1996a; 1996b; 1996c) it is suggested that each of the geotechnical parameters is assigned a probability distribution function based upon shear strength tests in comparable soils, as in Figure 2, and that the correlation relationships between the variables are defined in a manner similar to those in Figure 5. Then a Monte Carlo simulation could draw at random a value for each input variable from within its defined probability distribution, maintaining the correlation relationships between variables. Each set of randomly sampled input geotechnical parameters would be used to solve the BSTEM algorithm and calculate the corresponding factor of safety for that particular selection of values. After a sufficient number of iterations, the statistical distribution of the factor of safety would be generated. Whilst it is beyond the scope of this study to incorporate this within the BSTEM an example of a potential output is displayed in Figure 8.

Unlike the approach suggested by Darby and Thorne which simply results in the probability of failure occurring, this Monte Carlo based technique gives not only the probability of bank failure and the probability of bank F_s falling below or exceeding any other given value but also the most likely F_s value. In the hypothetical example in Figure 8 the probability of bank failure is the cumulative probability of all F_s values below 1, which is approximately equal to 10% or a probability of 0.1. The most likely F_s is given by the modal value, which is approximately equal to 1.125. Of particular value is that the output of this methodology, as exemplified by Figure 8, whilst providing the potential maximum range of factor of safety values possible for a given bank case, also identifies that those extreme cases are generally likely to be extremely improbable. For instance in Figure 8, whilst a F_s of below 0.9 is recognised as possible, it is also shown that's its probability of occurrence is 0.01. This demonstrates how this particular method for dealing with uncertainty both provides the user with all possible outcomes, as well as realistically recognising the most likely outcome. This depth of information regarding bank stability has the potential to be extremely useful to channel design practioners requiring stable riverbanks, giving them the ability to choose an appropriate probability of failure when set against the risk tolerance of a specific design specification.

A further benefit of the probabilistic approach to bank stability modelling was recognised by Darby and Thorne (1996b). They identified that deterministic bank stability models, when used in conjunction with downstream channel evolution analyses, over predict the longitudinal extent of mass failures since an unstable bank is assumed to fail along the entire reach of the model when in reality mass failures over bank lengths of more than a few meters is rare. Darby and Thorne hypothesised that more realistic predictions of reach-scale bank stability can be obtained using a probabilistic riverbank stability analysis such as that described above. This would be achieved through the assumption that the fraction of the reach that is unstable with respect to mass failure is equal to the probability of failure. Whilst this form of analysis is still essentially a two-dimensional solution to the three-dimensional problem of longitudinal channel adjustment it does present a more realistic means of representation than deterministic based two-dimensional approaches.

Whilst it is apparent that a probabilistic approach is useful in practical applications, El-Ramly et al. (2002) identify several factors that limit its employment by practitioners. The most relevant of these is the level of data acquisition required to generate the requisite probability distributions representing the material properties (Darby et al., 2000). In reality it is unlikely that a practitioner will undertake an extensive series of shear strength measurements for each study and therefore will not have the statistical distribution data available to perform the probability based analysis. A potential solution is the use of databases of generalised geotechnical parameter distributions based on measurements performed in similar materials. A small number of measurements within the materials for the study in question would enable a set of appropriate general distributions to be selected, upon which the probabilistic analysis could be based. In a similar approach, El-Ramly et al. (2005) use regional probability distributions of cohesion and friction angle to apply a probabilistic slope stability analysis of the Shek Kip Mei cut in Hong Kong. However, it is recommended that for best practice site-specific measurements of the parameters are taken for each study to ensure that the statistical distributions chosen are a good approximation of the values observed in the field.

6. Conclusions

It is important to consider the results of any study in the context they were obtained (Bauer, 1996) and the specific results from this study are delimited spatially to the seven surveyed cross-sections on the Goodwin Creek Bendway, Mississippi and temporally to the 8 weeks over which they were surveyed during the summer of 2005. Yet the results of this study have importance reaching far beyond these constricted boundaries and having implications for all issues involving bank stability, and any study within which variability and uncertainty is hidden behind deterministic model outcomes.

This study did not find any significant difference between the importance of within site (micro-scale) and between site (meso-scale) variation in bank material properties, but instead showed that they are both present, and both significant in influencing bank stability. The micro-scale variation is thought to be a result of the inherent variability of soil properties, with the meso-scale variation considered to be a relic of historic deposition patterns, although a lack of contextual information restricts any firm conclusions on this.

When the range of observed effective geotechnical parameter values was applied to bank stability analyses using the BSTEM it was found that the variability present produced a significant scope of uncertainty in bank factor of safety prediction. The current implicit means by which the BSTEM addresses this uncertainty is thought to be unsuitable, leading the authors to consider a probabilistic based method for dealing with the uncertainty caused by bank material property variability.

The core message from the above results is that bank material properties do vary spatially and therefore this variation should be considered during all bank stability analyses, with probabilistic based methods currently offering the most appropriate means of doing this. Further work following on from this study will aim to incorporate a probabilistic representation of bank strength parameters within the BSTEM and test its suitability. In addition, future studies aimed at the determination of the statistical distributions of geotechnical parameters in a range of material types would greatly assist in the widespread acceptance of probabilistic approaches.

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References

American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics and Modeling of River Width Adjustment – Thorne, C.R. (Chair). 1998a. River Width Adjustment. I: Processes and Mechanisms, Journal of Hydraulic Engineering 124(9): 881-902.

American Society of Civil Engineers Task Committee on Hydraulics, Bank Mechanics and Modeling of River Width Adjustment –Thorne, C.R. (Chair). 1998b. River Width Adjustment. II: Modeling, Journal of Hydraulic Engineering 124(9): 903-917.

Bauer, B.O. 1996. Geomorphology, geography and science. In: Rhoads, B.L. and Thorn, C.E. (eds.), The Scientific Nature of Geomorphology. Wiley: Chichester; 381-413.

Bull, L.J. 1997. Magnitude and variation in the contribution of bank erosion to the suspended sediment load of the River Severn, UK. Earth Surface Processes and Landforms 22: 1109–1123.

Casagli, N., Curini, A., Gargini, A., Rinaldi, M. and Simon, A. 1997. Effects of pore pressure on the stability of streambanks; preliminary results from the Sieve River, Italy. In: Wang, S.S.Y., Langendoen, E.J., Shields, F.D. Jr. (eds.), Management of Landscapes Disturbed by Channel Incision. The University of Mississippi: Oxford, Mississippi; 243-248.

Casagli, N., Rinaldi, M., Gargini, A., Curini, A. 1999. Monitoring of pore water pressure and stability of streambanks: results from an experimental site on the Sieve River, Italy. Earth Surface Processes and Landforms 24: 1095- 1114.

Coakes, S.J. and Steed, L.G. 2001. SPSS Analysis Without Anguish: Version 10.0 for Windows. John Wiley and Sons: Australia.

Cohen, J. 1988. Statistical Power Analysis for the Behavioural Sciences. Erlbaum: New Jersey.

Darby, S.E., and Thorne, C.R. 1996a. Stability Analysis for steep, eroding, cohesive riverbanks. Journal of Hydraulic Engineering 122(8): 443-454.

Darby, S.E., and Thorne, C.R. 1996b. Numerical simulation of widening and bed deformation of straight sand-bed rivers I: Model development. Journal of Hydraulic Engineering 122(4): 184-193.

Darby, S.E., and Thorne, C.R. 1996c. Development and testing of riverbank-stability analysis. Journal of Hydraulic Engineering 122(8): 443 – 454.

Darby, S.E., Gessler, D. and Thorne, C.R. 2000. Computer program for stability analysis of steep, cohesive riverbanks. Earth Surface Processes and Landforms 25: 175-190.

DeCoursey, D.G. 1981. Stream Channel Stability: Comprehensive Report. USDA Sedimentation Laboratory: Oxford, Mississippi.

Duncan, J.M., Navin, M. and Wolff, T.F. 2003. Discussion of “Probabilistic slope stability analysis for practice”. Canadian Geotechnical Journal 40: 848 – 850.

El-Ramly, H., Morgenstern, N.R. and Cruden, D.M. 2002. Probabalistic slope stability analysis for practice. Canadian Geotechnical Journal 39: 665 – 683.

El-Ramly, H., Morgenstern, N.R. and Cruden, D.M. 2005. Probabalistic assessment of stability of a cut slope in residual soil. Geotechnique 55(1): 77 – 84.

Fredlund. D.G., Morgenstern, N.R. and Widger, R.A. 1978. The shear strength of unsaturated soils. Canadian Geotechnical Journal 15: 313 – 321.

Grissinger, E.H. 1982. Bank erosion of cohesive materials. In: Hey, R.D, Bathurst, J.C and Thorne, C.R. (eds.), Gravel Bed Rivers. Wiley: Chichester; 273–287.

Grissinger, E.H., Murphey, J.B. and Little, W.C. 1982. Late-Quaternary valley-fill deposits in North Central Mississippi. Southeastern Geology 23(3): 147-162.

Huang, Y.H. 1983. Stability Analysis of Earth Slopes. Van Nostrand Reinhold: New York.

Istanbulluoglu, E., Bras, R.L., Flores-Cervantes, H. and Tucker, G.E. 2005. Implications of bank failures and fluvial erosion for gully development: Field observations and modelling. Journal of Geophysical Research 110: F01014.1-F01014.21.

Lohnes R and Handy RL. 1968. Slope Angles in Friable loess. Journal of Geology 76: 247-258.

Luttenegger, J.A., Hallberg, B.R. 1981. Borehole shear test in geotechnical investigations. ASTM Special Publication 740: 566–578.

Mitchell, J.K. and Soga, K. 2005. Fundamentals of Soil Behaviour. John Wiley and Sons: New Jersey.

Osman, A.M. and Thorne, C.R. 1988. Riverbank Stability Analysis I: Theory. ASCE Journal of Hydraulic Engineering 114: 134-150.

Parker, C. 2005. An Investigation into the Variability of Bank Material Properties on Goodwin Creek, Mississippi. Dissertation presented for the Honours degree of BSc Geography. School of Geography: University of Nottingham.

Rinaldi, M. and Casagli, N. 1999. Stability of streambanks formed in partially saturated soils and effects of negative pore water pressures: the Sieve River (Italy). Geomorphology 26: 253-277.

Rinaldi, M., Casagli, N., Dapporto, S. and Gargini, A. 2004. Monitoring and modelling of pore water pressure changes and riverbank stability during flow events. Earth Surface Processes and Landforms 29: 237-254.

Simon, A. 1989. A model of channel response in disturbed alluvial channels. Earth Surface Processes and Landforms 14: 11-26.

Simon, A. and Collison, A.J. 2002. Quantifying the mechanical and hydrological effects of riparian vegetation on streambank stability. Earth Surface Processes and Landforms 27: 527-546.

Simon, A. and Curini, A. 1998. Pore pressure and bank stability: the influence of matric suction. Proceedings of the 1998 International Water Resources Engineering Conference, Memphis, 3-7 August, Volume 1. 358–363.

Simon, A. and Darby, S. 1997. Bank erosion processes in two incised meander bends: Goodwin Creek, Mississippi. In: Wang, S., Langendoen, E., Shields, F.D. (Eds.), Management of Landscapes Disturbed by Channel Incision. University of Mississippi: Oxford, Miss; 256–261.

Simon, A., Curini, A., Darby, S.E. and Langendoen, E. 2000. Bank and near bank processes in an incised channel. Geomorphology 35: 193-217.

Simon, A., Rinaldi, M. and Hadish, G. 1996. Channel evolution in the loess area of the Midwestern United States. Proceedings of Sixth Federal Interagency Sedimentation Conference, Las Vegas, 10-14 March, Volume 3. 86-93.

Thorne, C.R., Murphey, J.B. and Little, W.C. 1981. Stream Channel Stability Appendix D: Bank Stability and Bank Material Properties in the Bluffline Streams of Northwest Mississippi. USDA Sedimentation Laboratory: Oxford, Mississippi.

Vanmarcke, E.H. 1977. Probabalistic modelling of soil profiles. Journal of the Geotechnical Engineering Division, ASCE 103(11): 1227 – 1246.

Wood, A.L. 2001. A geomorphological analysis of bank toe processes: the fate of failed blocks stored in the basal zone of incised channels [Ph.D. Thesis]. University of Nottingham, Nottingham.

Young, P.C. 1999. Data-based mechanistic modelling, generalised sensitivity and dominant mode analysis. Computer Physics Communications 117(1): 113-129.

Tables

Table 1: Summary of all data collected from cross-sections A through G on the Goodwin Creek Experimental Bendway

Depth / Layer of Measurement	*~ 1.00m (LH)*	*~ 2.00m (EH)*
Number of tests carried out	17	17
Mean effective cohesion values (c' in kPa)	4.37	0.410
Range of effective cohesion values (c' in kPa)	0 - 13.2	0 - 3.10
Standard Deviation of effective cohesion values (c' in kPa)	4.10	0.935
Mean effective friction angle values (ϕ' in degrees)	31.7	35.1
Range of effective friction angle values (ϕ' in degrees)	22.4 – 40.6	30.5 – 41.1
Standard Deviation of effective friction angle values (ϕ' in degrees)	5.69	3.02
Mean saturated unit weight of sediment values (γ in kN/m^3)	18.6	19.3
Range of saturated unit weight of sediment values (γ in kN/m^3).	18.0 – 19.3	17.8 – 21.1
Standard Deviation of saturated unit weight of sediment values (γ in kN/m^3).	0.428	0.908

Table 2: One way ANOVA test testing the impact of grouping geotechnical parameter values by cross-section. Where the necessary ANOVA assumptions have not been met a non-parametric alternative (the Kruskal-Willis test) is used instead. The 'eta-squared' value describes the amount of the total variance in the dependent variable that is predictable from knowledge of the levels of the independent variable. Cohen (1988) recommends the following guidelines to interpret the strength of eta squared values: 0.01 = small effect; 0.06 = moderate effect; 0.14 = large effect.

Parameter	*Friction Angle (LH)*	*Friction Angle (EH)*	*Effective Cohesion (LH)*	*Effective Cohesion (EH)*	*Unit Weight (LH)*	*Unit Weight (EH)*
One-way between groups ANOVA test	- (Assumptions not met)	No significant differences (Sig value = 0.243)	- (Assumptions not met)	- (Assumptions not met)	- (Assumptions not met)	Significant difference at the 95% significance level (Sig value = 0.002)
Kruskal-Wallis test	No significant difference (Sig value = 0.336)	- (Parametric alternative preferred)	Significant difference at the 90% significance level only (Sig value = 0.099)	Significant difference at the 90% significance level only (Sig value = 0.063)	No significant difference (Sig value = 0.128)	- (Parametric alternative preferred)
Eta-squared	0.376	0.490	0.556	0.842	0.635	0.833

Table 3: Input data used and resultant factor of safety values returned by the BSTEM model when predicting the range of possible bank stability conditions using the single bank profile and hydrologic condition from Cross-Section D at 0.00am on 31st November 2004 and the range of bank material properties measured at a single cross-section.

Parameter	*Most resistant effective geotechnical conditions*	*Mean effective geotechnical conditions*	*Least effective geotechnical conditions*
Bank Profile	Cross Section D (31st November 2004) surveyed profile		
Pore Water Pressures	31st November 2004 @ 0:00am tensiometer data		
Surface Water Elevation	80.5m		
Friction Angle in Late Holocene Layer	34.0	33.3	22.8
Friction Angle in Early Holocene Layer	41.1	39.3	30.5
Effective Cohesion in Late Holocene Layer	10.9	7.80	3.13
Effective Cohesion in Early Holocene Layer	0	0	0
Saturated Unit Weight in Late Holocene Layer	18.0	18.2	18.5
Saturated Unit Weight in Early Holocene Layer	17.8	18.5	19.3
Factor of Safety	1.02 (Conditionally Stable)	0.940 (Unstable)	0.590 (Unstable)

Figure Captions

Figure 1: Goodwin Creek experimental watershed, Mississippi.

Figure 2: Frequency distribution plots for the measured geotechnical input parameters in each layer.

Figure 3: Boxplot diagrams comparing the distribution of each soil parameter within Cross-Section B to the average values from each of the Cross-Sections from A to G for each layer.

Figure 4: Means plots across all seven cross-sections for each soil property parameter in each layer.

Figure 5: Regression plots with 95% prediction intervals displaying the correlations among geotechnical variables and the boundaries within which 95% of measurements should fall.

Figure 6: Sensitivity analysis of BSTEM predicted factor of safety to the ranges of each of the measured geotechnical parameters when the remaining parameters are set to mean values and one cross-section profile and hydrological condition is used (based on Cross-Section D, 31st November 2004 at 0.00am).

Figure 7: Range of F_s values predicted by the BSTEM for 9 separate hydrological events on Goodwin Creek based on the most resistant, least resistant and mean effective geotechnical parameter values measured within the layers of a single bank profile. Events plotted in red indicate that a bank failure was observed, those plotted in green indicate no observed failure.

Figure 8: A hypothetical example of an output from a probabilistic analysis perfomed within the BSTEM. The graphs show the % of the total frequency for each factor of safety bin class (left) and the cumulative frequency across the range of factor of safety values (right).