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Field measurements of rates of bank erosion and bank material strength

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ABSTRACT In this paper traditional and new methods of monitoring rates and locations of bank erosion are reviewed. These range from detailed measurements using erosion pins to large scale studies using aerial photos and maps. It is shown that ideally bank erosion should be studied using on-site measurements for detailed erosion data and remote sensing information for large scale and long term data. Techniques for the evaluation of soil erodibility and shear strength are reported. Particular attention is paid to new approaches being developed in the USA and to new instruments such as the borehole shear tester and unconfined tension tester.

Mesures sur le terrain du taux l'érosion des berges et de la cohésion des matériaux des rives

RESUME On passe en revue dans cette étude les procédés traditionnels et nouveaux pour surveiller les taux d'érosion et localiser les zones d'érosion des rives d'une rivière. Ceux-ci partent de l'usage des fiches d'érosion pour prendre note des mesures détaillées, pour s'étendre jusqu'à l'usage de cartes et de la photographie aérienne en vue d'études couvrant de vastes superficies. On montre ici que l'érosion d'une rive devrait être idéalement étudiée en se servant des mesures faites sur les lieux afin d'obtenir des données d'érosion détaillées, et en se servant d'informations prises d'un point de vue plus élevé pour obtenir des données à petite échelle et à long terme. Des techniques pour l'évaluation de l'érodibilité de la terre et sa résistance au cisaillement sont également présentées. L'attention s'attache particulièrement aux nouvelles méthodes qui voient le jour aux Etats-Unis en ce moment et aux nouveaux instruments tels que les appareils de contrôle du cisaillement dans un trou de sonde et le "unconfined tension tester".

INTRODUCTION

Scientific and engineering interest in river bank erosion has increased in the last decade for three main reasons. Firstly, bank erosion plays an important role in the control of channel width and in adjustments of the fluvial system. Secondly, bank erosion can make a significant contribution to the river's sediment load. Thirdly, destruction of flood plain land and a reduction in the resource value of the river is associated with serious bank erosion.

The study of bank erosion is complicated by its inter-disciplinary nature. Many approaches to the subject have been adopted and many methods of data collection employed, without any unification. It is not possible to review all the methods and techniques used in the study of bank erosion in a short paper like this. Instead attention is focussed on two aspects of basic data collection: the monitoring of the rate and location of bank erosion and the evaluation of bank material strength. The methods reported are limited to those with which the author has had some direct experience. The paper is not a review of the rapidly expanding literature on bank erosion.

METHODS OF MONITORING RATES AND LOCATIONS OF BANK EROSION

Methods of monitoring bank erosion fall into two main categories: on-site measurements and remote sensing.

On-site measurements

In an intensive study of bank erosion in a particular reach, the first requirement is a detailed map of the channel and bank lines. This may be constructed by plane tabling, but in the author's experience the compass and tape technique has advantages. This technique is described in detail in *Environmental Science Methods* (Haynes, 1981) and only a brief outline is included here. Ranging rods are arranged along and some distance behind both banks, to form a grid covering the reach to be mapped. Bearings and back-bearings between rods are taken. A Wild compass is recommended for this, but a prismatic compass used carefully yields sufficient accuracy. A tape is stretched between rods 1 and 2 to measure transect length and a second tape is used to measure the perpendicular offset from the first tape to features of interest (bank top, toe etc.) at points between the rods. The spacing of the points depends on the detail required, but should be between 0.1 and 2 m. The measurements are repeated for rods 2 and 3 and so on until the grid is closed. The map is drawn by constructing the grid at an appropriate scale and then plotting in the offsets. The locations of several of the rods are monumented so that the survey can be repeated to establish changes in bank lines. Wooden pegs may be used as monuments but are easily disturbed and may cause inconvenience to the land owner. A useful method is to drive a metal stake below ground level and relocate it using a metal detector.

With the channel planform established, cross sections are surveyed by levelling at points of interest along the reach. The locations of cross sections should be monumented and some semi-permanent structure is required to act as a local benchmark to permit relevelling subsequently.

Usually bank erosion is not distributed evenly but is highly variable in space and time. The data obtained from planform resurveys are usually not sufficient to pick up these spatial and temporal variations.

These type of data can be obtained using erosion pins. These are rods driven horizontally into the steep face of an eroding bank. The length of rod sticking out of the bank, less the amount left protruding when it was installed, defines the amount of surface erosion which has occurred locally. Erosion pins were first used by Wolman (1959). They have been used with success by numerous subsequent researchers including Thorne (1978) and Hooke (1979).

Reinforcing rod of about 6.35 mm diameter is usually used for erosion pins. It is recommended that the pins be knocked back into the bank until only the tip is protruding after each measurement. Otherwise they can easily be lost and may also present a hazard to livestock and fishermen. Pin spacing along the channel depends on the type of study but should usually be between 1 and 5 m. It is recommended that two or more pins be installed along a vertical section at each location to yield data on the vertical distribution of erosion. Measurements should ideally be made after every flood, rainfall and frost event and at intervals in between, but this may be constrained by the commitments of the researcher and location of the sites.

Erosion pins can be installed in most alluvial materials but their use in gravel deposits is not recommended. Such deposits rely for their strength on frictional forces related to the packing density and degree of imbrication of the particles. Inevitably the packing and imbrication are disturbed by the installation of a pin and this weakens the material locally, leading to accelerated erosion. The effect is apparent in the field as a cone-shaped depression in the bank surface, centred on the pin. In the case of gravel banks interesting information can be obtained by spray painting selected sections of intact *in situ* bank material in bright distinctive colours. Not only can it be noted immediately when surface particles are removed but also the movement and deposition of eroded material can be observed (Thorne, 1978).

The problem of disturbance does not seem to arise in fine grained soils where the presence of the pin does not appear to encourage or inhibit surface erosion (Hooke, 1979). There is however the danger that the pin will reinforce the soil and inhibit bank erosion by mass failure along a failure surface within the bank. This effect is particularly important if tensile forces are involved. Alluvial soils have very little strength in tension and are prone to tension cracking behind steep or vertical banks. The presence of pins in the bank increases the tensile strength considerably and by preventing the development of tension cracks, could slow down the rate of collapse and retreat of the bank.

This effect was evident in measurements made by the author on composite banks on the River Severn in Wales (Thorne & Lewin, 1979). Fluvial undercutting of composite banks leaves overhanging blocks of material. These overhangs or cantilevers fail subsequently as a result of crack development or weight increase due to wetting (Thorne, 1978). It was noted that where 1 m long erosion pins were installed in the upper bank, cantilever widths of 0.6-0.8 m developed. However, natural cantilevers seldom exceeded 0.3-0.5 m in width. Clearly the erosion pins reinforced the soil and increased cantilever stability. The danger of reinforcing the bank with respect to block failure by slumping, toppling or cantilever failure must be borne in mind when using erosion pins. If failure by these mechanisms is not significant on the banks studied then there is no problem. However, where block failures are significant it is recommended that the length of erosion pins be limited to less than the characteristic width of failure blocks. Such blocks usually have widths of the order of 0.4-0.8 m (Thorne, 1978; Hooke, 1979) and so erosion pins should not be longer than about 0.3-0.5 m. This approximates to the length originally used by Wolman (1959). Short pins may be more frequently lost and so it is essential that a backup system of bank line resurveys relative to a fixed transect line be operated. Then even when a pin is lost, the overall amount of retreat can still be determined and the new position of the bank established prior to the installation of a new pin.

On large rivers with high banks, erosion pins and bank line surveys are insufficient to monitor bank erosion. Bank profiles must be surveyed relative to datum pegs located well behind the bank edge. Brunsden & Kesel (1973) reported work on a 25 m high bluff on the Mississippi near Port Hudson. Reprofiling of bank sections together with measurements of many other soil properties have now been carried out for a decade. The data are being related to controlling variables associated with fluvial and climatic conditions to produce an excellent explanation of the causes and controls of bank retreat (R. H. Kesel, personal communication, 1980).

On large rivers like the Mississippi much erosion occurs deep below the water surface. At Port Hudson the *low flow* depth in the scour pool at the bluff foot is about 18 m. Under such conditions valuable data can be obtained using side-scan sonar to profile the subaqueous bank. This technique has also been applied by the US Army Corps of Engineers on the Mississippi, Ohio and Missouri rivers. Bed and bank topography, subsurface geology, lithologic features and manmade structures can be clearly identified (US Army Corps of Engineers WES, 1980; Kesel, personal communication, 1980). For example, Fig. 1 shows a side-scan sonar trace from the Ohio River near Vanceburg, Kentucky, in which subaqueous failures and basal accumulations of slump debris can be identified.

Remote sensing

In monitoring rates and locations of bank erosion there are two main sources of remote sensing data: aerial photographs and historical maps. These data sources have two major advantages over on-site measurements. Firstly, they make it possible to look at bank erosion over much greater lengths of channel and secondly, they allow much longer time periods to be considered. It is usually only possible to conduct a detailed field study of bank erosion over a short reach, perhaps 5 or 10 times the channel width. This is a disadvantage because the hydraulic and sedimentary conditions in such short reaches are highly dependent on conditions upstream and downstream. The value of the data will

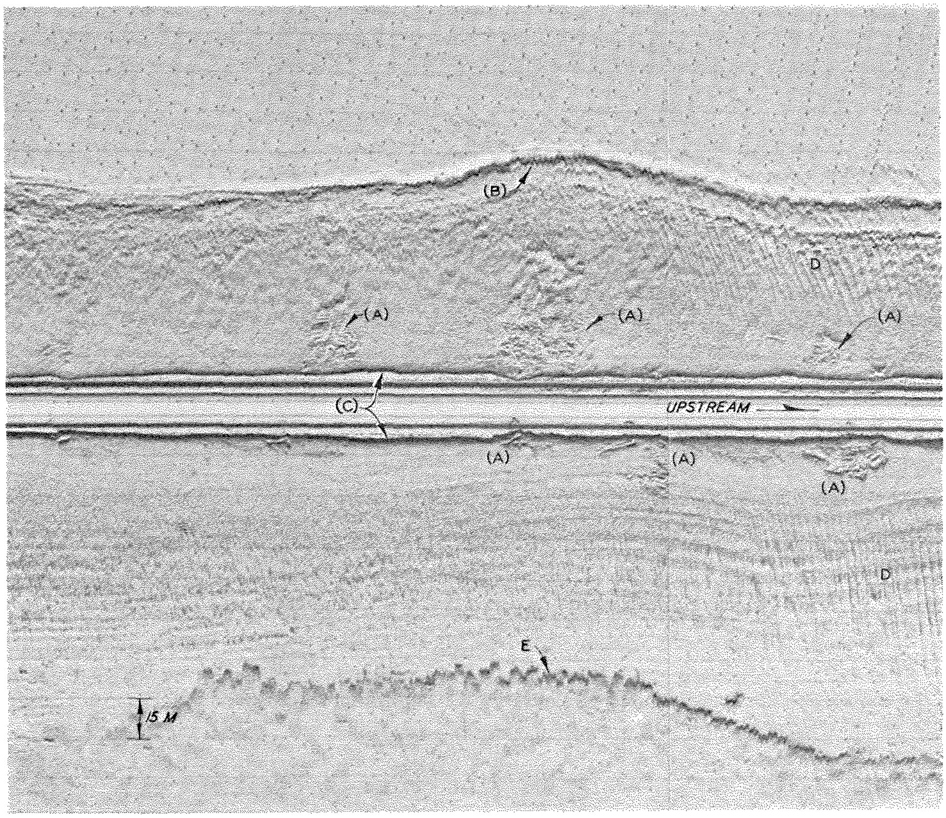

Fig. 1 Side-scan sonar record of the Ohio River near Vanceburg, Kentucky. Large subaqueous slumps (A) extend from near the toe of the right bank (B). Slump material at the toe gives the bed profile a hummocky appearance (C). Herringbone pattern (D) is noise interference from another boat. Toe of left bank is at (E). (After US Army Corps of Engineers WES (1980).)

be limited if they cannot be viewed in the context of the overall fluvial environment. Further, it will be difficult to interpret the significance of the rates and locations of bank erosion, and temporal changes in those rates and locations, without a good idea of changes occurring up and downstream.

Most intensive field studies are conducted over periods of 2 or 3 years. Whilst valuable information is collected in such periods, it is difficult to know whether the rates and patterns of erosion observed are typical of longer term channel changes. Also, the range of processes and mechanisms of erosion identified in a short study may not fully represent all of those which are important in eroding the banks and forming the channel. In particular processes associated with events of high magnitude but low frequency are unlikely to be observed.

Supplementary data from aerial photographs and historical maps are invaluable in putting a detailed field study into the context of larger scale and longer term channel changes.

Information on details of aerial photographs available for Britain can be obtained by writing to:

For England and Wales:
The Air Photographs Officer
Central Register of Air Photography
Department of the Environment
Whitehall, London SW1

For Scotland:
The Air Photographs Officer
Scottish Development Department
York Buildings, Queen Street
Edinburgh EH2 1HY

The area of interest should be specified by giving the National Grid Lines which bound it.

For the USA the sources of air photographs are listed in a report issued by the Waterways Experiment Station, Vicksburg, Mississippi (May, 1978).

Air photographs may be applied in many ways in studying bank erosion and there is insufficient space to describe them here. Instead the interested reader is referred to excellent examples of the application of air-photo interpretation and photogrammetry to be found in articles by Lewin (1975, 1977).

In Britain reliable large scale maps are not usually available prior to the Tithe surveys of the 1830's and 1840's. These maps are of a usefully large scale (1:6272), but their accuracy is limited. The first two editions of Ordnance Survey 1:10 560 or 1:2600 maps (1880's and early 1900's respectively) are very useful but subsequent provisional editions can be misleading due to undated partial revisions. The problems and pitfalls of using old maps together with advice on the extraction of the maximum amount of information may be found in a paper by Lewin (1976).

Neither aerial photographs or historical maps can provide the detailed information available from an on-site study and it would be folly to attempt to use either type of remote sensing without ground control data from on-site measurements. Clearly the two approaches to the monitoring of bank erosion are not alternatives, but complement one another. An integrated approach, incorporating on-site measurements and remote sensing data should be adopted when studying bank erosion. An example of this approach may be found in Thorne & Lewin (1979).

METHODS OF MEASURING BANK MATERIAL STRENGTH

In the context of river bank erosion, there are two basic aspects of bank material strength which are usually considered to be of interest. The first is the material's erodibility: that is its susceptibility to erosion by the flow in the channel. The second is its shear strength: that is its ability to withstand gravitational forces tending to cause bank failure by slumping or slipping. Thorne (1978) suggested that a third aspect of bank material strength, the tensile strength, might be significant. The tensile strength of the bank material (including the effects of plant roots) represents its ability to resist tension cracking in the upper part of steep banks.

Erodibility

Soil erodibility is being studied in the USA under the

"Section 32" Streambank Erosion Control and Demonstration Act of 1974 (US Army Corps of Engineers, 1978).

At the Waterways Experiment Station, research is being undertaken to determine which soil parameters influence erodibility. The approach adopted is to develop a method to predict the critical shear stress for the initiation of erosion and the rate of erosion, on the basis of the composition and structure of the soil, its moisture content, the type and amount of clay minerals and the chemistry of the pore and the eroding (river) water. Soils for testing come from 22 locations throughout the continental USA. Testing consists of index property tests (including sieve and hydrometer analyses, specific gravity, moisture content, unit weight and Atterburg limits), soil chemistry (exchangeable cations), dielectric dispersion on undisturbed soil, flume tests on undisturbed and remoulded soil and rotating tests on saturated, remoulded soil.

The flume tests are used to determine the influence of the initial degree of saturation and of remoulding on the erodibility. Distilled water is used in the flume. Rotating cylinder tests are used to investigate the effects of pore and eroding water chemistry.

The results of the tests have been used to produce empirical relationships between the initial degree of saturation of the soil,pore and eroding water chemistry and the dielectric dispersion; and the critical stress and rate of erosion. These relationships can explain about 60% of the observed variance, the relationship for the erosion rate being somewhat better than that for critical stress. The results are not yet generally available (1980) but will become so when the US Army Corps of Engineers submits its final "Section 32" reports in about June, 1981 (E. B. Perry, personal communication, 1979). Further details are available from Dr Ellis Pickett, WES, PO Box 631, Vicksburg, Mississippi 39180, USA.

Much of the unexplained variance in the WES study is attributed to problems and inconsistencies in the collection of soil samples. To avoid this problem the USDA Sedimentation Lab. has developed a portable flume so that erodibility tests can be carried out on bank materials *in situ*. Tests have been performed on friable soils of low cohesion and plasticity (P.I.<15) which are particularly susceptible to fluvial erosion. Sites chosen are in Georgia, Alabama, Mississippi and Tennessee, USA. The tests show that the structure of the soil influences its erodibility and that the initial degree of saturation is also very important. Very dry soil is eroded excessively upon wetting compared with rates of erosion in subsequent tests when the soil is near full saturation prior to testing. This effect seems to be associated with slaking and disturbance to the soil structure on wetting and demonstrates that soils of this type react very differently to those studied elsewhere (Wolman, 1959). The relationship between shear stress and erosion rate is significantly related to the clay content. Where the effects of soil morphology are minimal the pinhole test can be used to predict the erosion rate. This suggests that the pinhole test may be used as an indicator of erodibility. This research is reported in detail in a paper by Grissinger *et al.* (in preparation). Further details may be obtained from The Director, USDA Sedimentation Lab., PO Box 1157, Oxford, Mississippi 38655, USA.

Shear strength

The shear strength of a bank material is described by the revised Coulomb equation,

$$s = (\sigma - u) \tan \phi' + c' \tag{1}$$

where s = undrained shear strength, u = pore water pressure, ϕ' = apparent friction angle, σ = normal stress, and c' = apparent cohesion. Most methods of measuring the shear strength consist of *in situ* measurement of s or determination of ϕ, c and u from laboratory tests on soil samples. The various methods are described in detail in standard texts. A less well known technique, the Iowa borehole shear test (BST) has been developed recently. In this test the shear strength is measured directly *in situ* down an 8 cm diameter borehole. The main advantages over conventional methods are that the cohesion and friction angle can be evaluated separately in about one tenth of the time required for triaxial tests, that test data are plotted on-site during the test enabling immediate repetition if results are unreasonable and that tests can be carried out at various depths or locations in the bank to locate and investigate weak strata.

The BST is essentially a direct shear test performed on the soil at the edge of the borehole. An expanding head provides a known normal stress (σ) by using gas pressure to force two shear plates to bite into the soil (Fig. 2). The head is then pulled axially up the borehole using connecting rods and a lead screw. The pulling force is measured hydraulically. The maximum pulling force divided by the area of the shear plates corresponds to the

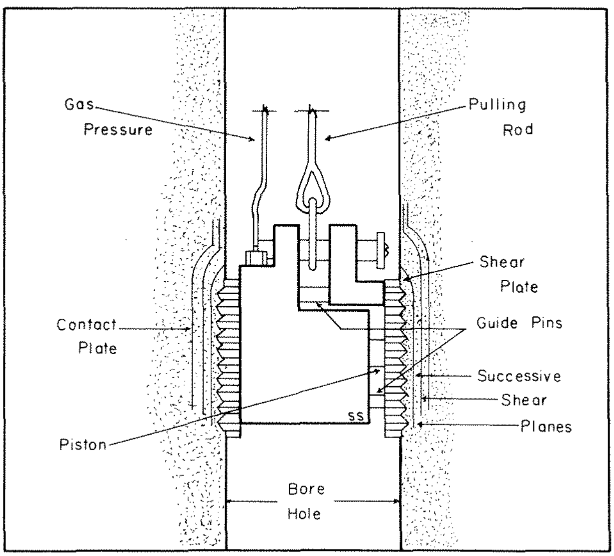

Fig. 2 Expanding shear head of borehole shear tester in position. A stage test produces "shells" of shear planes located progressively further out in the soil.

shear strength (s). The test is repeated at a higher normal stress either at the same location (a stage test), or at another location within the same soil unit (non-stage test), to produce pairs of σ and s values. When plotted on a graph of σ *vs.* s these points define the Mohr-Coulomb rupture line. The slope of the line gives the friction angle and the intercept on the ordinate axis the cohesion c (Handy & Fox, 1967).

The author used the BST extensively in an investigation of bank material properties in northern Mississippi and found the instrument quick and easy to use. The results obtained seem entirely reasonable and are consistent with data from unconfined compression and triaxial tests. In the banks studied the degree of saturation was low and pore pressures insignificant, but in saturated soils a problem arises as it is not clear whether the test is drained ($u = 0$) or undrained ($u \neq 0$). This problem may be overcome using new model BST instruments which are fitted with a pressure transducer in the nonexpanding shear plate (Fig. 2). The design of the shear plates can also present problems and should be tailored to the soil type (Luttenegger *et al.*, 1978).

Tensile strength

The tensile strength of a bank material can be measured using a modified compression tester as described by Thorne *et al.* (1980). The results of 38 tests on alluvial bank materials from northern Mississippi show that the unconfined tension strength is on average 13% of the unconfined compression strength, with a standard deviation of 5%. These figures are corroborated by the preliminary analysis of data for 35 sites on British rivers. This suggests that for engineering purposes the unconfined tension strength of intact soil may be taken as being 10-15% of the unconfined compression strength.

The situation changes however when the soil is reinforced by plant roots or rhizomes. In the case of strongly rooted samples the tensile strength can be as much as 50% of the compressive strength. This effect can be compared to those observed by Waldron (1977) for the effects of plant roots on shear strength of soils.

The presence of roots and rhizomes has a profound effect on soil strength as well as other parameters (for example unit weight and permeability) and must be taken into account when characterizing bank material properties. These effects may go some way towards explaining the role of vegetation in affecting bank stability and the hydraulic geometry of the channel.

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