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On scale effects in movable-bed river models

N. Struiksma and G. J. Klaassen

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INTERNATIONAL ASSOCIATION FOR HYDRAULIC RESEARCH

Symposium '86
on
Scale Effects in Modelling Sediment Transport Phenomena

Scale Effects in the Reproduction of the Overall Bed Topography in River Models

by

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Synopsis

In river scale models with movable bed a significant scale effect occurs due to the distortion of the model. This distortion is necessary in order to reproduce the flow pattern in a similar way (roughness condition). An attempt is made to clarify and quantify this scale effect by using experiences obtained during the development of a mathematical model for the computation of the 2-D bed topography. From a linear analysis of the steady state of this model an important parameter governing the interaction between the water and sediment movement could be defined which cannot be reproduced in a correct way. The parameter is used to quantify the scale effect in terms of wave length and damping of the 2-D bed deformation.

Résumé

Dans les modèles reduits fluviaux à fond mobil on a des dissimilitudes d'échelle signifiantes due à la distorsion du modèle. Cette distorsion est nécessaire afin de reproduire le champ d'écoulement (condition de rugosité). Un effort a été fait a éclaircir et quantifier cette dissimilitude en utilisant les expériences obtenues pendant le dévelopement d'un modèle mathématique qui sert à calculer la topographie du lit à deux dimensions. Dans une analyse lineaire d'une situation permanente dans ce modèle un paramètre important pouvait -tre défini qui gouverne l'interaction entre le mouvement de l'eau et des materiaux solides, un paramètre qui ne se reproduit pas d'une façon correcte à èchelle réduite. Ce paramètre est utilisé à quantifier la dissimilitude en terme de longueur de l'onde et de l'amortissement de la déformation bi-dimensionelle du lit.

1. Introduction

Most scaling procedures for river models with movable bed aiming at a simulation of the bed topography are based on an analysis of 1-D equations of water and sediment motion. In spite of this simple approach conflicts are generally present by applying the resulting scale relations. If these procedures are extended to an analysis of the 2-D equations in the horizontal plane then some additional conflicts arise which decrease the reliability of scale model investigations more. This 2-D analysis is facilitated due to the significant progress in the last decade of 2-D mathematical modelling for the computation of the flow field and bed topography (Engelund, 1974 and Struiksma et al, 1985). Using the experience obtained from this development interesting conclusions can be drawn about scaling conflicts which is the topic of this paper.

For simplicity sake the subject matter is restricted to the scaling of meandering rivers with relatively stable banks and shallow flow. Additionally only the equilibrium bed topography is considered and it is assumed that:

- the Froude Number is small to moderate (also in the model),
- the horizontal exchange of momentum in the vertical planes due to shear and spiral flow does not affect the flow pattern,
- the spatial variation of the hydraulic roughness (Chézy coefficient) can be neglected,
- the rate of sediment transport can be determined by local conditions (dominant bed load), and
- grain sorting is insignificant (uniform bed material).

Hereafter the scale n_X of any parameter X is defined as the ratio of prototype to model value ($n_X = X_p/X_m$). The physical phenomena are described in a orthogonal curvilinear coordinate system based on the depth-averaged flow field as indicated in Figure 1.

2. Water movement

As the bed topography depends on the flow pattern and the other way around it is necessary to aim at a similar reproduction of this pattern.

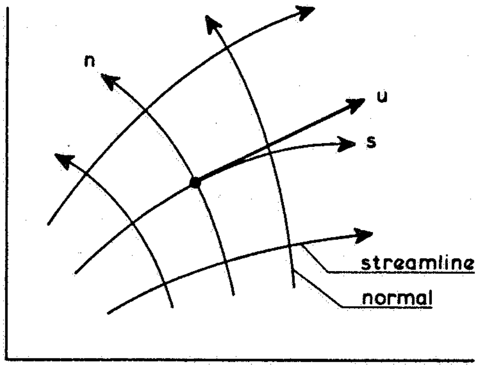

Figure 1 Coordinate system

The flow as indicated can be characterised by the Reynolds Number Re = uh/ν, Froude Number $F = u/\sqrt{gh}$ and the parameter gL/C^2h, in which u is the depth-averaged flow velocity which defines the main flow diredction and s-coordinate, h is the water depth, ν is the kinematic viscosity, g is the acceleration due to gravity, C is the hydraulic bed roughness coefficient (Chézy), and L is a characteristic length (for instance, the meander length).

To provide a sufficient reproduction of turbulence in a model the Reynolds Number has to exceed a certain value. Generally in a scale model with a movable bed this requirement can be fulfilled easily. The importance of the Froude Number and parameter gL/C^2h appears from an analysis of for instance the dimensionless vorticity equation describing the steady depth-averaged flow field in the coordinate system of Figure 1, which reads (De Vriend and Struiksma, 1983):

$$\frac{\partial \omega'}{\partial s'} + \omega'\left(2\,\frac{gL}{C^2H}\,\frac{1}{h'} - \frac{1}{h'}\,\frac{\partial h'}{\partial s'}\right) = \frac{gL}{C^2H}\,\frac{1}{h'}\left(\frac{u'}{R'} + \frac{u'}{h'}\,\frac{\partial h'}{\partial n'}\right) \quad (1)$$

in which $\omega' = \partial u'/\partial n' + u'/R'$ is the dimensionless vorticity, $s' = s/L$ and $n' = n/L$ are the dimensionless coordinates, $u' = u/U$ is the dimensionless flow velocity, $h' = h/H$ is the dimensionless water depth, $R' = R/L$ is the dimensionless radius of curvature of the stream lines (positive as the normal lines diverge), and L, H and U are characteristic measures for length, depth and velocity, respectively.

Order of magnitude estimates of the factors in damping and production terms of Equation (1) show that the Froude Number is of secondary importance for the flow as indicated before. It governs the deformation of the water surface which is small compared with that of the river bed. This gives the freedom to apply $n_F < 1$ provided that this leads to not too large Froude Numbers in the model. The freedom eases the selection of the bed material in a model. The consequences of the too steep water and bed surface gradients generated in this way are compensated by a tilting of the datum of the model in main flow direction.

The dominating factors in Equation (1) determining the behaviour of the vorticity are the bed topography represented by the water depth and the parameter gL/C^2H. Repreducing the flow pattern in a similar way implies that n_H has to be invariable in space and the parameter gL/C^2H is on scale 1. The latter condition gives the so-called roughness condition (Jansen, 1979):

$$n_C^2 = n_L/n_H \tag{2}$$

For alluvial roughness this condition will lead in most cases to distorted models due to relatively large bed roughness in the model ($n_C > 1$).

As has been shown by for instance De Vriend (1981) and Rozovskii (1961) the influence of spiral motion (generated by curved streamlines) on the main flow pattern can be remarkable. It results in an extra concentration of flow along the bank of an outer bend. This effect is not incorporated in Equation (1). Here suffice it to say that the effect is exaggerated in distorted models (scale effect).

3. Sediment motion and bed topography

A similar reproduction of the bed topography can only be archieved if the sediment transport scale is invariable in space. In fact it implies that the sediment motion pattern along the bed is reproduced similarly. If the sediment motion direction is characterised by the angle α with the s-coordinate (counter clockwise is positive) the condition is identical to:

$$n_{\tan\alpha} = 1 \tag{3}$$

in which $\tan\alpha = s_n/s_s$, s_n and s_s are the sediment transports including pores per unit length in n- and s-direction, respectively.

If it is assumed that the sediment transport s_s is varying according to:

$$s_s \propto u^b \tag{4}$$

then it can be expected that the condition might be fulfilled if the value of the exponent b in the model is equal to that in the prototype (the exponent b may vary in space). For this it is assumed further that an unique function (sediment transport formula) exists between the transport parameter $\psi = s_s/\sqrt{D^3\Delta g}$ and the Shields parameter $\theta = u^2/C^2\Delta D$, in which D is the grain size and Δ is the relative submerged density of the sediment. Then to arrive at $b_m = b_p$ it is stated that:

$$n_\theta = 1 \qquad \text{or} \qquad n_u = n_C\sqrt{n_{\Delta D}} \tag{5}$$

which will be called hereafter the "ideal" velocity scale (Jansen, 1979).

The question then arises if it is possible to fulfill the ideal velocity scale condition. For an answer the particle path direction $\tan\alpha$ will be considered in more detail. A composition of forces acting on particles moving along a mildly sloping bed leads approximately to the following dimensionless equation (Struiksma et al, 1985):

$$\tan \alpha \approx - A \frac{H}{L} \frac{h'}{R'} + \frac{H}{f(\theta)L} \frac{\partial h'}{\partial n'} \qquad (6)$$

in which A is a coefficient resulting from the depth integration of the flow. The coefficient depends slightly on the hydraulic bed roughness which will be ignored. The coefficient weighs the influence of the spiral motion whereas the f(θ) weighs the influence of the sloping bed in normal (transverse) direction on the transport direction. For a review on f(θ) reference is made to Odgaard (1981). If it is assumed that the function f(θ) is unique than from Equation (6) with $n_A = 1$ and $n_\theta = 1$, Equation (5), it is found that:

$$n_{\tan \alpha} = n_H / n_L \qquad (7)$$

For distorted models this is in conflict with the ideal velocity scale condition ($n_{\tan \alpha} = 1$). Consequently this leads to scale effects at places where tan α is relatively large. The conflict has also an implication for the morphological time scale. In fact this scale cannot be defined anymore because a distinction has to be made between the transverse (normal) and main flow direction. The conflict cannot be avoided because the roughness condition, Equation (2), has to be fulfilled (Struiksma, 1980).

For the special case of fully developed flow in a "long" circular bend with constant width tan α becomes negligible (particle path parallel to the banks). Then Equation (6) transforms into:

$$\frac{\partial h'}{\partial n'} = A \, f(\theta) \, \frac{h'}{R'} \qquad (8)$$

It can be seen easily that the assumption made about the function f(θ) together with $n_A = 1$ and $n_\theta = 1$ leads to a similar reproduction of the fully developed transverse bed slope.

4. Interaction of water and sediment motion

Due to the significant progress made in 2-D mathematical modelling of the bed topography it is possible now to estimate roughly the consequences of the scale conflict described in the foregoing chapter. Use will be made of the findings at the Delft Hydraulics Laboratory during the last decade. These findings can be found in Struiksma (1985), De Vriend and Struiksma (1983) and Struiksma et al (1985). The efforts made resulted ultimately in a mathematical model which incorporates the following physical phenomena:

- steady water motion,
- depth-averaged main velocity, including inertia, bottom shear stress and (crudely approximated) secondary flow convection,
- logarithmic vertical distribution of the main flow,
- spiral flow intensity, including inertial grow and decay,
- vertical distribution of spiral flow as in fully developed curved flow with a logarithmic main velocity profile,
- magnitude and direction of bed shear stress according to fully developed curved flow,
- rate of the sediment transport with a formula expressed in terms of the total bed shear stress and, if necessary, corrected for slope effects,
- direction of sediment transport influenced by direction of bed shear stress and sloping bed, and
- time-dependent bed level based on local sediment balance.

From a linear analysis of the steady state of the model (Struiksma et al, 1985) it appeared that the main features of the bed deformation can be described by the zero-order solution according to the fully developed bed deformation, Equation (8), which is determined by local parameters only and a wave-like first-order solution around the zero-order solution. The latter is casued by the retarded reaction of the water and sediment motion to changes of the zero-order solution. It can be characterized by a wave length and damping length which are governed by the interaction parameter:

$$\frac{\lambda_s}{\lambda_w} = \frac{2}{\pi^2}\frac{g}{C^2}\left(\frac{B}{h}\right)^2 f(\theta) \qquad (9)$$

in which $\lambda_s = \pi^{-2}\, h\, f(\theta)\, (B/h)^2$ is the relaxation length of the bed deformation, $\lambda_w = C^2h/2g$ is the relaxation length of the main flow, and B is the width of the river.
Another important factor is the exponent b in the sediment transport formula, Equation (4). In Figure 2 for b = 5 and for λ_s/λ_w ranging from 0.2 to 5 the relation between dimensionless wave numbers and interaction parameter is shown according to:

$$\frac{2\pi}{L_p}\lambda_w \approx \frac{1}{2}\sqrt{(b+1)\frac{\lambda_w}{\lambda_s} - \left(\frac{\lambda_w}{\lambda_s}\right)^2 - \frac{b-3}{2}} \qquad (10)$$

and

$$\frac{\lambda_w}{L_D} \approx \frac{1}{2}\left(\frac{\lambda_w}{\lambda_s} - \frac{b-3}{2}\right) \qquad (11)$$

in which L_p is the wave length (meander length approximately) and L_D is the damping length.
From these equations the significant influence of the exponents b can be found easily.

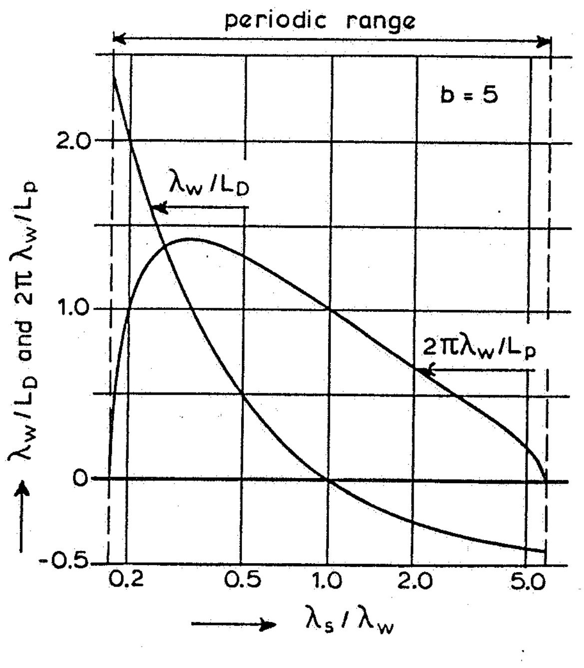

Figure 2 Wave length and damping length (Struiksma et al, 1985)

From Figure 2 it can be seen that for $\lambda_s/\lambda_w > 1$ the amplitude of the bed deformation will grow in downstream direction (negative damping length). Physically it implies that in the river islands will be formed resulting in a braided river which will not be treated here.

The results of the linear analysis are confirmed by computations with the complete mathematical model which includes also non-linear effects. In Figure 3 an example for a circular curved flume is given of such a computation compared with measurements. Also the solution of Equation (8) is indicated. Clearly it can be observed that the result has the form of a damped wave around the axi-symmetrical solution according to Equation (8). This behaviour is confirmed by the measurements. In the downstream straight section of the flume this behaviour results in a "waggling" of the bed. Figure 3 confirms the relevance of the linear analysis embodied by Equations (10) and (11) and Figure 2. For that reason it will be used here to estimate roughly the scaling conflict as described in the foregoing chapter.

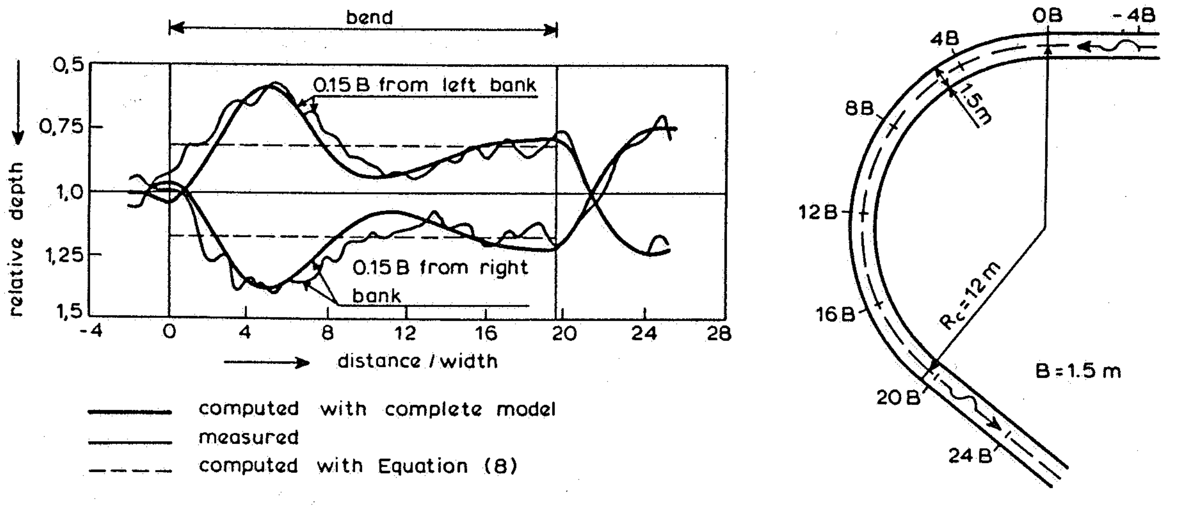

Figure 3 Measured and computed longitudinal bed profiles (Struiksma et al, 1985)

For a similar reproduction of the bed topography it is necessary that:

$$n_{L_p} = n_L \quad \text{and} \quad n_{L_D} = n_L \tag{12}$$

Together with $n_{\lambda_w} = n_L$ (roughness condition) this implies that the interaction parameter λ_s/λ_w, Equation (9), has to be reproduced on scale 1 or:

$$n_{\lambda_s} = n_L \tag{13}$$

This is impossible without violating other important scale conditions. Generally $n_{\lambda_s} > n_L$ which results according to Figure 2 in a shorter bed wave length and more damping (see Figure 4). In other words the bed topography in a scale model will be more dominated by Equation (8) than the bed topography in the prototype.

5. Discussion

Maybe a partly escape is possible because there is some evidence from experiences with computation with the complete mathematical model that with respect to the bed slope weigh function $f(\theta)$ (and also the spiral flow weigh coefficient A) a distinction has to be made between prototype and laboratory conditions with a diminishing effect on the scaling conflict. However, lack of adequate prototype data prevents a definitive conclusion for the time being.

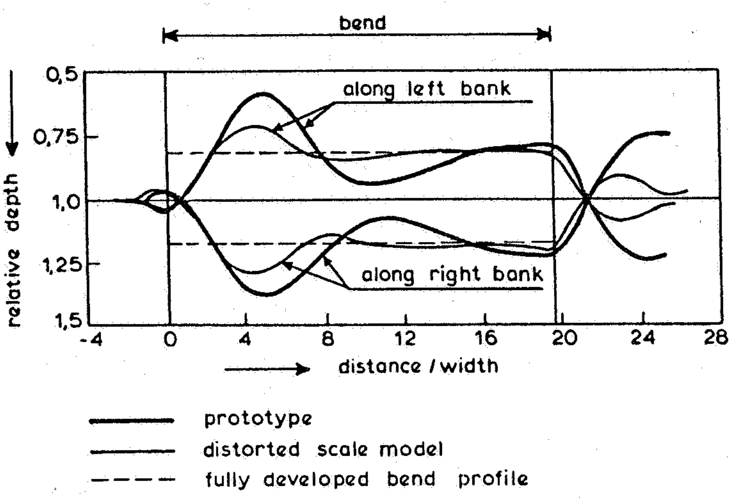

Figure 4 Scale effect in bend topography reproduction introduced by distortion of scale model

Another possibility to escape is to distinguish between transverse and longitudinal length scales as was suggested by Engelund (1981). A disadvantage of this method is a significant mutilation of the planform of the prototype.

A delicate point of discussion is that during the calibration of the model it will generally be possible to arrive at a similar reproduction of the bed topography by adjusting the boundary conditions. For instance, in a distorted scale model the interaction parameter λ_s/λ_w is too small. Enlarging the Shields parameter θ by simply increasing the discharge without changing the depth gives due to the form of the weigh function $f(\theta)$ also an enlarging of the interaction parameter and the fully developed transverse bed slope according to Equation (8). After some trial and error the object aimed at is gained. However, the scale effect described in the foregoing chapters is still present and this can lead during the progress of the investigation to wrong conclusions and recommendations.

If a river with dominant suspended load has to be modelled the described scaling conflict has to be added to other conflicts arising from the specific conditions met in such rivers. This will complicate the subject matter further more.

Good prospects are present in modelling gravel bed rivers if the grain size can be scaled down on length scale. Then most probably the bed roughness scale will be close to 1 which leads via the roughness condition to a non-distorted model.

6. Summary of conclusions

The conclusions concerning scale effects in models with movable bed can be summarized as follows:

- For the design of river scale models the Froude condition is of secondary importance. This gives the freedom to select $n_F < 1$ which is a great advantage because it facilitates the selection of other scales.
- A serious scale effect arises due to the fact that generally the alluvial bed roughness cannot be reproduced on scale 1 ($n_C > 1$). Then according to the rougness condition the model has to be distorted. In such a model it is not possible to reproduce the wave and damping length of the bed deformation on length scale.
- During the calibration of a model it is possible to arrive at a fair reproduction of the bed topography by adjusting the boundary conditions. However, the scale effects are obscured then because use is made of a groundless distortion of the ratio between the fully developed transverse bed slope and the overshoot phenomena embodied by the damped wave behaviour of the bed deformation.

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List of Symbols

A	weigh coefficient of spiral flow intensity
B	width
b	exponent in simplified sediment transport formula
C	bed roughness coefficient (Chézy)
D	grain size
F	Froude Number
$f(\theta)$	weigh function of influence of bed slope
g	acceleration due to gravity
H	characteristic depth
h	water depth
L	characteristic length
L_D	damping length of bed deformation
L_p	wave length of bed deformation
n_X	scale of parameter X
R	radius of curvature of streamline
Re	Reynolds Number
s,n	coordinates in main flow and normal direction, respectively
s_n, s_s	sediment transport including pores per unit length in n- and s-direction, respectively
U	characteristic velocity
u	depth-averaged main flow velocity
α	angle of sediment transport direction
Δ	relative submerged density of sediment
θ	Shields parameter
λ_s	relaxation length of bed deformation
λ_w	relaxation length of main flow
ν	kinematic viscosity
ψ	sediment transport parameter
ω	vorticity
p,m	indices, denoting prototype and model, respectively

- Nevertheless, the results of the experiments give the designer of a scale model more opportunity to arrive at a satisfactory set-up especially in the case of modelling rivers with a bed consisting of fine sand.

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List of Symbols

A	weighing coefficient spiral flow intensity
B	local width
$\bar{B}$	average width
C	Chézy coefficient
C_f	friction factor
D	grain size
D_{50}	median grain size (numerical subscript, in this case 50, denotes particle size in sediment for which percentage by weight corresponding to subscript is finer)
F	Froude Number
$f(\theta)$	weighing function of influence of bed slope
g	acceleration due to gravity
h	local water depth
$\bar{h}$	average water depth
i	water surface slope
L	characteristic length
L_D	damping length bed deformation
L_m	meander length (chord length)
L_w	wave length bed deformation
n_X	scale of parameter X
Q	discharge
R	radius of curvature of axis model
Re	Reynolds Number
S	sediment transport including pores
s	sediment transport per unit width including pores
u	local flow velocity
$\bar{u}$	average flow velocity
Δ	relative density of sediment
θ	flow parameter
λ_s	relation length bed deformation
λ_w	relation length flow
ν	kinematic viscosity
ρ	density of water
ρ_s	density of sediment
σ_g	geometric standard deviation of sieve curve; defined as $\sigma_g = \frac{1}{2}(D_{50}/D_{16}+D_{84}/D_{50})$
ψ	transport parameter

INTERNATIONAL ASSOCIATION FOR HYDRAULIC RESEARCH

Symposium '86
on
Scale Effects in Modelling Sediment Transport Phenomena

Experimental Comparison of Scaling with Sand and Bakelite as Bed Material

by

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Synopsis

In a scale model with movable bed of the Nile River in South Sudan it was checked whether or not the light weight material bakelite (density 1350 à 1450 kg/m^3) can be used as a substitute for sand as bed material. Two series of experiments were carried out under different steady flow conditions. Each series consisted of a run with bakelite and a run with sand, the flow conditions being adjusted according to the scaling procedure applied at the Delft Hydraulics Laboratory. Consequently within each series the run with bakelite could be considered as a scale model of the run with sand or vice versa.

From the experiments it appeared that bakelite and sand used as bed materials will reproduce the bed topography of rivers in a similar way. Only significant differences were observed in the reproduction of the pool depths. This scale effect can be attributed to the applied distortion in the bakelite experiments.

Résumé

Dans un modèle reduit à fond mobil du fleuve Nil au Sudan-Sud on a vérifié si bakelite (densité reduit entre 1350 et 1450 kg/m^3) pouvrait être utilisé au lieu du sable comme matérial solide. Deux pairs d'essais sont exécutés chaqu'un à une différente condition permanente. Chaque pair comprenait d'un essai avec du bakelite et un essai avec du sable, les conditions d'écoulement étant adaptées en accord avec les procédures de modelage comme utilisé au Laboratoire de l'Hydraulique de Delft. Alors dans chaque pair l'essai avec le bakelite pouvait être considéré comme une modelage de l'essai avec du sable et vice versa.

Les expériences montrent que les deux, le bakelite et le sable, réproduisent de même façon la topographie des fleuves. Seulement des différences significantes étaient observés dans la réproduction de la profoundeur prés du bord concave. Cette dissimilitude d' échele peut être attribué à la distortion plus grande des essais avec du bakelite.

1. Introduction

For many years light weight materials have been used as a substitute for natural sand in scale models with a movable bed. The main reason for this is that sand grains cannot always be scaled down on a linear scale without losing their main physical features. At the Delft Hydraulics Laboratory (DHL) bakelite (density ρ_s = 1350 to 1450 kg/m^3) is often used in river scale models with dominant bed load transport. Until recently it was not sufficiently checked whether or not this material yields a reproduction of the bed topography which is similar to results obtained with sand as bed material. For this reason some experiments were carried out from April to July 1980 in a river scale of the Bahr el Jebel (the River Nile) in South Sudan. For details on the purpose and the set-up of the original model reference is made to Klaassen (1979).

Two series of experiments were carried out under different steady flow conditions. Each series consisted of a run with bakelite and a run with sand, the flow conditions being adjusted according to the scaling procedure applied at the Delft Hydraulics Laboratory for this type of model. Consequently within each series the run with bakelite could be considered as a scale model of the run with sand or vice versa. In this investigation only the locally time-averaged equilibrium bed topography was considered.

In the following chapters the model features, the scaling of the process involved and the results are described. Conclusions as to the applicability of bakelite as bed material as compared to sand are presented in the final chapter.

2. Model features

The layout of the river model and the operational equipment are shown in Figure 1. The planform of the model can be classified as meandering; in addition it is characterized by gradually varying width and bend curvature. The meander length L_m, the total model length L measured along the axis and the averaged with $\bar{B}$ were 14.8 m, 31 m and 1.09 m, respectively. The model was provided with vertical plastered brick side walls with a height of approximately 0.5 m above a concrete floor. The area contained by the walls was filled up to a height of about 0.3 m above the floor with bed material (bakelite and sand, respectively). The sieve curves of the bed materials used are given in Figure 2.

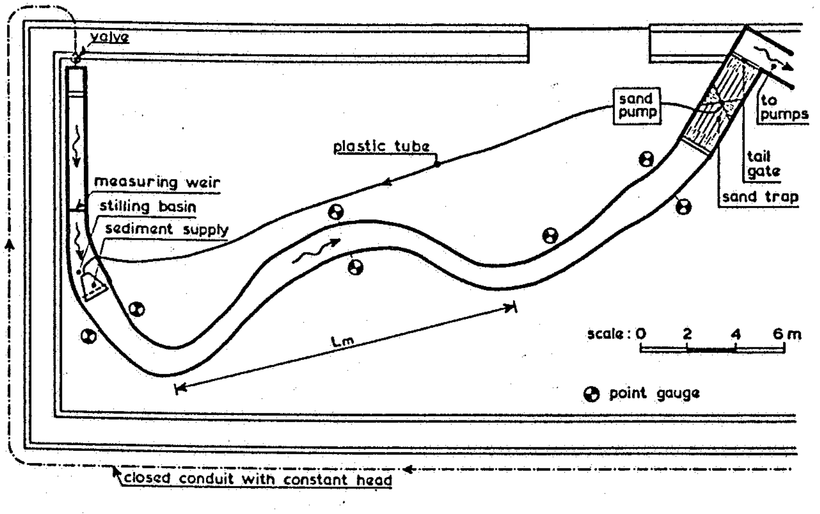


Figure 1 Layout of the model

The water was taken from an elevated constant head tank and conveyed to the model entrance via an underground conduit. The discharge was adjusted by a valve and measured using a Rehbock weir before it was supplied to the model. After running from where it was pumped up again into the constant head tank. As there is evidence that the water temperature affects the morphological processes it was kept constant at 18°C during all experiments. This was achieved by using an existing heating or cooling facility.
The water level at the downstream end of the model was adjusted by the tailgate. The water levels in the model were measured at the locations indicated in Figure 1. These locations were connected to stilling wells provided with a point gauge.

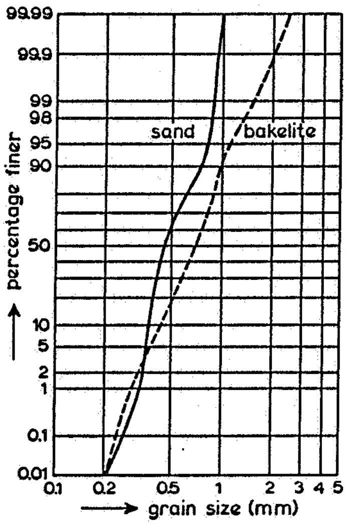


Figure 2 Sieve curves of used sand and bakelite

Before the water flowed over the tailgate its sediment was deposited in a sand trap. From there the sediment was pumped continuously via a plastic tube to the upstream boundary of the model. Here it was returned to the model. Twice a day the through the model and pouring over the tailgate the water was returned to a sump sediment transport was measured by pumping during one hour the sediment-water mixture into a sedimentation box. The volume (including pores) of the sediment which settled in the box was measured. During this one hour period the sediment supply to the model was done by hand by feeding in the quantity of sediment collected during the preceding sediment transport measurement period.

Measurements of the bed topography (as presented in Chapter 4) were obtained during the equilibrium state which for each run was reached after about two weeks. This relatively short period was achieved by running the model continuously day and night and also during the weekends. The equilibrium state was assumed to be established when major changes in the time-averaged values of the sediment transport, average water depth and water surface slope no longer occurred. Soundings were then carried out in the cross-sections indicated in Figure 3.

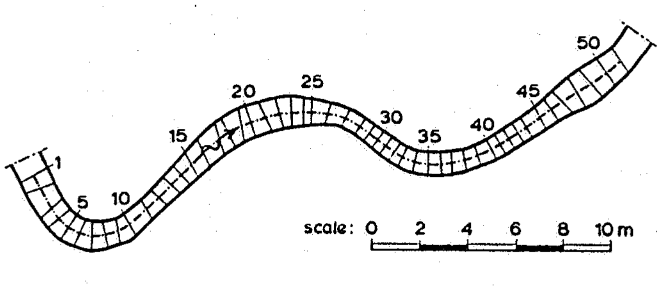


Figure 3 Layout of the cross-sections

The sampled cross-sections had been set up for a previous investigation (Klaassen, 1979), i.e. they were not selected specifically for the investigations described here. The cross-section distribution, as can be seen in the figure, was irregular, but was judged to be adequate. In the cross-sections the distance between the measuring points was 0.1 m, the first point being situated 0.05 m from the left bank. A simple rod provided with a sounding foot and millimeter scale was used to measure the bed level at each point. During the equilibrium state, the bed level at each measuring point was sounded 25 times while the model was in operation. The equilibrium measurements covered a period of several days. This large number of soundings spread over such a long period was judged to be necessary in order to obtain reliable time-averaged data per point in view of the "noise" of the slowly propagating bedforms.

3. Scaling of the processes involved

In this paper the scale n_X of any parameter X is defined as the ratio of the value of X in the prototype and the value of X in the model. The runs with sand are considered as "prototype" and those with bakelite as "model".

The scaling procedure applied for this investigation has been in use for many years at the Delft Hydraulics Laboratory (De Vries, 1973; Struiksma, 1980). The procedure holds for rivers with shallow friction-controlled flow and dominant bed load transport. In this flow field the Froude Number is assumed to range from small to moderate; the shear in the vertical planes, the non-uniformity of the vertical velocity distribution (spiral flow) and the spatial variations of the hydraulic bed roughness coefficient are neglected.
The flow field can be characterized by the Reynolds Number $Re = uh/\nu$ Froude Number $F = u/\sqrt{gh}$, and the roughness-distortion ratio gL/C^2h, in which u is the depth-averaged flow velocity, h is the water depth, ν is the kinematic viscosity, g is the acceleration of gravity, C is the hydraulic bed roughness coefficient and L is a characteristic length (for instance, the meander length L_m).
To provide a sufficient reproduction of turbulence in a model the Reynolds Number must exceed a certain value. Generally in movable bed models this requirement can be easily fulfilled. The importance of the Froude Number and roughness-distortion ratio is indicated by an analysis of the governing equations.
Struiksma (1980) shows that for the flow field considered the Froude Number is of secondary importance for the reproduction of the flow pattern. The flow field is mainly governed by the bed topography and the roughness distortion ratio. The roughness-distortion ratio has to be reproduced at full scale which leads to the so-called roughness condition:

$$n^2_C = n_L/n_h \tag{1}$$

For the alluvial roughness this condition leads in most cases to distorted model ($n_C > 1$).

Correct reproduction of the bed topography might be expected if the sediment transport scale is constant in space. According to De Vries (1973) this might be achieved when the "ideal velocity scale" is fulfilled. This scale follows from the assumption that there is a unique relationship (sediment transport formula) between the transport parameter $\psi = s/\sqrt{D^3 g\Delta}$ and the flow or Shields parameter $\theta = hi/\Delta D$, in which s is the sediment transport (by volume, including pores) per unit width, D is the grain size, $\Delta = (\rho_s - \rho)/\rho$ is the relative density of the sediment, ρ_s is the density of the sediment, ρ is the density of the water, and i is the water surface slope. For a constant sediment transport scale the flow parameter has to be reproduced at full scale, hence:

$$n_\theta = 1 \tag{2}$$

The flow parameter can also be written in terms of the Chézy equation and then the "ideal velocity scale" appears:

$$n_u = \sqrt{n_C^2 \, n_\Delta \, n_D} \tag{3}$$

It can be shown that the flow parameter is not only the main factor in the sediment transport formula but that also it affects the sediment transport pattern along the bed and the lateral bed slope (Struiksma, 1980).

For this investigation the boundary conditions were adjusted in such a way that the roughness and ideal velocity scale conditions were fulfilled.

4. Results

The average independent and dependent parameters governing the phenomena in the model are tabulated in Table 1 (for an explanation of the parameters see the "List of Symbols"). From this table it can be seen that for both test series (T1-T3 and T2-T4) the roughness condition and the ideal velocity scale are fulfilled satisfactorily (boxed figures).

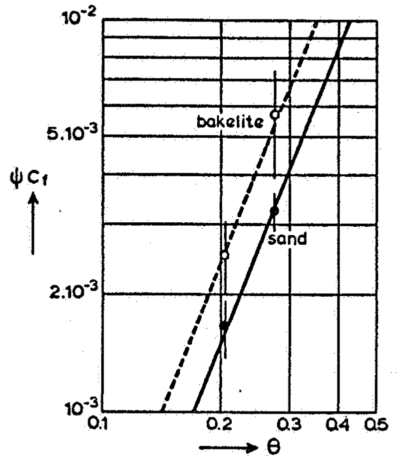
How far the condition of a spatially constant sediment transport scale n_s is achieved can be investigated very roughly by considering for instance the sediment transport formula of Engelund and Hansen (1967). This formula reads (porosity is 0.4 and characteristic grain size is the median size):

$$\psi C_f = 0.084\ \Theta^{2.5} \tag{4}$$

in which, $C_f = g/C^2$ is the friction factor. This formula is plotted in Figure 4 in a (ψC_f-Θ) diagram as a solid line. The results of the sediment transport measurements given in Table 1 are also indicated. The vertical lines through the measured points indicate the range of observations. It can be seen that the sediment transport in the experiments with sand agree very well with Equation (4). For the experiments with bakelite the equation underestimated the transport significantly. Maybe this is caused by differences in the porosity and shape factor of the grains.

		BAKELITE T1	SCALE	SAND T3	BAKELITE T2	SCALE	SAND T4
Q	[l/s]	18.42	1.33	24.51	27.46	1.37	37.50
$\bar{B}$	[m]	1.09	1	1.09	1.09	1	1.09
$\bar{h}$	[m]	0.095	0.65	0.062	0.120	0.68	0.082
$\bar{u}$	[m/s]	0.178	2.04	0.363	0.210	2.00	0.420
$i * 10^3$	[-]	0.60	4.28	2.58	0.64	4.08	2.61
C	[$m^{\frac{1}{2}}/s$]	23.4	1.23	28.7	24.0	1.20	28.7
D_{50}	[mm]	0.70	0.67	0.47	0.70	0.67	0.47
σg	[-]	1.39	0.95	1.32	1.39	0.95	1.32
Δ	[-]	0.40	4.13	1.65	0.40	4.13	1.65
S	[m^3/day]	0.48	1.15	0.55	1.16	0.93	1.08
L_m	[m]	14.8	1	14.8	14.8	1	14.8
F	[-]	0.18	2.52	0.47	0.19	2.42	0.47
$C_f * 10^2$	[-]	1.79	0.66	1.19	1.70	0.70	1.19
Θ	[-]	0.206	1.00	0.206	0.274	1.01	0.276
$gL_m/C^2\bar{h}$	[-]	2.78	1.02	2.84	2.10	1.02	2.15
ψ	[-]	0.14	1.00	0.14	0.34	0.83	0.28
$\bar{h}/\bar{B}$	[-]	0.087	0.66	0.057	0.110	0.68	0.075

Table 1 Governing parameters and scales



LEGEND
- ● sand test
- o bakelite test
- ___ Engelund-Hansen transport formula
- -- do with adapted coefficient

Figure 4 Results of sediment transport measurements-v Engelund-Hansen formula

However, it is the slope of the lines through the measured points which is an indication of the uniformity of the transport scale and not the actual amounts. For both bed materials the slope is more or less the same and is equivalent to approximately the exponent (2.5) in Equation (4). Consequently for these experiments the ideal velocity concept holds. Nevertheless the foregoing reasoning is doubtfull because it is based on average conditions. In fact, when local conditions are considered it can be shown that in case of distortion ($n_L \neq n_h$), following from the roughness conditions, the goal of the ideal velocity scale concept can never be reached (Struiksma, 1980). From Table 1 it can be seen that $n_L > n_h$ indicating that scale effects occurred.

The measured bed topography data together with data of the water surface of each experiment (T1, T2, T3 and T4) were processed to local water depth (h). These depths were normalised by dividing them by the averaged water depth (see Table 1) resulting in the local relative water depth ($h/\bar{h}$). Three longitudinal bed profiles of these values were then composed, viz. two at a distance of one sixth of the local width (B/6) from the left and right bank, respepctively, and one along the axis of the model. The longitudinal profiles of the experimental combinations

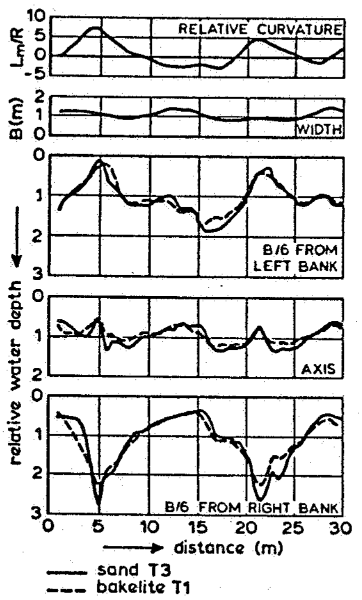


Figure 5 Longitudinal profiles, T1 and T3

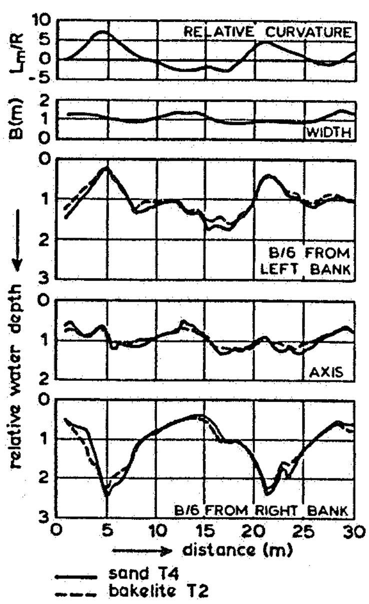
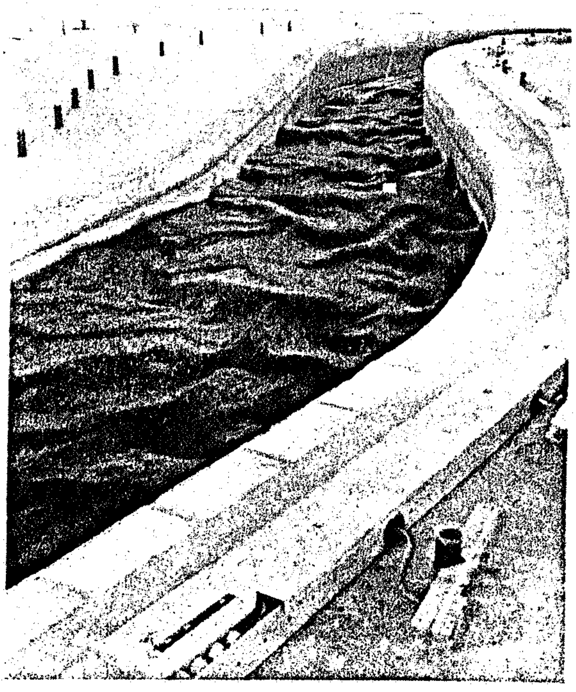


Figure 6 Longitudinal profiles, T2 and T4



Photograph 1 Upstream view of bakelite bed

Photograph 2 Upstream view of sand bed

T1 (bakelite) - T3 (sand) and T2 (bakelite) - T4 (sand) are shown in Figures 5 and 6, respectively. The distance indicated is that measured along the axis of the model. It can be seen that by presenting the results of each experiment in this way an overall picture of the bed topography is obtained which gives sufficient information for comparison purposes. All data of the local relative water depth are presented in the form of cross-sections in the original report (Struiksma, 1983a), which gives a more detailed presentation of the results.

Figures 5 and 6 also show the local relative curvature of the axis of the model, defined as the ratio of meander length (see Table 1) to the radius of curvature (R) of the axis of the model (bend turning to the left defined as positive), and the local width (B) both as functions of the distance measured along the axis of the model. Upstream views of the dry model bed are shown in Photographs 1 and 2 for bakelite and sand, respectively. In these photographs it can be seen that the bedforms of bakelite are more pronounced than those of sand. The photographs were taken after experiments T2 and T4.

5. Discussion

The most important conclusion from the foregoing chapter is that bakelite and sand bed materials in scale models with movable bed will reproduce the bed topography of rivers with dominant bed load transport in a similar way. This conclusion follows from the comparison of the longitudinal profiles given in Figures 5 and 6. The differences between the sand and bakelite profiles are generally not significant. However, the pools along the concave banks in the bakelite experiments shown consistently too small relative depth. Most probably this is caused by the greater depth-width ratio in the bakelite experiments which was required to satisfy the roughness condition. This is illustrated in Table 2, where the relaxation lengths of the main flow (λ_w) and of the bed deformation (λ_s) are given for the four tests. From the table it follows that the ratio λ_s/λ_w is consistently smaller for the bakelite tests than for the tests with sand. This underlines the conclusions of Struiksma et al (1985) that this will result in a scale effect in the wave and damping length of the bed deformation (L_p,L_D) in such a way that it decreases overshoot phenomena. From the data series in Table 2 it follows also that there is only a small scale effect in the reproduction of the fully developed transverse bed slope in the bends (determined by A $f(\bar{\theta})$) which contributes further to the explanation of the differences.

		T1 bakelite	T3 sand	T2 bakelite	T4 sand
relaxation length bed	λ_s (m)	0.98	1.49	0.89	1.32
relaxation length flow	λ_w (m)	2.65	2.60	3.52	3.44
interaction parameter	λ_s/λ_w (m)	0.37	0.57	0.25	0.38
spiral flow intensity coefficient	A (-)	8.32	9.09	8.42	9.09
bed slope weighing function	f (θ) (-)	0.38	0.38	0.44	0.44
wave length	L_p (m)	11.9	12.9	16.7	15.4
damping length	L_D (m)	3.11	6.90	2.35	4.22
relative damping	λ_w/L_D (-)	0.85	0.38	1.50	0.82

Table 2 Parameters of the various tests, according to Struiksma (1986) relevant for the reproduction of bend phenomena

When the longitudinal profiles of all experiments are compared there appears to be no significant differences between T1, T2, T3 and T4. This would suggest that the scale conditions on which this investigation was based (given in Chapter 3) are not relevant. This might imply that the flow pattern was not significantly affected by the bed friction and that the influence of the flow parameter on the lateral bed slopes was weak. However, this conclusion contradicts the findings from other experiments including in a circular curved flume in the Delft Hydraulics Laboratory in which the flow parameter was varied by a factor 2 (Struiksma, 1983b) a factor much larger than the variation (Table 1) applied in the present experiments.

A plausible explanation of the insignificant differences can be found from Table 2. From the table it follows that the factors A f(θ) and λ_w/L_D are smaller for the experiment T1 and T3 than for the experiments T2 and T4. Consequently for the experiments T1 and T3 the fully developed transverse bed slopes are smaller but overshoot phenomena are stronger than for the experiments T2 and T4. Hence, these effects counter balance each others to some extent.

Finally the following additional remarks can be made:

- According to Table 1 (boxed figures) the main scale conditions were fulfilled satisfactorily.
- Because extensive erosion-resistant layers are present in the Bahr el Jebel River no attempt was made to compare the data of the experiments with those of the real prototype.
- An advantage of the use of bakelite, although of minor importance, is that relatively low flow velocities can be used in a model giving generally a better approximation of the Froude condition. However, a serious disadvantage is the presence of the relatively large hydraulic bed friction making, in order to satisfy the roughness condition, a relatively large distortion of the geometry necessary.

6. Summary of conclusions

The conclusions of this study can be summarized as follows:

- Bakelite and sand will approximately reproduce a bed topography in a scale model with movable bed in a similar way provided that the same scaling conditions are applied.
- Due to the relatively large hydraulic bed roughness models with bakelite have to be more distorted than models with sand in order to satisfy the roughness condition. For that reason the bakelite models will be subject to larger scale effects in the reproduction of the point bar dimensions and the dimensions of the associated pool in the outer bends.

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