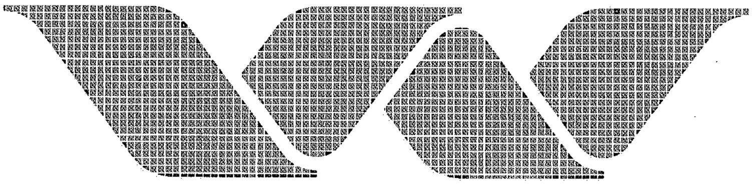

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presented at the IAHR Symposium
on River Engineering and its
Interaction with Hydrological and Hydraulic
Research, Belgrado, May 26 - 28, 1980

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October 1980

INTERNATIONAL ASSOCIATION FOR HYDRAULIC RESEARCH

Symposium on River Engineering and Its Interaction
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RECENT DEVELOPMENTS IN DESIGN OF RIVER SCALE MODELS WITH MOBILE BED

Subject D

by

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Synopsis

Scale models with a mobile bed can be useful tools to judge river channel regulation design. Some recent developments in scaling of the processes involved and schematisation of the regime are discussed. Attention is also paid to the occurrence of scale effects due to the distortion of a model. An example of a scale model of the Waal River near Nijmegen in the Netherlands is introduced to elucidate some aspects. Furthermore a description is given of a new bed level measuring device.

Résumé

Les modèles réduits à fond mobile peuvent être d'utiles instruments pour l'évalution des projets de régulation des fleuves. Quelques développements récents concernant la reproduction des phénoménes en vigeur et le schématisation du régime dans les modèles réduits sont dicutés. L'attention est également attirée sur les erreurs dues à la distortion d'un modèle. Un example d'un modèle réduit du fleuve Waal près de Nimegues aux Pay-Bas est donné pour illustrer certains aspects. En outre, un nouveau système de mesure du niveau du fond est décrit.

1. Introduction

Since decades mobile bed scale models are useful tools to judge river channel regulation design. In spite of the growing capacity of computers, which enables complicated mathematical models to be programmed, it cannot yet be expected that in the field of morphology every type of mobile bed scale model will be replaced. Especially those scale models which aim at a detailed reproduction of the bed topography still have a future. But as river authorities are continually claiming more accuracy for the prediction of the consequences of river-training works the scaling of and operational techniques for scale models will have to be improved.

In view of this, some recent developments in the Delft Hydraulics Laboratory are being briefly discussed. The subject matter is restricted to the scaling of rivers with steady shallow flow and dominant bed load transport. In this shallow flow field the Froude number is assumed to range from small to moderate, whereas the shear in the vertical planes, the non-uniformity of the vertical velocity distribution and the spatial variation of the hydraulic bed roughness are neglected in describing the flow pattern.

In the following sections attention is paid to the scaling of the processes involved, the schematisation of the regime, the bed level measuring technique, and the results of the calibration of a scale model of the Waal River near Nijmegen (main Rhine branch in the Netherlands). In this paper the scale n_X of any parameter X is defined as:

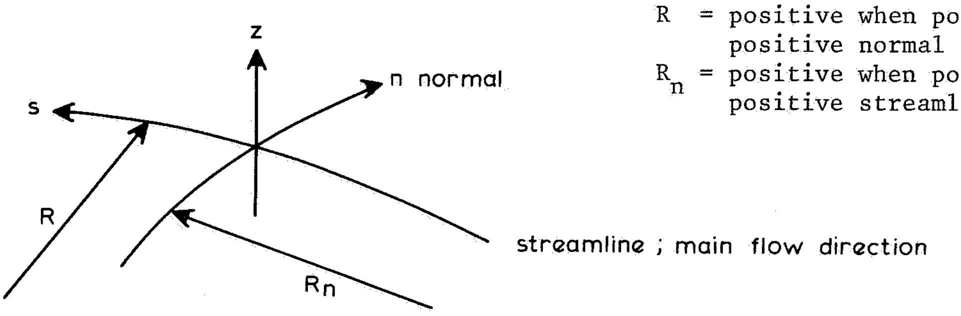
$$n_X = \frac{\text{value of X in prototype}}{\text{value of X in model}} = \frac{X_p}{X_m} \qquad (1)$$

The physical phenomena are described in a curvilinear coordinate system for the depth-averaged flow field as indicated in Figure 1.

2. Scaling of the processes involved

2.1 Flow pattern

As the bed topography depends on the flow pattern and the other way about, it is necessary to aim at a similar reproduction of this pattern. The flow as indicated in the introduction can be characterised by the Reynolds number $Re = vh/\nu$, Froude number $F = v/\sqrt{gh}$, and the roughness-distortion ratio gL/C^2h, in which v is the depth-averaged flow velocity, h is the water depth, ν is the kinematic visocity, g is the acceleration of gravity, C is the hydraulic bed roughness coefficient, and L is a characteristic length (for instance, the radius of curvature R of a streamline).



R = positive when pointing in positive normal direction
R_n = positive when pointing in positive streamline direction

Figure 1 Curvilinear coordinate system for the depth-averaged flow field

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 mobile bed, this requirement can be fulfilled easily. The importance of the Froude number and roughness-distortion ratio appears from an analysis of the dimensionless vorticity equation describing the depth-averaged flow pattern in a curvilinear coordinate system (Figure 1), which reads (De Vriend [1]):

$$\frac{R^2}{v}\frac{\partial\omega}{\partial s} + \frac{R}{v}\omega\left\{(2 + F^2)\frac{gR}{C^2h} + \frac{R}{h}\frac{\partial Z_b}{\partial s}\right\} = -\frac{gR}{C^2h}\left(1 + F^2 - \frac{R}{h}\frac{\partial Z_b}{\partial n}\right) \qquad (2)$$

in which $\omega = -\partial v/\partial n - v/R$ is the vorticity and Z_b is the bed level.

Order of magnitude estimates of the factors in the damping and production terms show that the Froude number is of secondary importance. This gives the freedom to choose $n_F < 1$ provided that this also leads to a moderate Froude number in the model. This freedom eases the selection of the bed material for a model investigation. Then the consequences of the too steep water and bed surface gradients generated in this way are compensated by a tilting of the model. So the flow pattern is mainly governed by the bed topography ($\partial Z_b/\partial s$ and $\partial Z_b/\partial n$) and the roughness-distortion ratio (gR/C^2h).

Reproduction of the flow pattern in a similar way implies that n_v (or n_h) is invariable in space and $n_R = n_{R_n} = n_L$. According to Equation (2) this can be achieved when the dimensionless factors in the damping and production terms are reproduced in full scale. In other words a correct reproduction of the bed topography is required and the so-called roughness condition has to be fulfilled (Jansen [2]):

$$n_C^2 = n_L/n_h \qquad (3)$$

For alluvial roughness this condition will lead to distorted models ($n_C > 1$).

Equation (2) has been based on a simplified depth integration. Factors and coefficients that represent the influence of the non-uniform flow distribution in the vertical have been neglected. For instance this is the case with the secondary flow advection generated by curved streamlines. De Vriend [1] has shown that when this advection is acting over a relatively long distance the influence on the main flow pattern can be remarkable. The phenomenon cannot be reproduced in a satisfactory way in distorted models (scale effect).

2.2 Bed topography

For a scale model with a mobile bed the correct reproduction of the bed topography is the main target. The occurrence of a correct reproduction may be expected if the sediment transport scale is invariable in space. According to De Vries [3] and Jansen [2] this might be achieved when the so-called "ideal velocity scale" is fulfilled. This scale follows from the assumption that an unique function (sediment

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1 VRIEND, H.J. de
Streamline curvature and bed resistance in shallow water flow. Internal Report No. 1-79, Laboratory of Fluid Mechanics, Department of Civil Engineering. Delft University of Technology, Delft, The Netherlands, 1979

2 JANSEN, P.Ph.
Principles of river Engineering, The non-tidal alluvial river. Pitman Publishing Limited, London, 1979

3 VRIES, M. de
Application of physical and mathematical models for river problems, DHL Publication No. 112, 1973

transport formula) exists between the transport parameter $\Psi = s_s / \sqrt{D^3 \Delta g}$ and the flow parameter $\theta = \mu h i / \Delta D$, in which s_s is the bed load transport per unit width in main flow direction, D is the grain size (diameter), Δ is the relative density of the sediment, μ is the ripple factor, and i is the water surface slope in main flow direction (downward slope is positive). These dimensionless parameters have to be reproduced in full scale. If this approach holds, it implies automatically that the particle path pattern of the sediment grains along the bed is similar to that in the prototype. In other words, the sediment transport direction at any place in the model, defined with respect to the main flow direction as $\tan \gamma = s_n / s_s$ is equal to that in the prototype, in which s_n is the bed load transport per unit length in normal direction. Hence:

$$ {}^{n}{\tan\gamma} = 1 \qquad (4) $$

If grain sorting is present Equation (4) is valid for each separate fraction.

The question then arises if it is possible to fulfill the ideal velocity scale condition. For this the particle path direction tan γ will be considered in more detail. Figure 2 shows the forces acting on a particle moving along a mildly sloping bed. Composition of the forces leads to a resultant of which the direction coincides with that of the particle path (Koch [4]):

$$ \tan\gamma = (K_n - G \frac{\partial z_b}{\partial n}) / (K - G \frac{\partial z_b}{\partial s}) \qquad (5) $$

Note that the friction has no influence on this direction.

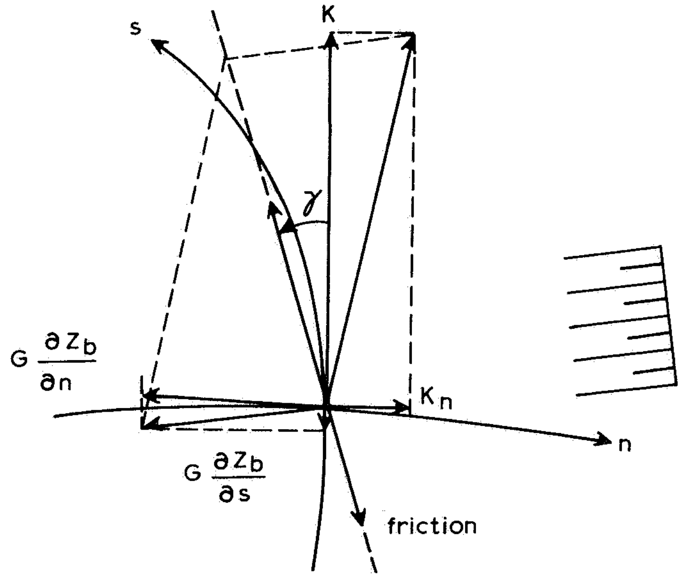

Figure 2 Composition of forces acting on a particle moving along a mildly sloping bed

In Equation (5) K and K_n are by the flow generated forces in main flow and normal directions respectively and G is the submerged grain particle weight. These forces are defined here as: $K = f_1 D^2 \tau_{sb}$, $K_n = f_1 D^2 \tau_{nb}$ and $G = f_2 (\rho_s - \rho) g D^3$, in which τ_{sb} and τ_{nb} are the bed shear stresses in main flow and normal directions respectively, ρ_s and ρ are the specific densities of sediment and water respectively,

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4 KOCH, F.
Bed level computations for axisymmetric curved channels, DHL, TOW Rivers, Report R 657-IX, 1980

and f_1 and f_2 are shape factors of the grain particle. Eventually a lift force can be incorporated in the factor f_2. The bed shear stresses are assumed to be $\tau_{sb} = \rho ghi$ and $\tau_{nb} = - \alpha\ h\ \tau_{sb}/R$, in which α is a coefficient resulting from the depth-integration of the flow field (Jansen [2]). The coefficient depends slightly on the hydraulic bed roughness. The latter stress is a consequence of curved streamlines (spiral flow).

Introduction of these relations in Equation (5) leads to an expression for the bed topography, which in dimensionless form reads:

$$\frac{B}{h} \left(\frac{\partial Z_b}{\partial n} - \frac{\partial Z_b}{\partial s} \tan \gamma\right) = - \frac{Ahi}{\Delta D} \left(\frac{B}{R} + \frac{B}{\alpha h} \tan \gamma\right), \tag{6}$$

in which $A = \alpha\ f_1/f_2$ is a coefficient and B is a characteristic length introduced to provide dimensionless factors (for instance, the river width). In river bends the factor $\tan \gamma\ \partial Z_b/\partial s$ is small compared with $\partial Z_b/\partial n$ and can be neglected.
Similar reproduction of the cross-sectional slope in a model requires that all factors in Equation (6) have to be in full scale. For the direction of the sediment transport this implies that (assuming $n_\alpha = 1$):

$$n_{\tan \gamma} = n_h/n_L \tag{7}$$

For distorted models this is in conflict with the ideal velocity scale ($n_{\tan \gamma} = 1$). Consequently this leads to scale effects at places where $\tan \gamma$ is relatively large (beginning of a bend) or under changing flow conditions (regime). Only in non-distorted models can this conflict be avoided, but then the roughness condition will be violated (see Section 2.1).

Although the reasoning is based on incomplete theories, empirism and assumptions the indicated conflict is the main source of errors in distorted scale models with mobile bed (scale effects).

3. Schematisation of the regime

Schematisation of the river regime to one single discharge, the so-called "dominant discharge", is common in river engineering practice. It simplifies the correlation of river characteristics and leads to easy computations. However, many definitions exist producing different results. For a discussion on this subject, reference is made to Prins [5] . To demonstrate these differences this author made computation of the dominant discharge for the Waal River near Nijmegen (Figure 4). By using the several definitions he arrives at a discharge range of 1,200 to 1,700 m^3/s. Comparatively in this river reach the discharge corresponding to the average water level is 1,300 m^3/s and the bankful discharge is 1,750 m^3/s.

Also for scale model studies the dominant discharge concept is frequently introduced. The main advantage is that it allows an easy model operation. For that reason the concept was used for the model investigation of the Waal River near Nijmegen, of which the results of the calibration are briefly discussed in Section 5. A discharge was selected which gave the best results with respect to the reproduction of the bed topography. After some pilot runs, the dominant discharge was established. It corresponded with a prototype value of 1,250 m^3/s which lies within the range computed by Prins.

It will be, clear that the concept is only able to reproduce a kind of dynamic

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5 PRINS, A.
Dominant discharge, DHL, Research Report S78-III, 1969

equilibrium. As in reality the bed is changing in space and time, interpretation of the results may be hampered, depending on the aim of the investigation. Therefore recently the dominant discharge concept has been tested in the Waal River model as a conclusion of the investigation. This has been achieved by comparing the results of runs with dominant discharge with those with a varying discharge (regime). The tests were carried out in an alignment which deviated strongly from the existing prototype situation (Figure 4). The discharges in the model have been varied within a range corresponding with prototype values of 600 to 2,000 m^3/s. Although the results have not yet been fully elaborated and interpreted, some interesting preliminary conclusions can already be drawn.

Three typical reaches can be distinguished in this case: i.e. the crossing, the beginning and the downstream part of the bend characterized by undefined, steep and moderate cross-sectional bed slopes respectively. Concerning these bed slopes a remarkable time-dependency was observed in the crossing and the down-stream part of the bend. The bed at the beginning of the bend was stable even under long-term variations of the discharge. Apparently only here does the dominant discharge concept hold.

4. Bed level measuring device

When sounding a cross-section in a river or a model the bedforms mostly disguise the "true" bed level. Usually its appearance is considered to be of a stochastic nature. Hence to restrict their influence many soundings have to be carried out and averaged. However, if many cross-sections have to be measured, such a procedure can be very time-consuming or need many surveyors.

That is why for the scale model study of the Waal River near Nijmegen a new sounding device has been developed. With this device it is possible to measure 80 cross-sectional profiles within a quarter of an hour. The device consists of a light-weight bridge with a span of 5 m, needing only two man to carry and attend to it (Figure 3). In this bridge 14 slide holes at mutual distances of 20 cm have been introduced each containing a sounding rod with a foot (4 x 4 cm^2). In each rod 240 holes have been drilled on mutual distances of 2.5 mm. All rods can be maintained in an upward position with their feet about 20 cm above the water surface during transport from cross-section to cross-section. In a cross-section to be sounded the device is placed on supports on both banks and the feet are put on the bed after a simultaneous free fall of the rods. For sand beds the impact of the feet is about 5 mm (systematic). During the free fall the holes in the rods pass two electronic eyes attached to the slide holes in the bridge, so that the number of holes passing can be counted. The level of the cross-sectional supports and the dimensions of the sounding device are known, so the counting results can be transformed to bed levels. The data collection and data processing is executed by means of a computer facility.

Because the device is able to collect a lot of data within a short time it has greatly facilitated the regime investigation described in Section 3.

Figure 3 Bed level measuring device

5. Results of calibration of a scale model

In this section the results of the calibration of a scale model of the Waal River near Nijmegen with a distortion of 2.5 will be briefly discussed. The bed in the model consisted of sand graded in a similar way as in the prototype. Near Nijmegen navigation is obstructed by a very sharp bend, so that the aim of the model investigation was to advise with respect to a navigation channel improvement. Because the Waal River is a very intensively-used fairway, mainly the width of the navigation channel in the river has been studied.

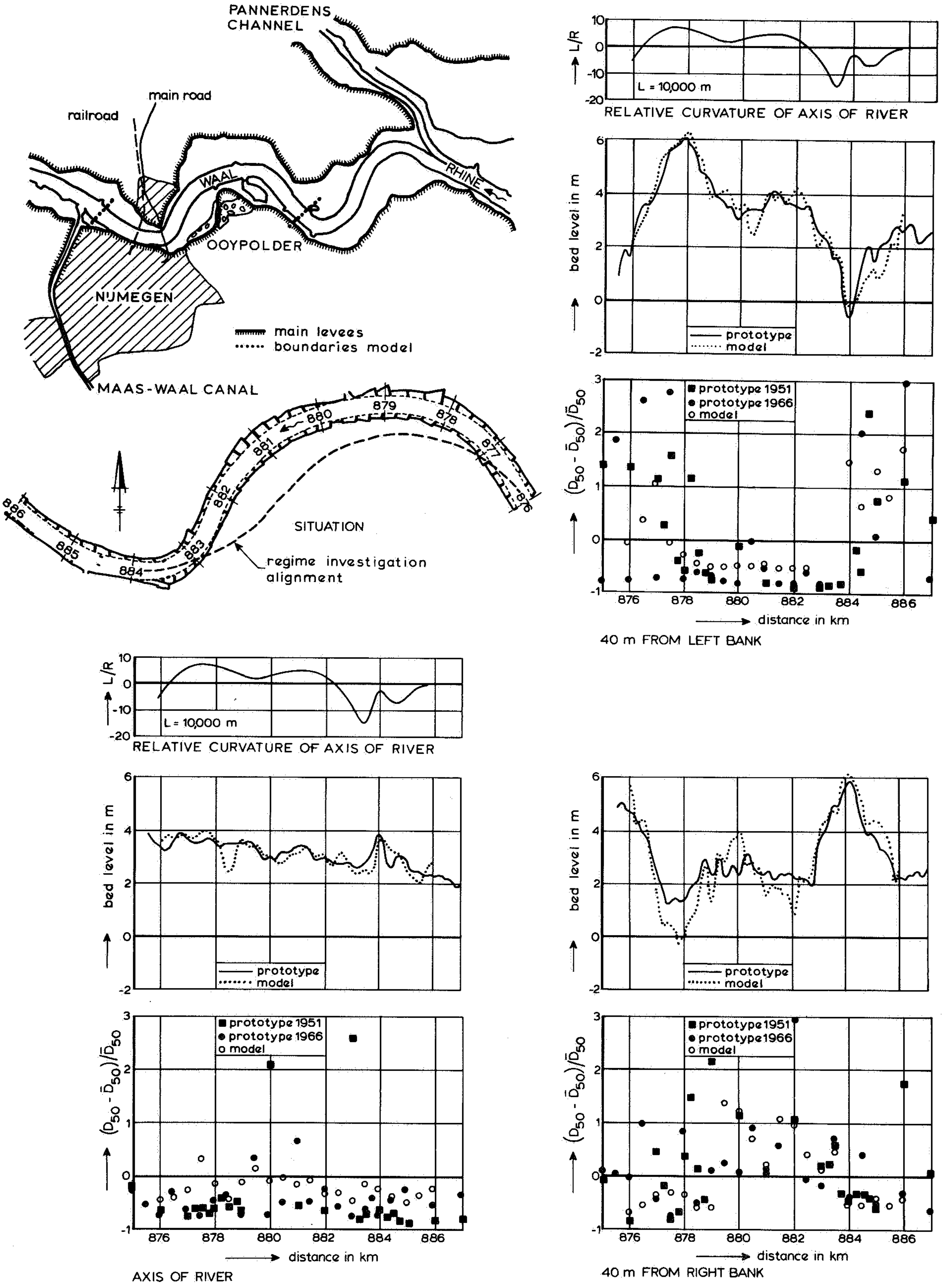
In Figure 4 the situation and the results of the calibration are depicted. The results are presented in the form of longitudinal profiles of the bed level and the relative bed composition (grain size sorting). The profiles have been situated 40 m from each bank and in the axis of the river, thereby obtaining an overall picture. The prototype bed level profiles were determined by the averaging of 8 yearly soundings (1965-1973), while the profiles of the grain sorting were the result of bed sampling campaigns in 1951 and 1966. The model profiles were measured during equilibrium under dominant discharge conditions. The bed profiles have been smoothed by averaging of 25 soundings, so that the profiles are hardly influenced by bed forms. The grain sorting profiles were obtained from one bed sampling in the model.

Considering the results, it can be seen that a reasonable overall similarity is present. However, a more detailed inspection shows that large differences have occurred locally. Concerning the bed level profiles, attention is specially drawn to to the reach KM 877-879, where much too steep cross-sectional bed profiles have been measured in the model. Most probably this has been caused a great deal by the scale effect treated in Section 2.2. The same difference should be present in the reach KM 883-884. However here a fixed layer in the bed (only exposed to the flow in the outer bed) has prevented this. The modelling of this layer can be justified, because in the prototype such a layer has been proved to exist. It came into existence during a glacial period. Because of the large scatter the profiles of the grain sorting are insufficient for a detailed inspection. Nevertheless, a reasonable agreement between prototype and model concerning tendencies of sorting can be observed.

In spite of the shortcomings which did not meet the accuracy claimed by the authorities as some locations, it was felt after all that the results of the calibration were reliable enough to proceed with the model study.

Acknowledgement

The contents of this paper are mainly based on a study in relation to the mentioned Waal River model. The study was commissioned by Rijkswaterstaat (Ministry of Transport and Public Works) to which grateful acknowledgement is made for its approval to publish this paper.



$n_L = 100$ $n_h = 40$ $n_D = 4$ $n_\Delta = 1$ $\bar{D}_p = 4$ mm $F_p = 0.15$ $F_m = 0.39$

Figure 4 Comparison of longitudinal profiles in prototype and model