Sand-Dune Geometry of Large Rivers during Floods

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Abstract: The geometry of lower regime bed forms in several large sand-bed rivers is investigated during average and flood conditions. The van Rijn method is revised because it generally underpredicts the dune height of most large rivers around the world. During floods in large sand-bed rivers, upper-regime plane bed is not necessarily obtained when $T = 25$. Both parameters describing dune height and dune steepness do not decrease as the transport-stage parameter T increases in the range $10 < T < 25$. The analysis of bed-form data during large floods on the Meuse River and the Rhine River branches indicates that both the dune height and length generally increase with discharge while dune steepness remains relatively constant. A reasonable approximation of the wavelength is $\lambda \cong 6.5\, h$, where h is the flow depth. The dune height Δ varies as a function of the depth h and median grain size d_{50}. Estimates can be obtained by $\Delta \cong 2.5\, h^{0.7}\, d_{50}^{0.3}$.

INTRODUCTION

At a given discharge in the Mississippi River at St. Louis, Jordan (1965) observed that the gauge height was lower for increasing discharge than for decreasing discharge. He attributed his observations to a combination of changes in roughness and bed configuration, and changes in turbulence. The prediction of water level during floods in large sand-bed rivers depends primarily on bed-form resistance caused by the presence of large sand dunes. For instance, the diagram of Engelund and Hansen (1967) shows that bed-form resistance can be twice as large as grain resistance. In turn, the length and height of dunes is viewed as a complex function of hydraulic and sediment parameters pertaining to sediment motion in alluvial rivers. van Rijn (1984) developed a method for the determination of dune height, dune length, and dune steepness in alluvial channels. van Rijn's method is based on an analysis of flume data and limited field observations with particle diameters ranging from 190–3,600 μm. Only experiments in the lower and transitional flow regime with dune-type bed forms were considered. Given the applied grain shear stress on bed particles τ' and the critical shear stress τ_c corresponding to the beginning of motion of bed particles, the relative excess shear stress defines the transport-stage parameter T as $T = (\tau' - \tau_c)/\tau_c$. van Rijn assumed plane-bed conditions at low and high values of the transport-stage parameter, respectively when $T = 0$ and $T > 25$.

Considering that the method of van Rijn is essentially based on laboratory data, it is important to test its applicability to large rivers. The consequences in terms of setting appropriate design heights for levees and dikes cannot be understated. An adequate determination of bed-form geometry is essential to evaluate resistance to flow and flow depth in large rivers. Another significant question relates to the prediction of flood conditions from average flow conditions. Specifically, given bed-form profiles describing dune height and dune length during average flow conditions, is it possible to determine the changes in dune geometry likely to occur during floods? Essentially, are the amplitude and wavelength of sand dunes increasing or decreasing during floods?

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Objectives

The present investigation extends the applicability of van Rijn's method (particularly at high values of the Shields parameter or transport-stage parameter T) for prediction of bed-form height and wavelength in large rivers under average flow conditions and during floods. The analysis focuses on (1) changes in dune geometry within the Rhine River branches and the Meuse River during recent floods; and (2) field measurements of dune geometry in large sand-bed rivers around the world.

BACKGROUND

Van Rijn's Method

A method for the classification of bed-forms and the prediction of bed-form dimensions was presented by van Rijn (1984) after defining a dimensionless particle diameter d_* and a transport-stage parameter T as follows:

$$d_* = d_{50}\left(\frac{(G-1)g}{\nu^2}\right)^{1/3} \tag{1}$$

and

$$T = \frac{(u'_*)^2 - (u_{*c})^2}{(u_{*c})^2} \tag{2}$$

where d_{50} = median bed particle diameter (50% passing by weight); G = particle specific gravity; ν = kinematic viscosity; the critical grain shear velocity u_{*c} is obtained from the Shields diagram; the grain shear velocity $u'_* = \bar{u}\sqrt{g}/C'$ varies with depth-averaged flow velocity $\bar{u}$, gravitational acceleration g, and grain Chezy coefficient $C' = 18 \log(12R_b/3\, d_{90})$ given the hydraulic radius related to the bed R_b obtained from the Vanoni-Brooks method, and the 90% passing bed particle diameter d_{90}.

Bed-form dimensions in terms of height and steepness were analyzed by van Rijn (1982) after selecting the data according to (1) dune bed forms; (2) width-depth ratio larger than 3; (3) flow depth larger than 0.1 m; and (4) transport-stage parameter T smaller than 25. This last restriction ($T < 25$) is reconsidered in this study. Regression analysis was originally performed considering 84 data points from flume experiments with particle diameters from 190–2,300 μm and 22 field data points with particle diameters ranging from 490–3,600 μm. van Rijn proposed the bed-form classification diagram in which ripples are found for $d_* < 10$ and $T < 3$. Dunes occur when $T < 15$, with washed-out dunes at $15 < T < 25$, and upper regime plane bed as $T > 25$.

The best agreement obtained by regression analysis for the dune height Δ and dune length λ as a function of the average flow depth h, bed particle diameter d_{50}, and transport-stage parameter T is respectively given by

$$\frac{\Delta}{h} = 0.11 \left(\frac{d_{50}}{h}\right)^{0.3} (1 - e^{-0.5T})(25 - T) \tag{3}$$

and

$$\frac{\Delta}{\lambda} = 0.015 \left(\frac{d_{50}}{h}\right)^{0.3} (1 - e^{-0.5T})(25 - T) \tag{4}$$

Comparisons between predicted bed-form height and steepness with 84 laboratory measurements and 22 field measurements were very good. Accordingly, the expression for the bed-form length λ can be derived from (3) and (4), thus

$$\lambda = 7.3h \tag{5}$$

which is close to $\lambda = 2\pi h$.

Difficulties Inherent to Parameter Evaluation

Van Rijn's method figures among the most practically oriented techniques available for the analysis of bed-form geometry. The parameters for bed-form height and steepness are simple functions of flow depth and median grain size d_{50}. Errors in the evaluation of the flow depth may arise from estimating the average bed elevation for dune beds of large amplitude.

The evaluation of the average dune height is not a trivial matter. In many cases, the bed is perturbed by the presence of dunes of smaller amplitude, also called megaripples, separated from or superposed onto large sand dunes. The problems associated with the calculation of average wavelength and wave height are illustrated in Fig. 1. In this case, one may count four to six dunes of amplitude exceeding 1 m and 40–60 megaripples reaching about 20 cm in amplitude over the 100-m reach. The average wavelength λ ranges from 17 to 25 m when considering the dunes only, compared to 1.7–2.5 m for the megaripples. The presence of megaripples thus reduces the effective wavelength of bed forms in natural channels when dividing the total reach length 100 m by the total number of dunes and megaripples. The average wave height Δ ranges from 1.5 m for the dunes compared to 0.2 m for the megaripples. As a result, the bed-form height parameter in (3) varies by almost an order of magnitude between dunes and megaripples. The corresponding dune steepness Δ/λ would be about 0.075 for dunes, and about 0.1 for megaripples. Bed-form steepness Δ/λ is therefore preferable to wavelength in the analysis of bed-form profiles.

Wijbenga (1991) developed computer programs for separating dunes from megaripples on digitized bathymetric profiles, and he separately reported heights and wavelengths of both dunes and megaripples. Another difficulty in the analysis of bed forms arises as bed-form configurations change with time, even under equilibrium conditions. Klaassen et al. (1986) reported significant changes in spectral density functions of laboratory bed-form profiles during equilibrium conditions at time intervals as short as 10 min.

The method used by Julien (1992) for the analysis of bed-form profiles from large rivers emphasizes large dunes at the expense of megaripples. For the case shown in Fig. 1, the average wave height $\Delta = 1.5$ m and the average wavelength $\lambda = 20$ m would be used in this paper to describe the bed-form geometry.

The grain size is also subject to interpretation in that the sediment size distribution locally varies in natural channels. One may also appropriately question using the median grain size d_{50} instead of a coarser fraction d_{84} or d_{90} in van Rijn's method. The accuracy obviously increases for uniform sediment size distributions, and the effects of sediment gradation on sediment transport were explored by Klaassen et al. (1988). In van Rijn's method, however, the exponent of sediment size is far less than unity (0.3), which dampens the effect of inaccuracies in particle diameter on bed-form height and steepness. Reasonable accuracy can be obtained through the analysis of several bed-material samples.

Another point of discussion in van Rijn's method is the transport-stage parameter T, which depends primarily on grain roughness and critical shear stress. As bed forms reach large amplitude, the grain shear stress calculated from the logarithmic relationship easily reaches the same order of magnitude as the critical shear stress; thus calculated values of $T < 0$ are possible at low transport rates. Large bed forms were observed at very low values of the parameter T. This can result in large variability in the calculation of dune height and dune steepness in natural channels when using (3) and (4) at values of $T < 2$.

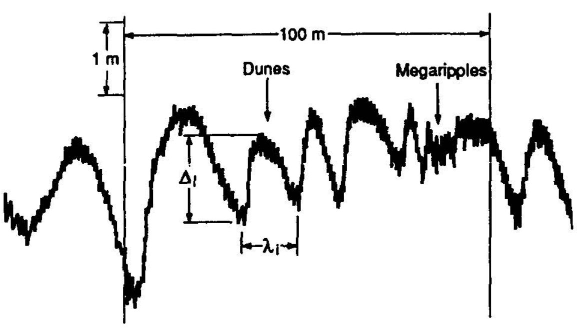

FIG. 1. Example of Dunes and Megaripples

ANALYSIS OF RECENT LABORATORY DATA

In recent laboratory experiments at Delft Hydraulics, Termes (1986) observed that sand-bed roughness is decreasing with increasing discharge due to bed-form stretching while the bed-form height remains more or less constant. Klaassen et al. (1986) also stated that the bed forms increase in length instead of decreasing in height at increasing discharge. The most relevant conclusions of the Delft Hydraulics sand flume tests as compiled by Termes (1986) are

- The relative bed-form height Δ/h is almost constant at $5 < T < 25$.
- The Chezy coefficient increases with increasing grain shear stress τ'.
- Complete flat bed did not occur, even for $T = 25$ and F $= 0.8$.
- Van Rijn's method underestimates the bed-form height by a factor 2 at $T > 8$.
- The bedform steepness is underestimated by a factor 1.5 at $T > 8$.
- Both the bed-form height and steepness appear not to approach zero when $T = 25$.
- At high values of T, the bed-form height is not drastically decreasing but the bedform steepness does decrease.

At Colorado State University, the extensive data set compiled by Guy et al. (1966) was used by van Rijn (1984) in the development of the original method. A recent investigation by Raslan (1991) with laboratory data from a 15-cm-wide flume indicates that

- The dune height at low values of the parameter $T (T < 5)$ are higher than predicted by van Rijn's method, and seem independent of the parameter T.
- The measured bed-form steepness parameters for labo-

ratory data at $T < 5$ are several times larger than predicted by van Rijn's method.

These observations in a small flume reflect on time-scale effects associated with flume size. Starting from plane-bed conditions, the time required to reach equilibrium bed-form configuration at low sediment transport rates ($T < 5$) is much shorter in a small flume with small dunes than the time required to form large dunes in large flumes.

BED FORMS OF MEUSE RIVER AND RHINE RIVER BRANCHES DURING RECENT FLOODS

Flow resistance and bedform dimensions have been the subject of numerous studies in the Netherlands. Recent additions to the literature include Adriaanse (1986), Brilhuis (1988), Kamphuis (1990a, b), Klaassen et al. (1986, 1988), Ogink (1984, 1989), Termes (1986, 1989), van Rijn (1982, 1984), and Wijbenga (1990, 1991). The analysis of bed forms in the Rhine River branches and the Meuse River specifically focuses on the growth and decay of dune height and dune steepness. Field data on changes in bed-form geometry from four reaches, shown in Fig. 2, were examined during recent floods of the river. Brilhuis (1988) carried out an analysis of bed-form configurations of the Rhine River branches in the Netherlands based on existing bed-form predictors. Accordingly, bed-form configurations, which are predominantly dunes during average flow conditions, are expected to reach the transition to upper flow regime during floods. From extrapolating bed-form configurations under average flow to the expected upper regime during floods, resistance to flow during floods should decrease while velocity should increase.

Bed Forms of Rhine River Branches during 1988 Flood

During the 1988 flood, the discharge Q of the Rhine River at Lobith, The Netherlands, reached 10,274 m^3/s on March 30, after a first peak of 8,324 m^3/s on March 20. Bathymetric

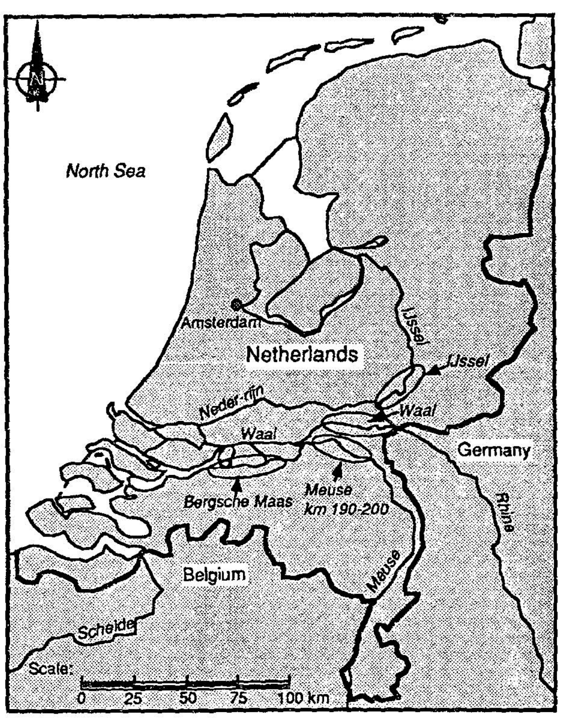

FIG. 2. Map of Meuse and Rhine River Branches in The Netherlands

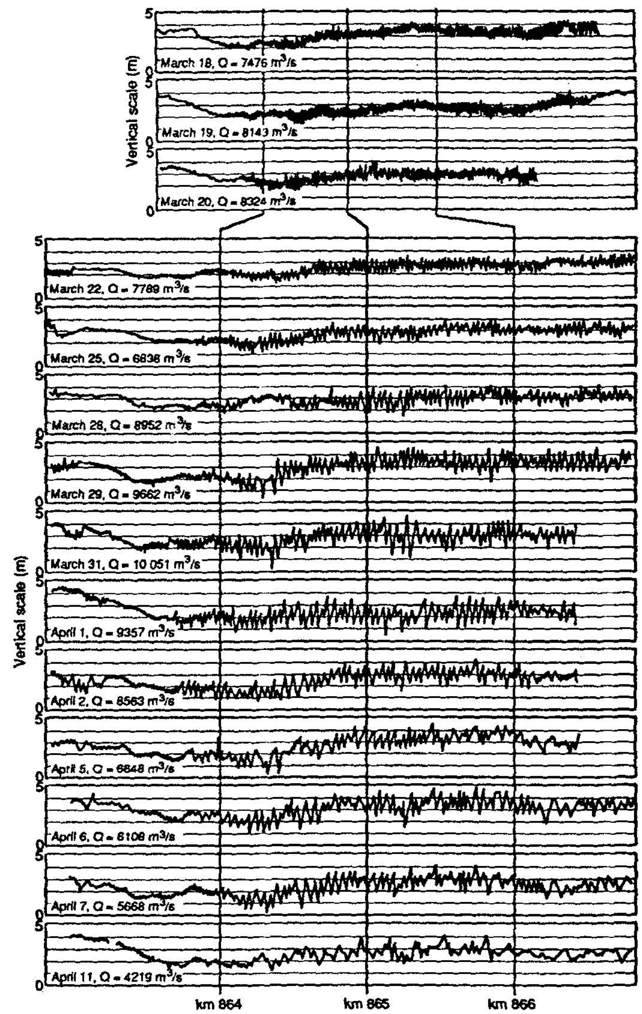

FIG. 3. Changes in Bed-Form Profiles in Rhine River during 1988 Flood

records of the Rhine and the Waal were previously analyzed by Wijbenga (1991) for comparisons between steady and unsteady flow conditions. Characteristic dune heights between kilometers 863–867 of the Rhine River and kilometers 867–884 of the Waal show some longitudinal changes in bed-form geometry. Similar graphs for the IJssel River between kilometer 879 and kilometer 903 were also analyzed. The most interesting reach for the analysis of dune growth is located on the Rhine River between kilometer 864 and kilometer 866, given the symmetrical cross-sectional profile of this relatively straight river reach. Sequences of bathymetric profiles of the Rhine between kilometers 863 and 866 are compiled on Fig. 3 for the period between March 18 and April 11, 1988. Dunes are shown to form rather rapidly as a result of increasing discharge. At high flow, the dune crests are rounded, and irregular profiles form during the falling limb of the hydrograph.

The bathymetric profiles of the Rhine River between kilometer 865 and kilometer 866 were scrutinized to determine the average dune height Δ from the total bed elevation drop on the lee side of the dunes divided by the number of dunes n over the 1 km reach. The average dune length λ is calculated from the reach length over the number of dunes. This average dune height roughly equals one-half to two-thirds of the maximum dune height Δ_m over the 1-km reach. It is also noticed that the average dune height is also roughly equal to the sum

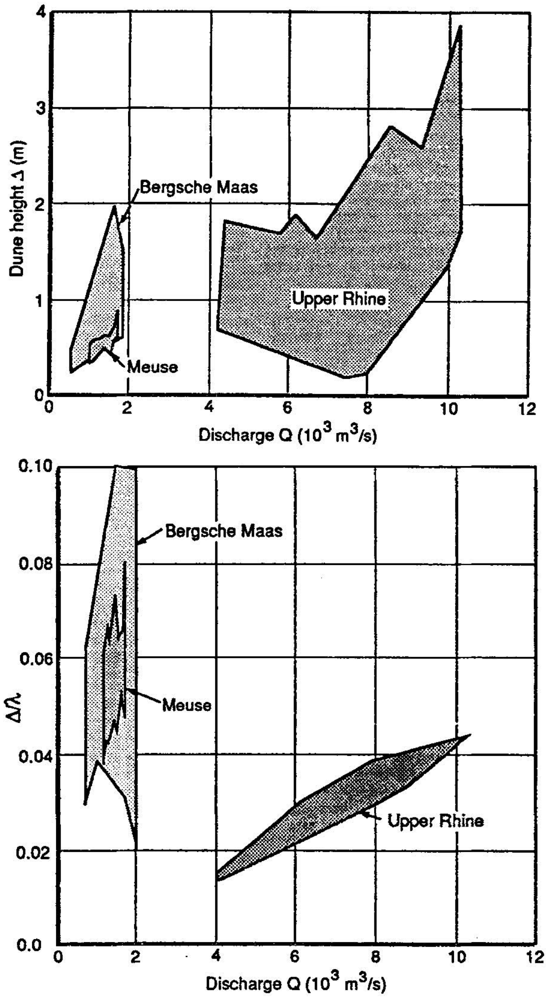

FIG. 4. Changes in Bed-Form Geometry during Floods: (a) Height; (b) Steepness

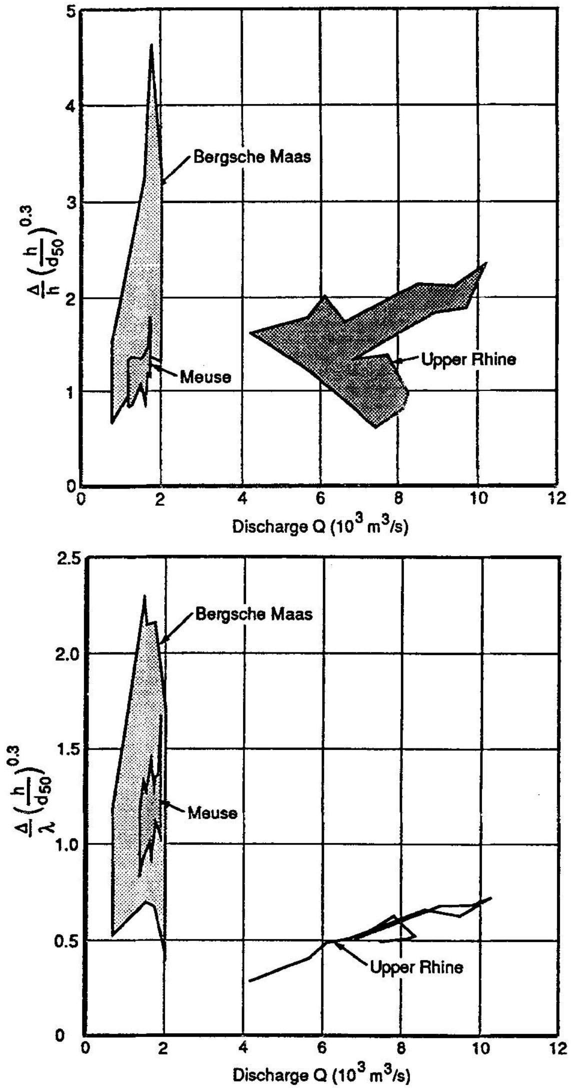

FIG. 5. Changes in van Rijn Bed-Form Parameters during Floods: (a) Height; (b) Steepness

of the dune height and the megaripple height reported by Wijbenga (1991). Fig. 4 shows the variability of the average dune height Δ and average dune steepness Δ/λ as a function of discharge. The dune length steadily changes in proportion with the discharge. The dune height and the dune steepness increase with discharge. Loop-rating effects are not significant on daily records because the time scale for the formation of dunes is of the order of 6–12 h.

The corresponding dune height and steepness parameters are also presented in Fig. 5. It is found that the dune-height parameter generally increases with the transport-stage parameter T, whereas the dune steepness parameter slightly increases with T. During floods, it can be concluded that both parameters increase with discharge and the parameter T. These results contrast with those predictable from van Rijn's diagram in which both parameters are expected to decrease with T as $T > 5$. At high discharge, van Rijn's method underpredicts both the dune height and the dune steepness.

Bed Forms of Meuse River during 1988 Flood

The 1988 flood of the Meuse River is particularly interesting. The peak flow discharge reached 1,743 m^3/s on March 19, followed by a second peak at 1,310 m^3/s on March 30. Bathymetric records were available during the falling limb of the hydrograph on a daily basis from March 19 until March 24. As the discharge gradually decreased from 1,743 m^3/s on March 19 to 1,163 m^3/s on March 24, both the dune height Δ and wavelength λ significantly decreased. Graphs of the variability of the dune height Δ and steepness Δ/λ with discharge are presented in Fig. 4. The corresponding dune height and steepness parameters, defined by van Rijn, are then presented in Fig. 5, indicating changes in van Rijn's dune height and dune steepness parameters during flood recession. It is found that all parameters increase with discharge, the dune steepness Δ/λ, however, slightly increases with discharge. The time scale for the formation of typical bedforms ($\Delta = 0.8$ m, $\lambda = 10$ m) at peak flow discharge is of the order of 3–5 h. Loop-rating effects due to bed-form growth are therefore not significant on daily records.

The spatial variability in either grain size distribution or bed-form dimension observed during this flood between kilometer 176 and kilometer 190 was negligible. The dune height that is quite uniform in the downstream direction decreases rather uniformly in time during the considered period of falling discharge.

Bed Forms of Bergsche Maas during 1984 Flood

The 1984 flood of the Meuse River was somewhat larger in magnitude than the 1988 flood. The peak discharge reached 2,231 m^3/s on February 12 at Lith, The Netherlands. Bathymetric records of the lower Meuse (Bergsche Maas) between kilometer 220 and kilometer 250 were analyzed by Adriaanse (1986). Sequences of bathymetric profiles at kilometers 223, 224, 230, 234, 236, 246, and 247 were compiled for January 8, 13, 14, 15, and 20. The data analysis shows that the amplitude and wavelength of bed forms change rapidly during floods. Soundings prior to the flood, discharge Q = 1,434 m^3/s on February 8, are quite similar to those after the flood, Q = 654 m^3/s on February 20. At higher discharge, the largest bed forms showed rounded crests and some dunes measured up to 3 m in amplitude.

Changes in dune height and steepness are plotted as function of discharge in Fig. 4. Both the average dune height Δ and wavelength λ generally increase as a function of discharge. The dune steepness Δ/λ remains quite constant during the flood. A loop-rating effect can be observed for dune height and wavelength. This indicates that at a given discharge, both the dune height and wavelength are larger under falling discharge than increasing discharge. The loop-rating effect pertains to the time scale required for the formation of bed forms that is of the order of 1–3 days as calculated from bed-load equations. The corresponding dune height and steepness parameters, defined by van Rijn, are also presented in Fig. 5. The dune height parameter increases with discharge while the dune steepness parameter was larger prior to the flood on February 8.

DUNE GEOMETRY IN LARGE RIVERS

The forthcoming analysis of bed-form dimensions focuses on dune height and steepness measured in large sand-bed rivers around the world. The data sets from several large rivers are considered including the Mississippi, Missouri, Red Deer, Jamuna, Parana, Zaire, Rhine, Waal, and Meuse rivers. Julien (1992) compiled recent data sets from bathymetric profiles on the Rhine, Waal, and Meuse, including the following additional data sets: (1) Jamuna River data provided by Klaassen (unpublished data); (2) Rhine and Waal data sets from Wijbenga (1991); (3) Parana River data provided by van Rijn (personal communication); (4) Mississippi River data from Schumm and Jorgensen (personal communication, available in Raslan 1991); (5) Missouri River data from Shen et al. (1978); (6) Zaire river data from Peters (1978), previously analyzed and reported by Termes (1986); and (7) Bergsche Maas river data from Adriaanse (1986).

The recent investigations of Termes (1986), Adriaanse (1986), Brilhuis (1988), Kamphuis (1990a, b), and Wijbenga (1991) included field measurements of dune height and dune length of the Meuse River and Rhine River branches. The corresponding graphics for dune height and steepness parameters are shown in Figs. 6 and 7. Note that although Wijbenga (1991) separately reported the height of dunes and mega-ripples, the sum of both heights were used for the Waal data set as it better reflects the dune height measured on bathymetric profiles. Most of the data points were measured during relatively average flow conditions. It is observed in Fig. 6 that most of the data at low values of the parameter T ($T \cong 5$) are in relatively good agreement with van Rijn's dune height and steepness predictors. It is also noticeable that there is absolutely no decreasing trend in van Rijn's parameters at values of T exceeding 5. Similar remarks apply to the dune steepness parameter in Fig. 7. It is interesting that all values of dune steepness are confined within the range prescribed by van Rijn for the Waal and IJssel, whereas all measurements for the Meuse and Bergsche Maas plot above van Rijn's upper curve. Likewise, it is noticeable in Fig. 7 that the dune steepness parameter does not decrease as T increases.

PREDICTION OF BED FORM GEOMETRY

This analysis of changes in bed-form geometry in several large sand-bed rivers suggests that both the dune height and the dune length parameters do not vary significantly with the transport-stage parameter T. It is recognized that some sand-bed rivers reach upper-regime plane-bed during floods. Our analysis indicates, however, that this does not necessarily occur at T = 25. A possible explanation is offered after writing the transport-stage parameter T as a function of the Froude number F as

$$T = -1 + \left\{ \left[\frac{\mathsf{F}}{5.75 \log \left(\dfrac{4R_b}{d_{90}} \right)} \right]^2 \frac{R_b}{1.65 d_{50}\, 0.047} \right\} \qquad (6)$$

where R_b = hydraulic radius related to the bed; g = gravitational acceleration; and d_{50} and d_{90} = bed particle diameters (50% and 90% passing by weight, respectively). From this formulation, T is a function of the Froude number F and relative submergence R_b/d_{50}. For laboratory conditions, the parameter T corresponding to critical flow (F = 1) is $T \cong 25$ when $R_b/d_{50} \cong 800$, which corresponds to a flow depth of 0.4 m for a grain size $d_{90} \cong d_{50}$ = 0.5 mm. It is shown from (6) that the parameter T increases with R_b/d_{50}. For field conditions corresponding to the same Froude number (F = 1) when

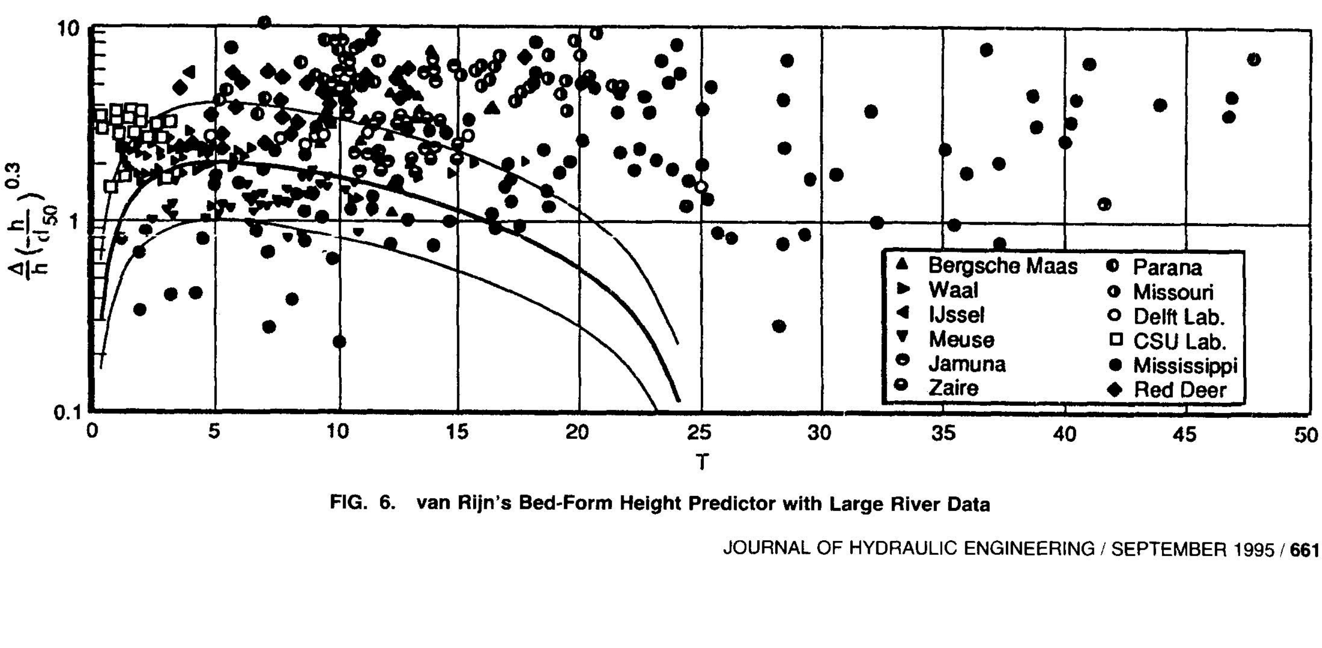

FIG. 6. van Rijn's Bed-Form Height Predictor with Large River Data

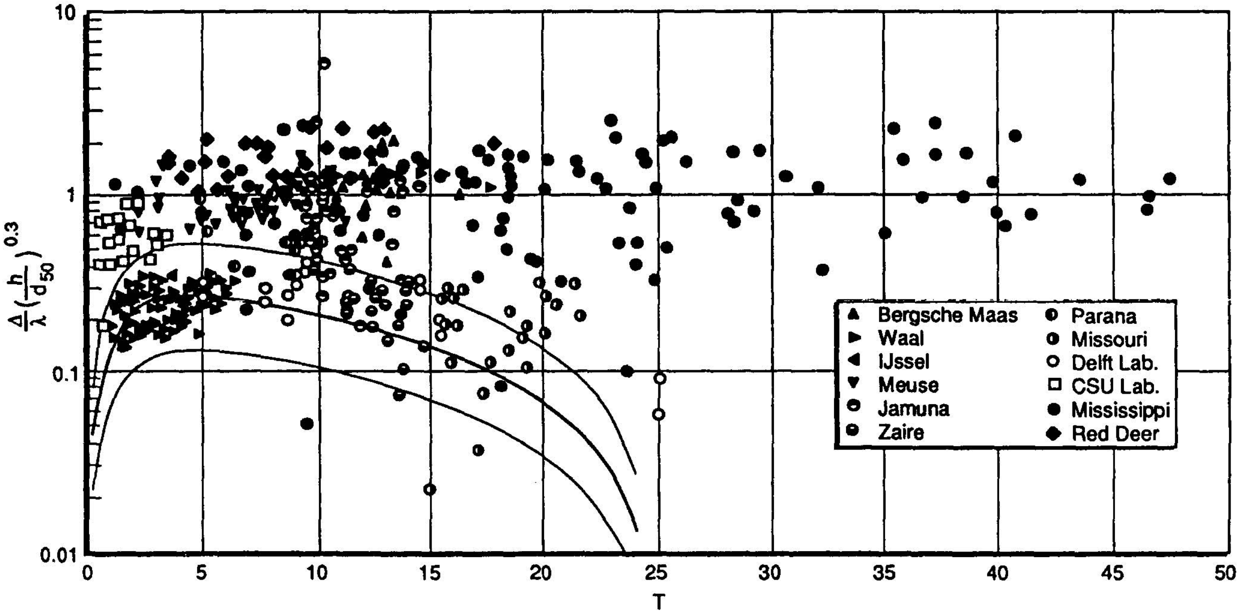

FIG. 7. van Rijn's Bed-Form Steepness Predictor with Large River Data

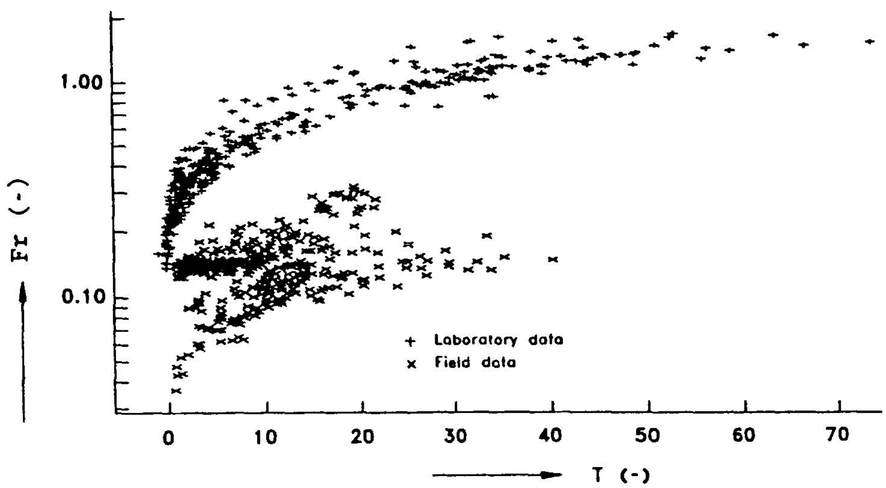

FIG. 8. Transport-Stage Parameter *T* versus Froude Number F for Laboratory and Field Data

R_b = 10 m at grain sizes $d_{90} = d_{50} = 0.5$ mm, the parameter becomes very large, for example, $T \cong 325$. One may therefore expect a larger value of T for upper-regime plane bed in large sand-bed rivers.

In Fig. 8, the parameter T is plotted against the Froude number F for the laboratory and field data examined under this study. At a given value of the parameter T, the Froude number is much higher for laboratory data than field data. Notice that the flow in laboratory channels becomes critical (F = 1) as T approaches 25, which corresponds to van Rijn's upper-regime plane bed. Despite the scatter displayed in Figs. 6 and 7, the dune height and dune length of large rivers may be best predicted from the dune height

$$\Delta = \xi h \left(\frac{d_{50}}{h}\right)^{0.3} \quad (7)$$

where 95% of the points are within $0.8 < \xi < 8$ and the average value $\bar{\xi} \cong 2.5$, and the dune length

$$\lambda = \eta \Delta \left(\frac{h}{d_{50}}\right)^{0.3} \quad (8)$$

where 95% of the points are within $0.5 < \eta < 8$ and the average value $\bar{\eta} \cong 2.5$. Notice that $\lambda = \xi \eta h$ is obtained from (7) and (8). One may use $\lambda \cong 6.25\, h$ as a reasonable first approximation. Furthermore, higher values of ξ and lower values of η may be encountered during floods, and in situ measurements as well as bed-form geometry monitoring provide accurate results.

SUMMARY AND CONCLUSIONS

This study extends the applicability of van Rijn's method for the prediction of dune height and dune length in large rivers during floods. Several field data sets from large sand-bed rivers were scrutinized, including major floods in the Rhine River branches and the Meuse River.

Considering an alluvial stream of flow depth h, median grain size d_{50}, dune height Δ, and dune length λ, van Rijn defined a dune height parameter $\Delta h^{0.3}/h\, d_{50}^{0.3}$ and a dune steepness parameter $\Delta h^{0.3}/\lambda d_{50}^{0.3}$ as a function of the transport-stage parameter T. The following can be concluded regarding the applicability of the dune height parameter to large sand-bed rivers:

- The dune height parameter represents quite well the average flow conditions of the Rhine River branches and the Meuse River.
- Both the dune height and the dune height parameter increase with discharge, as observed on the Rhine River and the Meuse River during major floods.
- As opposed to van Rijn's diagram, the dune height parameter does not decrease with discharge at values of $T > 10$; this parameter remains relatively constant at values of T exceeding 40.

With regard to the dune steepness parameter, van Rijn's method generally underestimates the dune steepness of large sand-bed rivers, including the Meuse and Rhine rivers during floods. The dune length generally increases with discharge while the dune steepness slightly increases with discharge.

As a first approximation, the average dune height and the average dune length in large sand-bed rivers can be calculated from (7) and (8), respectively. Despite wide scatter of field measurements around the mean value, both the dune height and the dune length parameters in large sand-bed rivers do not vary significantly with the transport-stage parameter T. Large sand-bed rivers do not necessarily reach upper-regime plane bed when $T = 25$.

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APPENDIX II. NOTATION

The following symbols are used in this paper:

C' = grain Chezy coefficient;
d_{50} = mean bed particle diameter;
d_{84} = 84% passing bed particle diameter;
d_{90} = 90% passing bed particle diameter;
d_* = dimensionless particle diameter;
F = Froude number;
G = specific gravity of particles;
g = gravitational acceleration;
h = flow depth;
n = number of dunes;
Q = flow discharge;
R_b = hydraulic radius at bed;
T = transport-stage parameter;
$\bar{u}$ = depth-averaged velocity;
u'_* = grain shear velocity;
u_{*c} = critical shear velocity;
Δ = dune height;
Δ_m = maximum dune height;
η = dune length coefficient;
λ = dune length;
ν = kinematic viscosity;
ξ = dune height coefficient;
τ' = grain shear stress; and
τ_c = critical shear stress.