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Flow resistance of flexible and stiff vegetation: a flume study with natural plants

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Abstract

Flow resistance of natural grasses, sedges and willows was studied in a laboratory flume. The objective was to investigate, how type, density and placement of vegetation, flow depth and velocity influence friction losses. The plants were studied in various combinations under nonsubmerged and submerged conditions in a total of 350 test runs. The results show large variations in the friction factor, f, with depth of flow, velocity, Reynolds number, and vegetative density. The friction factor was dependent mostly on (1) the relative roughness in the case of grasses; (2) the flow velocity in the case of willows and sedges/grasses combined; and (3) the flow depth in the case of leafless willows on bare bottom soil. Leaves on willows seemed to double or even triple the friction factor compared to the leafless case despite the fact that the bottom was growing sedges in both cases. For the leafless willows, f appeared to increase with depth almost linearly and independently of velocity. Unexpectedly, different spacing of the same number of leafless willows with grasses did not have any significant effect on f. Based on the experimental work, a better understanding of flow resistance due to different combinations of natural stiff and flexible vegetation under nonsubmerged and submerged conditions was gained.

Keywords: Hydraulics; Roughness; Vegetation; Rivers; Floodplains; Wetlands

1. Introduction

Estimating the flow resistance of vegetation is of great importance in river management, since it may have a significant effect on the conveyance of the channel. Indeed, the presence of vegetation has traditionally been regarded as a problem which hinders flow capacity. However, it is well known that vegetation has fundamental ecological functions in the riverine environment. Thus, current environmental river engineering prefers to preserve natural riverbank and floodplain vegetation. Furthermore, river restoration and rehabilitation are widely practised. In addition, there is an increased interest in application of various bioengineering methods. Thus, in order to cope with new management objectives a better knowledge of the hydraulic effects of vegetation is required.

Flow resistance of natural open channels, in particular the effects of flexible and stiff vegetation, is one of the current key areas of research at the HUT Laboratory of Water Resources. Studies have been carried out both in the field and in a laboratory flume. This paper will discuss the flume studies. Living natural grasses, sedges and willows were used in the experiments. The plants were investigated in various combinations under submerged and nonsubmerged conditions. Particular emphasis was put on studying flow through unsubmerged willows, which were studied both with and without leaves.

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Nomenclature

A	cross-sectional area
C	drag coefficient
f	Darcy–Weisbach friction factor
g	acceleration due to gravity
h	flow depth
H_f	energy loss
k	deflected height of vegetation
L	length of the channel reach
MEI	flexural rigidity per unit area
n	Manning's n
Q	discharge
R	hydraulic radius
Re	Reynolds number
S_e	energy slope
v	average flow velocity
α	velocity distribution coefficient
ν	kinematic viscosity

The purpose of this paper is to investigate, how type, density and placement of vegetation, flow depth and velocity influence friction losses. The paper is not intended to address the scaling of vegetation, nor does it focus on the biomechanical properties of the plants. The results show large variations in the friction factor with depth of flow, velocity, Reynolds number and vegetative density.

2. Previous research

Traditional, empirical approaches to estimate flow resistance are often based on relating Manning's n to some parameters selected to describe the flow conditions. The method of n–vR curves, where vR is the product of the average velocity and the hydraulic radius, is widely known. For a review of the traditional approaches, the reader can refer to Chow (1959). A recent development is the use of the dimensionless Darcy–Weisbach friction factor; however, in practical river management Manning's n still dominates.

Flow resistance problems are usually classified into two groups: flow over submerged, short vegetation and flow through nonsubmerged, tall vegetation. Most efforts to study vegetal resistance have concentrated on studying submerged and rigid roughness. Less is known about the effects of flexible roughness and alterations in flow depth. There is only little available field data other than overall roughness coefficients representing limited flow conditions. Some field data of the biomechanical properties of vegetation have been published (Kouwen and Li, 1980; Kouwen, 1988; Tsujimoto et al., 1996). Most laboratory studies have been conducted using artificial roughness. Recently, however, some investigations have been performed using actual plants (Stephan, 2001; Kouwen and Fathi-Moghadam, 2000).

Li and Shen (1973) studied the effects of tall nonsubmerged vegetation on flow resistance by investigating the wake caused by various cylinder set-ups. Experimental results indicated that different patterns or groupings of cylinders significantly affected flow rates. Petryk and Bosmajian (1975) presented a model to estimate Manning's n as a function of hydraulic radius and vegetation density for unsubmerged rigid vegetation. In the case of vertically uniform dense vegetation, Manning's n increased in proportion to the 2/3 power of the hydraulic radius assuming that the channel boundary shear is negligible. In the 1980's, an extensive research programme on the hydraulic problems of environmental channels was undertaken by four German universities (Rouvé, 1987). The purpose of the programme was to develop methods for determining the friction factor and calculating discharge in complex river sections with variable bank and floodplain vegetation. Particular emphasis was put on friction losses due to momentum transfer between main channel and vegetated zones. In addition, floodplain flow processes were investigated with scale models using rigid cylindrical roughness elements. As a part of the programme, various approaches for calculating discharge in vegetated zones were developed. For nonsubmerged vegetation the work of Li and Shen (1973) was extended resulting in a method to calculate the drag coefficient for a single plant in a group, C_{WR}, and further the friction factor for the vegetation, f_P. The governing equation for f_P utilised readily measurable physical properties in addition to C_{WR}: longitudinal and lateral distances between the plants, and plant diameter. C_{WR} was determined through an iterative process including empirical relationships, which were formulated from experiments on rigid cylinders (Pasche, 1984; Pasche and Rouvé, 1985).

Kouwen and Unny (1973) developed a method to estimate the roughness for flow over submerged and flexible grass. Based on laboratory flume experiments they concluded that in the case of flexible plastic strips the friction factor was a function of the relative roughness for the erect and waving regimes, and appeared to be a function of the *Re* for the prone roughness. Chen (1976) conducted experiments on natural turf surfaces in the laminar-flow regime and found that the friction factor decreased with the *Re*, but increased with the slope. Fathi-Maghadam and Kouwen (1997) showed using coniferous tree saplings and branches in flume experiments that the friction factor varied greatly with the mean flow velocity due to bending of the vegetation and with flow depth as a result of an increase in the submerged momentum absorbing area. Later Kouwen and Fathi-Moghadam (2000) extended their earlier study with experiments on large coniferous trees. Their results indicated good correlation of the friction factor with the flow velocity normalised with a vegetation index, a parameter which takes into account the effects of shape, flexibility, and biomass of the particular tree species.

Oplatka (1998) studied flow resistance of 1.8–4.5 m high flexible willows in a towing tank up to the velocity of 4 m/s. The product of the drag coefficient and the effective plant area, $C_D A_V$, was shown to decrease rapidly with increasing velocity until an asymptotic value was reached. Flow velocity strongly influenced the projected plant area perpendicular to flow. For example, at a velocity of 1 m/s, the projected area was only approximately 25% of the initial value with no flow. Wu et al. (1999) studied the variation of the vegetative roughness coefficient with the depth of flow, both in submerged and nonsubmerged conditions. A horsehair mattress was used to simulate floodplain bushes and shrubs assuming that the bending of the mattress can be ignored. Experiments revealed that the roughness coefficient decreased with increasing depth under the unsubmerged condition. Further, when fully submerged, the roughness coefficient increased at low inundation but then decreased to an asymptotic constant with rising water level.

Recently, Stephan (2001) investigated three species of flexible aquatic vegetation under submerged conditions in a laboratory flume. Two lines of research were employed: drag force and velocity studies. Deflected plant height summarising all the flow and plant characteristics was found to be an appropriate parameter to describe the geometric roughness height. Subsequently, hydraulic roughness was defined on the basis of equivalent sand roughness using a modified log-law approach. Based on velocity measurements it was concluded that the computed equivalent sand roughness was directly proportional to the deflected plant height. The absolute values of the equivalent roughness, the deflected plant height, and the zero plane displacement of the log-law were close to each other. Further, the vegetal drag, $C_D A_V$, appeared to be a function of the ratio of the flow depth to the deflected plant height, h/k, independent of the biomass distribution, plant type, and flow condition.

3. Laboratory experiments

Experiments were conducted in a 50 m long, 1.1 m wide and 1.3 m deep glass-walled flume (Fig. 1). The slope of the flume is fixed at 0%. Discharge is conducted through one or two valves from a head tank, in which water level can be maintained at a constant level. Water entered the flume first through a fixed stilling basin and second, designed for the present study, through a set of parallel pipes. This permitted a smooth approach into the 15 m long section of crushed rock (diameter 16–32 mm) before the test area. The coarse bottom material was chosen to gain fully turbulent flow. The last 2.5 m of the section before the test area were covered with smoother crushed rock (diameter 3–5 mm).

The test area was 6 m long. Grasses, sedges and willows were mounted in the flume in metal boxes with dimensions of 1 m × 0.275 m × 0.1 m (length, width and height in the principal flow direction, respectively). Downstream from the test area there was another 15 m long section of crushed rock. At the downstream end of the flume there was an overflow weir, which was used to adjust the desired flow depth. A fixed set of seven flow depths at the approach to the test area, herein called the entrance flow depth, h_0, (25, 30, 40, 50, 60, 70, 80 cm) and six discharges, Q, (40, 70, 100, 143, 201, 292 l/s) was adopted for the study. Head loss along the test section was measured by a differential pressure transducer. Water depth was

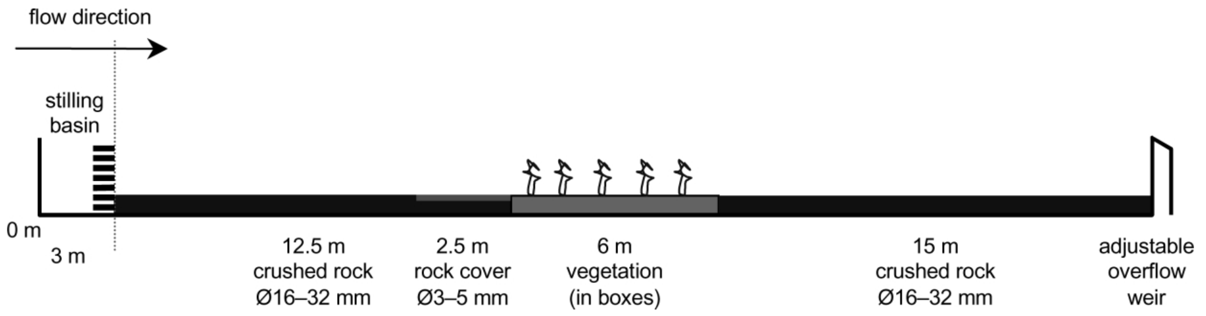

Fig. 1. Experimental set-up in the flume (long-view; not to scale).

recorded at the upper end with a pressure transducer. The transducers were connected to measuring software running on a PC.

3.1. Test series descriptions

Series group S3 (sedges–willows).* Natural yet nursery-grown slender tufted-sedges (*Carex acuta*) were placed in the natural floodplain topsoil layer by boring holes for the planting pots (diameter 4 cm). Otherwise, the natural root structure and soil compaction were left intact. The sedges were positioned in a staggered pattern averaging 512 stems/m^2. In each plant pot there were several stems of 3 mm in average diameter. In the pots, the stems were randomly in clusters or apart; usually the diameter of the stems as a group was ~20 mm. The lower part of the stems up to the height of ~5 cm was more or less stiff. The average height of the sedges was approximately 30 cm. The maximum stem length was kept at 35 cm by cutting. The willows (*Salix* sp.) averaged 70 cm in length and 8.6 mm in diameter at a height of 10 cm from the bottom. Willows were installed without roots in the boxes in two different patterns with the sedges (Fig. 2, Pa and Pf). One example is presented in Fig. 3. The same branched willow stems were investigated first with leaves and in the next phase without leaves. Based on small sampling, the leaf area of the willows per square meter of the bottom was estimated to be 3.2 m^2.

Series group R2 (grasses–willows).* The vegetation boxes were filled in the field with a 10-cm thick natural floodplain topsoil layer growing mixed grasses. The length of the grasses was in average 30 cm with the individual stem length ranging between 20 and 40 cm. When visually observed, the grass cover was relatively homogeneous, but spatial analysis of dry biomass in the vegetation boxes revealed up to 35% variations from the average (130 g/m^2, dried 1.5 h in 105 °C). In series R2*, only leafless willows were used. The willows were installed in five various patterns with the grasses

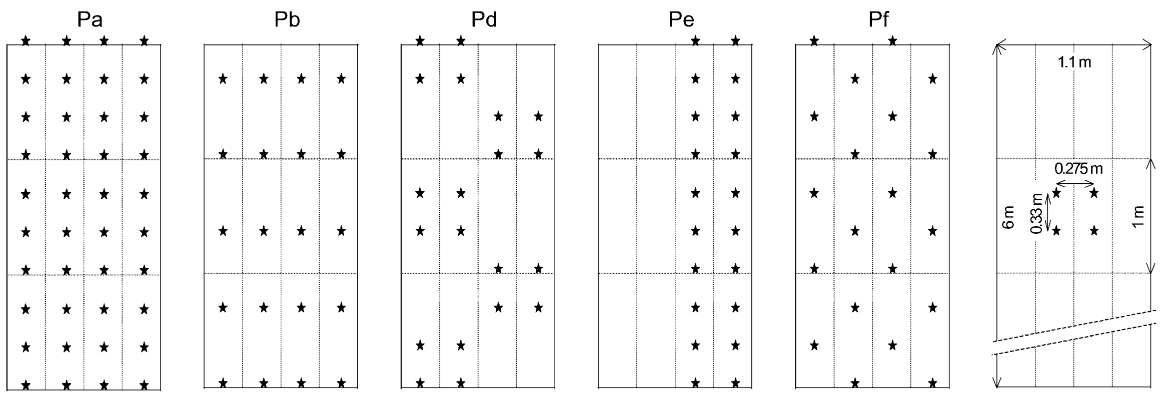

Fig. 2. Spacing of willows in the set-ups Pa, Pb, Pd, Pe and Pf. Figures show only half (3 m) of the 6 m long test area (not to scale).

Fig. 3. Test run 010607-21 of series S3_Pa with willows and sedges. The average flow velocity is 38.7 cm/s.

(Fig. 2). The main stems of the willows were approximately 70 cm in length with several small branches. The average diameter of the stems at a height of 10 cm from the bottom was 8.3 mm.

4. Experimental results

Due to the physical nature of the experimental set-up the flow was gradually varied. At the beginning of the test area there was an abrupt change in roughness, which introduces transition into the flow. However, a new equilibrium was developed and a declining surface profile with a constant slope was produced for part of the test area. Flow resistance was determined by measuring head loss and then calculating the friction factor, f, from the energy loss, H_f, using Bernoulli's Eq. (1) and the Darcy–Weisbach Eq. (2). Both potential and velocity heads were incorporated in the calculations. The validity of this approach was checked by applying a momentum equation including pressure, velocity, and drag terms for channel bottom soil, glass walls, and vegetation. The drag contributed by the glass walls was negligible. By conducting experiments without any vegetation the average base friction factor for the test section (bottom and walls) was determined to be 0.055 and 0.061 for series S3* and R2*, respectively. For further analysis, the base friction factor of the bottom and walls was subtracted from the results given by Eq. (2). For simplicity, the base friction factor was assumed to be independent of depth and velocity for the studied depth and velocity ranges.

$$\alpha\frac{v_1^2}{2g} + h_1 = \alpha\frac{v_2^2}{2g} + h_2 + H_f \quad (1)$$

$$f = \frac{H_f}{L}\frac{8gh}{v^2} \quad (2)$$

where v, the average flow velocity; g, acceleration due to gravity; h, the flow depth; and α, the velocity distribution coefficient represent the flow properties. Subscripts 1 and 2 refer to upstream and downstream sections, respectively, and L is the distance between the sections. In Eq. (2) the characteristic length is h. Data for 15 test series totalling 350 test runs were selected for this paper. Depending on the vegetation set-up, 18–32 h–Q combinations were studied for each test series. A summary of the experiments is presented in Table 1.

4.1. Results by test series groups

Series group S3 (sedges–willows)*. The range of the Reynolds number, $Re(= vh/\nu)$, was 24,200–177,000 indicating that all the test runs were above the laminar-flow range. The Froude number was 0.25 at the maximum. The average flow velocity, $v(= Q/A)$, varied between 7.2 and 46.8 cm/s. The energy slope, S_e, ranged between 0.0001 and 0.0127. Willows were erect in all test runs with minor bending in a few experiments resulting in 5–10 cm reduction in the height of the tips. More important than the bending of the main stems was the streamlining of the small branches and leaves at higher velocities. Bending of the sedges was dependent on the velocity and depth showing a wider range of deflected height than the grasses (R2). At low velocities the sedges formed roughly an erect layer, but at higher velocities 12–15 cm thick a waving layer was produced.

Series group R2 (grasses–willows)*. The range of the Re was 24,200–178,000 and the average flow velocities 6.1–45.7 cm/s. The energy slope ranged between 0.0001 and 0.0065, and the Froude number was below 0.21. The grasses in every test run were submerged, but conditions for the leafless willows ranged from through-flow to a full overflow of 10–20 cm. In most test runs, the willows did not bend but oscillated slightly. However, in a few test runs the

Table 1
Summary of the experiments

Series	Description	No. of $Q-h$ combinations	Range of f	Range of Re $(= vh/\nu)$	Range of S_e
S3	Sedges (*Carex acuta*)	32	0.26–2.43	24,200–177,000	0.0001–0.0059
S3Pa	Sedges with leafy willows (*Salix* sp.)	23	2.07–6.78	24,200–177,000	0.0009–0.0127
S3Pa_x	Sedges with leafless willows	23	1.21–2.27	24,200–177,000	0.0003–0.0063
S3b_Pa_x	Leafless willows	23	0.26–0.83	24,200–177,000	0.0001–0.0036
S3Pf	Sedges with leafy willows	23	1.27–4.29	24,200–177,000	0.0005–0.0069
S3Pf_x	Sedges with leafless willows	23	0.67–1.75	24,200–177,000	0.0002–0.004
S3b_Pf_x	Leafless willows	23	0.12–0.38	24,200–177,000	0.0001–0.0016
R2	Grasses (mixed natural growth)	23	0.18–1.93	24,400–176,700	0.0001–0.0033
R2Pa_x	Grasses with leafless willows	26	0.65–1.78	24,400–176,700	0.0003–0.0065
R2Pb_x	Grasses with leafless willows	18	0.29–1.04	24,500–176,400	0.0001–0.0037
R2Pd_x	Grasses with leafless willows	18	0.36–1.28	24,300–177,900	0.0001–0.0042
R2Pe_x	Grasses with leafless willows	18	0.23–1.09	24,500–176,700	0.0001–0.004
R2Pf_x	Grasses with leafless willows	26	0.34–1.92	24,300–176,700	0.0002–0.0056
R2b_Pa_x	Leafless willows	26	0.24–0.57	24,200–177,000	0.0001–0.0022
R2b_Pf_x	Leafless willows	25	0.13–0.31	24,200–177,000	0.0001–0.0012

Note: S3* and R2* refer to the series as a group of seven and eight series, respectively.

willows bent at high discharges with large inundation resulting in a maximum reduction of willow height by 10 cm. The grasses were very flexible and formed a wavy surface. After each day of experiments the grasses were found lying on the flume bottom with the combed appearance which is commonly seen in nature after floods.

For both series groups, the measured values of the friction factor were plotted against the corresponding Re, flow depth, h, and relative roughness, k/h, or relative submergence, h/k, where k is the deflected height of the vegetation and h is the flow depth. In Figs. 4a–d and 5 the friction factor is plotted against the Re for series S3* and R2*, respectively. For the grasses and the sedges, the values of k/h lay in the range 0.26–0.80 and 0.21–0.95, respectively. Herein, the results are presented with respect to the absolute flow depth to allow simple comparisons (Fig. 4e–h).

5. Analysis of results and discussion

5.1. Series S3*: effects of flow condition and vegetation characteristics

The data of series S3* enable examination of how the friction factor depends on the Re, depth, velocity, and various conditions of vegetal flexibility such as density and type (single species or mixed). Plotting f against Re for the sedges overall produces a nice declining curve, but there is considerable deviation in the friction factor corresponding the equivalent Re (e.g. for $Re \sim 24,200; f \sim 1.6–2.4$, Fig. 4a). The same type of plot for leafless willows on bare bottom soil indicates that f is more or less independent of Re (Fig. 4d). Combinations of sedges and leafless willows behave approximately in the same way as only sedges; the values are just shifted upwards (Fig. 4c). It should be noted that the frontal area of the leafless willows is relatively small. Combinations of sedges and leafy willows give the highest values of f, and produce the most scattered plot, but distinctive patterns are found, when the data are classified according to the flow depth (Fig. 4b). Interestingly, leaves on willows seemed to double or even triple the friction factor compared to the leafless case despite the fact that the bottom was growing sedges in both cases.

When the friction factor is investigated against the flow depth for the various vegetative covers, the series of leafless willows without sedges differ from the rest (Fig. 4h). The friction factor increases with depth almost linearly despite the fact that velocity varies by a factor of up to four between the various test runs. Doubling the willow density approximately doubles also the f values for the same flow conditions. For all the other series, flow velocity is an important parameter together with depth (Fig. 4e–g); however,

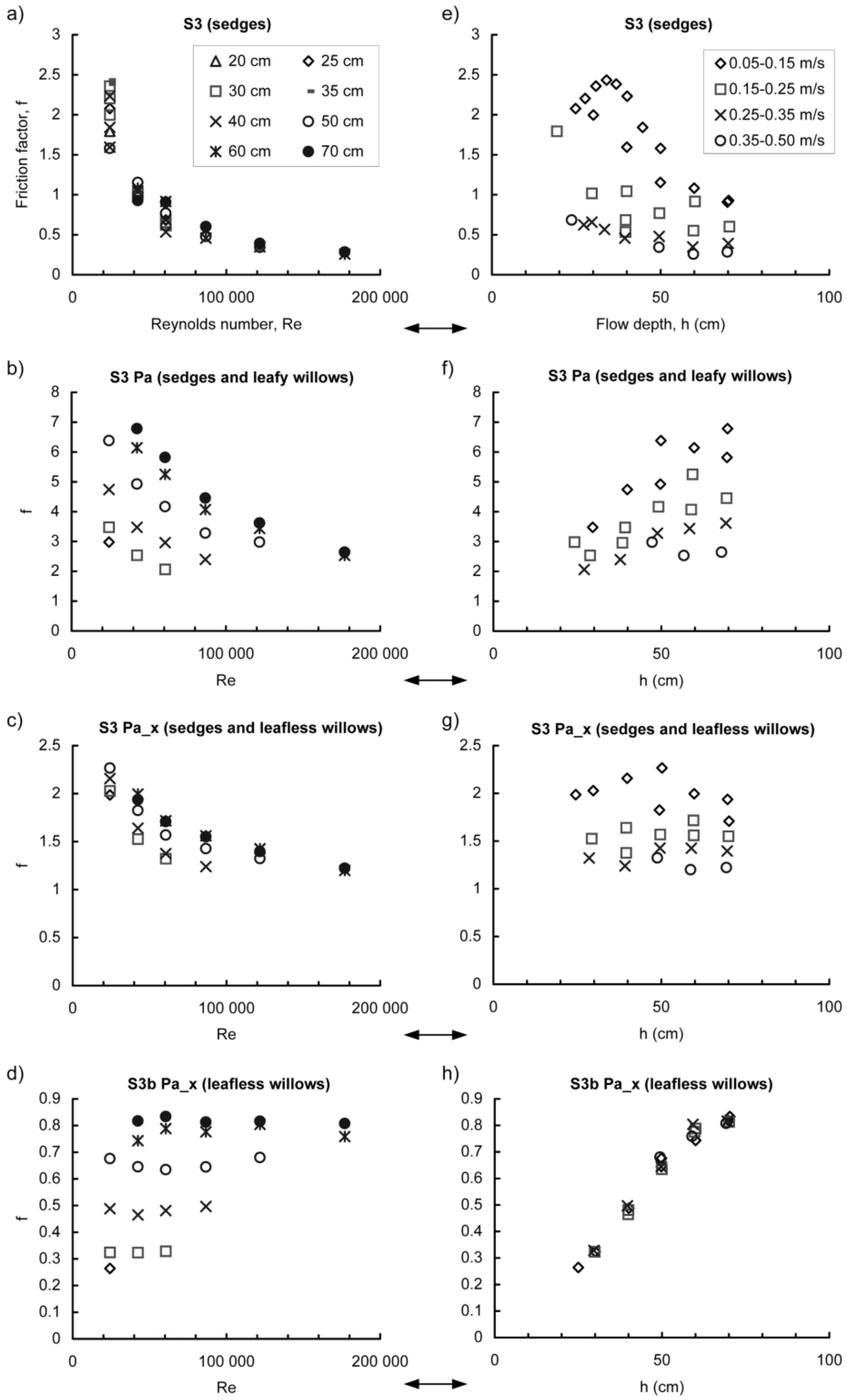

Fig. 4. Friction factor vs. Reynolds number (a–d) and flow depth (e–h) for series S3* (see Table 1 for series description). Data are classified according to the entrance flow depth, h_0, and flow velocity, respectively.

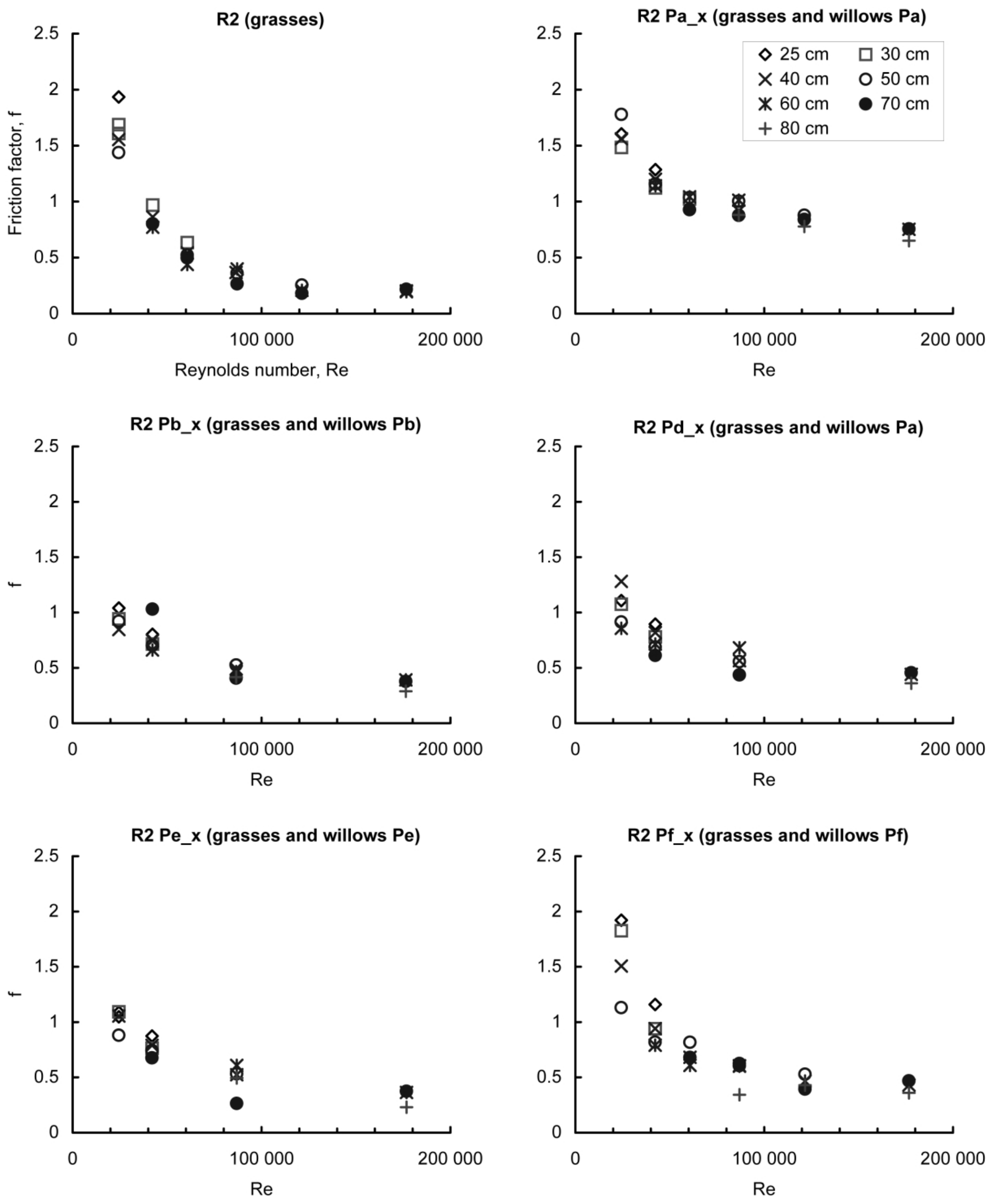

Fig. 5. Friction factor vs. Reynolds number for series R2* (see Table 1 for series description). Data are classified according to the entrance flow depth, h_0.

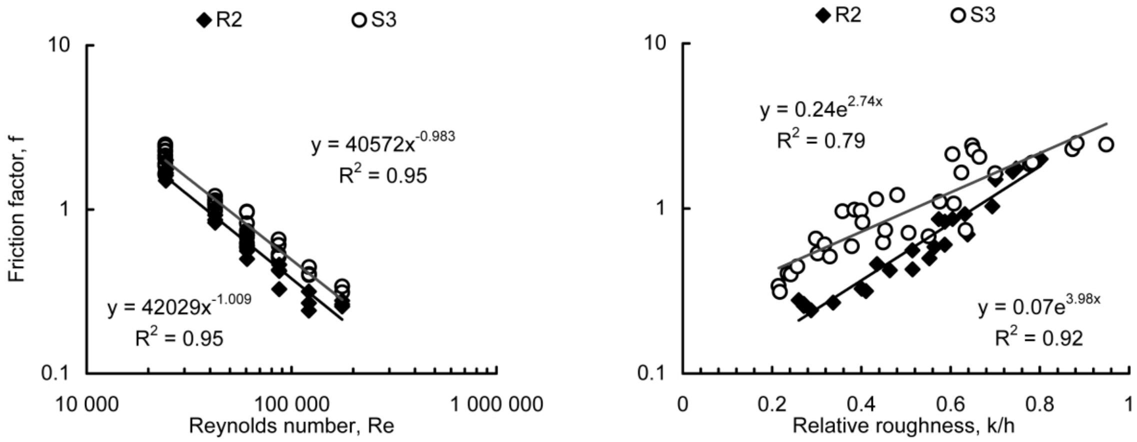

Fig. 6. Comparison of series R2 (grasses) and S3 (sedges): fitted curves f vs. Re (left) and f vs. k/h (right).

f is not directly proportional to the product vh or the Re. Despite the fact that the main stems of the willows were not markedly bent, the streamlining of the leaves and smaller branches explains the relatively large scatter in the f vs. h plots. Indeed, when plotting the friction factor against the average flow velocity for each of the four combinations of willows and sedges, the data points fall almost on the same curves, except for the most densely vegetated case.

5.2. Series R2*: effect of vegetation spacing

The data for series R2* enable to investigate how different spacing of leafless willows affect the flow resistance. Five different spacings, of which four had the same number of willows with grasses per unit area, were investigated (Fig. 5). In series R2Pa_x willow density is double compared with the other four series (R2Pb_x through R2Pf_x), which results in almost doubled f values for the same flow conditions. Interestingly, different spacing of the same number of willows in the four different patterns seems to have a small or even negligible effect on f (Fig. 5). This is understandable for low flow depths and velocities due to the dominance of grass drag; however, no significant spacing dependence was detected either for higher depths and velocities. This finding may be explained by the branched shape of the willows and the small values of projected willow area per unit volume.

In the experiments on two spacings of leafless willows without grasses (R2b_Pa_x and R2b_Pf_x), the friction factor increases with depth and seems to depend on velocity at higher flow depths but not for lower depths. The same f vs. h trend without any significant velocity effect was detected for the comparable series S3bPa_x and S3bPf_x (leafless willows without sedges). In the series of willows and grasses combined, f vs. h plots show declining trends, but a lot of scatter can be observed. For the case of grasses only (R2), plotting f vs. h produces a very scattered graph indicating that the flow depth is not able to explain the measured resistance. For series R2, f starts to fall rapidly with increasing Re as a result of the bending of the grasses (Fig. 5). However, it is not justified to express f as a function Re only.

5.3. Remarks on sedges and grasses

Plotting f against Re for series S3 (sedges) and R2 (grasses), and fitting power functions through the data points gives relatively good R^2 values (Fig. 6, left-hand side). However, there is considerable scatter especially at lower Re. Kouwen and Unny (1973) put forward the conjecture that in the case of flexible prone or waving vegetation f is a function of the relative roughness, k/h. The results of series R2 agree well with this, but series S3 acts differently (Fig. 6, right-hand side). There are several factors, which may contribute to this difference. As opposed to the grasses, the sedges were in a staggered pattern not fully covering the bottom. The flexural rigidity of the sedges was not constant over the height, and there was a considerable difference in the flexibility of the individual stems. The deflected height of the sedges was taken as the mean height, where the tips of the more flexible stems were found. However, defining the deflected height of waving grasses and sedges was not unambiguous. In particular, for the sedges difficulties were encountered.

Applying the approach of Kouwen and Li (1980) the average flexural rigidity per unit area (MEI) of the grasses was determined to be 1.9 N m^2. This value agrees well with the data presented by Kouwen and Li (1980). The average MEI of the sedges was determined to be 1.3 N m^2. Herein it should be noted that the number of roughness elements per unit area is lower than in the case of grasses. This is expected to result in the lower MEI value despite the observation that the stems of the sedges appeared to be stiffer than the stems of the grasses. In addition, the MEI value is sensitive to the ambiguity in determining the deflected height of the sedges.

Extra test runs were performed in the transition zone between nonsubmerged and fully submerged regimes for series S3 (sedges) by varying the flow depth at ~3 cm increments in the depth range of 25–35 cm at a constant discharge of 40 l/s. The experiments show that the maximum value of the friction factor is achieved, when the sedges are just submerged (diamond symbols in Fig. 4e). The friction factor increases almost linearly with increasing flow depth (and momentum absorbing area if the sedges are assumed to be homogenous along the particular depth range) up to the point of submergence, after which f starts to fall rapidly. It should, however, be noted that because of the constant discharge the friction factor is dependent also on the changing flow velocity.

5.4. Limitations

During the test period, the plants were subject to unnatural growing conditions such as frequent flooding and reduced sunlight. During the test runs on series S3 it was observed that thicker sedge stems might break just above the stiffer lower part resulting in a non-recoverable fracture. After the tests on series R2 a considerable amount of the grasses died. However, they were naturally substituted by a new growth comparable to the previous state. Nevertheless, it was observed that the general vitality of the vegetation had a downward trend, which was expected to result in reduced flow resistance.

After the test runs on series R2 (grasses only), a problem in the location of the pressure measurement instrumentation was detected. For all the other 14 series a new location for the pressure transducer was selected and the data for series R2 were corrected with new data from series R2Pa–f. For these series, head losses were measured using both the old and new transducer locations allowing to determine appropriate correction for each h–Q combination. However, data points for series R2 are judged to be less reliable than those for the other 14 series.

6. Conclusions

This paper presents an analysis of a flume study about flow resistance of flexible and stiff vegetation in various combinations. Natural grasses, sedges, and willows were used in the experiments in the scale of 1:1. Grasses were submerged in all test runs, but the stiffer sedges were partly unsubmerged. Conditions for willows ranged from through-flow to over-flow. The studied Reynolds and Froude number ranges were 24,200–178,000 and 0.03–0.25, respectively. The aim of this paper is to present an analysis of the experimentally attained Darcy–Weisbach f values against the corresponding Re, flow velocity, flow depth, and relative roughness. Data from 15 test series totalling 350 test runs were selected for this paper.

In all the test series, the friction factor decreased with increasing Re, except in the series of leafless willows on bare bottom soil, for which f was more or less independent of Re. The maximum values for the friction factor were obtained when the Re or the flow velocity were at their lowest. However, the Re alone was insufficient to explain the resistance. The friction factor was dependent mostly on (1) the relative roughness in the case of grasses; (2) the flow velocity in the case of willows and sedges/grasses combined; and (3) the flow depth in the case of leafless willows on bare bottom soil.

In the series of leafless willows on bare bottom soil, the friction factor increased almost linearly with depth and independently of velocity. In all the other series, flow velocity had a considerable effect on f. For the combinations of willows and sedges the friction factor correlated reasonably with the average flow velocity. However, considerable variation was detected between the series, which results from the differences in the vegetation density and velocity profile. For the series of grasses only, the friction factor correlated well with the relative roughness. Similar analysis for the series of sedges produced weaker correlation; the relative roughness alone seemed not to be appropriate for estimating the friction factor. Unexpectedly, different spacing of the same number of leafless willows with grasses did not have any significant effect on the friction factor. Doubling the density of leafless willows approximately also doubled the f values for the same flow conditions. Leaves on willows seemed to double or even triple the friction factor compared to the leafless case despite the fact that the bottom was growing sedges in both cases.

Based on the experimental work, a better understanding of flow resistance due to different combinations of natural stiff and flexible vegetation under nonsubmerged and submerged conditions was gained. Functional relationships for various combinations of stiff and flexible vegetation can be derived from the data, and they can further be incorporated into numerical models. Furthermore, the experiments on natural plants are a useful reference basis for other investigations utilising artificial vegetation. In the next phase of the analysis velocity distributions and turbulence inside and above the vegetation layer will be studied in more detail.

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