Reproducing natural levee formation in an experimental flume

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ABSTRACT: Natural levees are deposits of sediment often found in compound channels, in the region between the main channel and the floodplain. They have a strong influence on the morphological development of floodplains and the flow resistance of compound channels. Nevertheless, formation of natural levees, which arises from complex interactions between flow, vegetation and sediment, is barely understood. This work reports preliminary results of an ongoing project to study the formation of natural levees by means of flume experiments. In the experimental runs, vegetation was mimicked with synthetic grass, while light-weight particles were used as granular material. We show that the process is strongly dependent on the relation between water depths in the main channel and the floodplain, and the characteristics of the bed forms developed. Most important, we also show that uniform vegetation has a key role in stimulating levee formation, by capturing and sheltering particles.

1 INTRODUCTION

A natural levee is an embankment along river banks, composed of sediment and riverine vegetation, which can be found in almost every river with meadow-like floodplains (see Fig. 1). They are formed when sediment transported during floods is directed toward the bordering floodplain, where it settles over low velocity areas. Such deposits are mainly composed of fine sands, whose grain size exhibits a fining trend with increasing distance from the main channel (Smith & Pérez-Arlucea, 2008, Cazanacli & Smith, 1998). This occurs because, during transport over the floodplain, coarser material settles before fine material, primarily on the top edge of the channel banks (Adams et al., 2004).

Thus, natural levees are formed immediately on the border of the main channel. They normally show a relatively steep slope in the direction of the main channel, and fall off gradually toward the floodplain. Accordingly, they often depict the highest elevation of the floodplain (Rommel, 2013, Wolfert et al., 2002, Brierley et al., 1997).

1.1 Significance of natural levees

Natural levees are found particularly in rivers with fixed banks, and a river corridor constricted by embankments. Along such river courses lateral erosion is negligible. Accordingly sedimentation processes prevail at the river banks and natural levees grow with every flood that overflows onto the floodplain. With this, they have an increasing effect on the subsequent events that would be able

Figure 1. Natural levee in River Enz, in Pforzheim, Germany (Photo: Geitz, 2000).

to spill over the banks (Hudson, 2005). Moreover, with the formation of natural levees the floodwaters cross-section of a river corridor is reduced, and the lateral connectivity, between main channel and floodplain, deteriorates through a late overflow onto the floodplain (Klasz et al., 2014, Rommel, 2013). A late overflow leads to higher water stages on the main channel, inducing a more significant flow attack over the stream bed (increase of bed shear stress). In addition, natural levees affect stream courses during floods and thereby they also control the entry of sediment to the floodplain, as well as the spots where sedimentation occurs (Brierley et al., 1997; Smith & Pérez-Arlucea, 2008).

Since with increasing levee height less sediment is taken off the main channel, sedimentation on the floodplain decreases, and in the long-term its cross-section is potentially reduced slower than without levees. In addition, in rivers affected by ice jams, natural levees and accompanying vegetation,

prevent the entering of ice floes to the floodplain; with this, they protect existing flood-levees from ice effects.

As natural levees grow over time, so does the bankfull discharge (Fig. 2). Since in stream restoration practice bankfull discharge is often used as a surrogate of the so-called *dominant discharge* (Goodwin, 2004), e.g., the most significant discharge for stream morphology, understanding the formation processes and stability of natural levees is essential to reconsider the validity of the dominant discharge concept.

1.2 *The genesis of natural levees*

According to Adams et al. (2004), in principle, there exist two distinct transport processes through which sediment from the main channel is transported onto the floodplain. Such processes lead to two distinct morphologic phenomena, respectively. For the first process, the sediment is directed toward the floodplain through a shear flow between the main channel and the plain, and through the turbulent diffusion associated to this flow (natural levee in Fig. 3). For the second process, an advective transport may occur, which results from the differences in water level between the main channel and the floodplain, mainly when the flood wave arrives (widespread sedimentation in Fig. 3).

When the plain is flooded, different flow velocities occur between the main channel and the floodplain of a compound channel. As a consequence, a shear flow develops which leads to the formation of turbulent structures and eddies, which causes an interchange of mass and impulse between the two channel components (Sellin, 1964, Dittrich, 1998). The strength of the interaction depends to a great extend on the relation between the flow velocities on the floodplain (u_f) and in the main channel (u_m). Since the relation of flow velocities is linked to the bed slope, to the ratio between the water level on the floodplain and in the main channel, as well as to the plain roughness, it can be expected that each of these variables will also have a strong influence
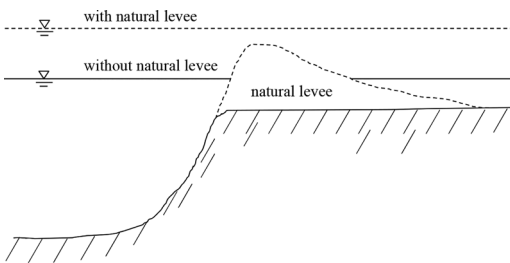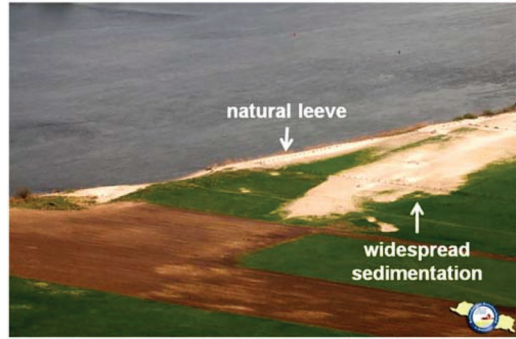

Figure 3. Sedimentation over the floodplain of the low Middle—Elbe River, in Germany (Photo: Artlenburger Deichverband).

on the intensity of the eddies in the area of interaction (Fernades et al., 2012, Knight & Shiono, 1990).

Secondary flows and turbulence induced by the bed of the main channel, have an influence over the eddy structures too. Hence, the zone of interaction is characterized by the overlapping of different types of eddies (Czernuszenko et al., 2007, Nezu et al., 1999).

The strong distinctive turbulent structures near the border of the bank, between the main channel and floodplain, lead to transport induced by turbulence of the suspended sediment in the main channel, which in this manner is conveyed to the floodplain. In this region, the process is dominated by *diffusive sediment transport* (Adams et al., 2004), as it was observed in laboratory experiments with a rectangular compound channel by James (1985). At the same time, the transport is also affected by the secondary currents occurring in the channel. Secondary currents support or prevent sediment exchange between the main channel and the floodplain, according to the water level. Nezu et al. (1999) suggested that the momentum and impulse exchange between plain and main channel is hindered by a strongly increasing secondary flow action for ratios $h_m / D \geq 1.6$ (where h_m = water depth in the main channel, D = elevation of the flood plain).

Significant amounts of coarse sand can be delivered to the floodplain only during large flood events. Thus, the sediment exhibits larger deposition rates over zones with high water depths than over zones with lower depths (Filgueira-Rivera et al., 2007, Cazanacli & Smith, 1998). A major control over natural levees' formation is exerted by sediment mobilized in the main channel, while the duration of the flood waters is of secondary importance (Smith & Pérez-Arlucea, 2008).

Figure 2. Sketch of the relation between natural levees and water level.

1.3 Summary

From the description above, it is clear that there is some knowledge available regarding the hydraulics of the processes that lead to natural levee formation. Nevertheless, a complete explanation that links the hydraulics to the related morphodynamic processes is still lacking. Aiming to contribute in filling this gap, we present in this paper some results of flume experiments intended to study some variables expected to have a direct influence on the development of natural levees, such as water depth, bed slope, bed forms and experiment duration. The main goal in this work is the study of natural levees developed by diffusive transport. Therefore, the flow occurring in the area between the main channel and the floodplain is for this study of central importance.

The effect of bank vegetation was considered in this first phase of our investigation only for the particular case of low vegetation covering the floodplain evenly. Future phases of the study will consider other typologies and sizes of plants.

2 EXPERIMENTAL SET UP AND PROGRAM

2.1 Hydraulic and sedimentological boundary conditions

For the experimental runs, it was necessary to ensure the formation of an interaction zone between the main channel and the floodplain, so that diffusive sediment transport could be developed. Moreover, in the main channel a sufficient amount of sediment transported in suspension was required. An imposed condition to fulfill was that the flow should be subcritical (Froude < 1), so the hydraulic conditions are similar to most natural streams with floodplains. Similarly, normal flow conditions were imposed, in order to obtain identical flow conditions all along the flume.

The model set up was based on the cross-section of a straight river course with half a trapezoidal compound channel, whose floodplain is uniformly overgrown with vegetation (Fig. 4). For the dimensions of the section, a ratio between the width of main channel and floodplain, based on typical values for straightened streams in Germany, was used. This ratio was $b_m / b_f = 70\,cm / 130\,cm = 0.54$ (where b_m = width of the main channel and b_f = width of the floodplain). A detailed description and dimensions of the experimental set up are given in Branß (2015).

A polystyrene granulate, with $d = 2.06\,mm$ uniform grain size, and a density of $\rho_S = 1058\,kg/m^3$, was chosen as granular material for the experi-

ments. The use of synthetic material facilitated the emergence of transport in suspension in the main channel, since this material has very low critical and falling velocities ($u_{crit} = 0.095\,m/s$ and $w_S = 0,031\,m/s$, respectively).

Runs with different amounts of material in the flume were conducted, so bed forms with different characteristics were developed on top the flat fixed bed of the channel. To ensure a sufficient suspension of sediment in the main channel, the flow velocities were adjusted to a range of values of u_m/u_{crit} between 2 and 4 (where u_m = flow velocity in the main channel and u_{crit} = critical flow velocity of the sediment). Furthermore, in order to achieve deposition of the entrained particles, it has to be assured that the flow velocities on the floodplain were lower than the critical flow velocity for the beginning of motion.

2.2 Experimental set up

The experimental runs were performed in a tilting flume, at the hydraulics laboratory of the Leichtweiß-Institut für Wasserbau of the Technical University Braunschweig. The flume has 30.0 m usable length, 2 m width, and 0.8 m height. Water is supplied to the flume by the pumping system of the laboratory, and the water discharge is controlled with a magnetic flowmeter. At the downstream end of the flume, water is conducted to a deep deposit, to be recirculated by the laboratory's pumping system. Sediment is collected with a funnel-shaped tank and delivered to the inlet of the flume with a sediment recirculation system (Fig. 5).

The half trapezoidal compound channel was built along 20 m of the flume. The floodplain and the main channel had 130 cm and 70 cm width, respectively, while the banks of the main channel had a 1:1 slope. In order to simulate roughness of low vegetation on the plain, artificial grass with a

Figure 4. Model set up with half a trapezoidal compound open—channel.

height of 3 cm was used to cover banks and floodplain (see Fig. 6). The main channel bed had 60 cm width, and consisted of film faced plywood plates covered with a one-diameter thick layer of glued polystyrene granulates. The height of the floodplain was D = 10.4 cm, including the 4 mm height of the artificial grass carpet.

In order to assure a regular distribution of the water, without allowing the particles to be conveyed onto the floodplain at the beginning of the model, a sieve with smaller openings than the diameter of the particles was placed vertically along 3 m of the edge of the floodplain. The sieve was attached after the runs 1 and 2 (see Fig. 5b).

Water elevation and sediment deposits were measured using two point gauges. For this, x-coordinate was defined in the direction of flow, y-coordinate horizontal and transversally to the main flow, and z-coordinate along the vertical direction. In the same order, the flow velocity components u, v and w were defined. Further details of the experimental set up are given in Branß (2015).

2.3 *Experimental program*

Preliminary tests were performed, in order to obtain the water discharges, bed slopes and water stages suitable for the definitive experimental runs. It was found that a bed slope of $I_S = 0.05\%$ was convenient to reach a compromise between the required lower than critical flow velocities on the floodplain, and the movement in suspension of the polystyrene grains in the main channel. In general, the conditions for suspension of the material were well anticipated by the formula of van Rijn (1984), but underestimated by the formula of Bagnold (1966). Adjustment of water stages was possible only to a limited extent, because very low water stages in the floodplain showed
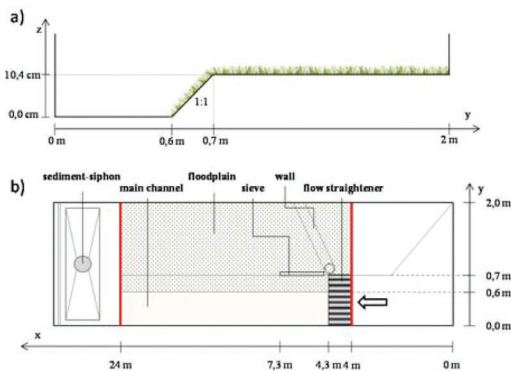
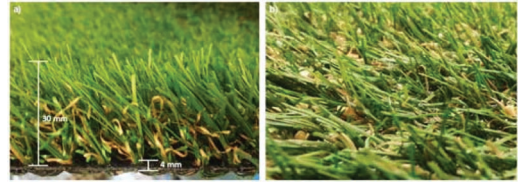Figure 5. a) Cross-section and b) plan view of the experimental set up.

Figure 6. Artificial grass used in the experiments, a) dry conditions, b) wet conditions.

not to be suitable for the described constraints, and also in the floodplain the condition of flow velocity being lower than the critical value had to be satisfied. Altogether, 9 experimental runs for levee formation were performed, as described in Table 1.

For all runs, except run 4, the ratio for the water stage was $h_f/h_m = 0.35$ (where h_f = water depth on the floodplain and h_m = water depth in the main channel); this value was obtained from the criterion of Nezu et al. (1999) described above, and the best performing values in the tests runs.

The flume was divided in two distinct zones during each run. Zone 1 included the upper part of the channel, from x = 4 m to x = 17.3 m, while zone 2 extended from the end of zone 1 to the end of the channel at x = 24 m. A single row of pebbles (d 2 cm) was randomly laid along the edge of the floodplain in zone 2, while zone 1 was left unchanged. The pebbles were intended to provide a rough assessment and a first test of the likely effect of dense vegetation growing in the transition area to the floodplain on levee formation.

Two runs (run 1 and run 2) were carried out without the development of bed forms on the bed surface of the main channel. Identical conditions for these two runs were replicated in runs 6 and 7, respectively, with slight variations on the border conditions: Run 6 and 7 were conducted with a larger duration of the experiment and the vertical sieve at the beginning of the model already in place. In addition, 5 runs with the development of bed forms were carried out. From the latter, one run was performed with a 1 cm lower water stage (run 4, Dr = 0.3), another was performed with twice the time of experiment duration (run 9, $\Delta t = 38$ h), and a third one (run 5) with a gentler bed slope of $I_S = 0.01\%$.

3 RESULTS

In the experiments, deposition of the granular material on the floodplain occurred through diffusive and advective transport. Processes of advective

Table 1. Summary of conducted experiments.

Run	Bed forms	I_S [%]	Q [l/s]	Δt [h]	h_f/h_m [-]	u_m/u_{crit} [-]	Fr_m [-]
1	without	0.05	32	7.0	0.34		
2	without	0.05	32	16.0	0.35		
3	with	0.05	22	19.0	0.35	3.00	0.24
4	with	0.05	21	19.5	0.30	3.05	0.24
5	with	0.01	19	19.5	0.35	2.23	0.18
6	without	0.05	36	19.5	0.36	3.85	0.32
7	without	0.05	36	19.5	0.35	3.85	0.29
8	with	0.05	22	19.0	0.35	2.95	0.23
9	with	0.05	22	38.0	0.34	3.05	0.23

transport led to the formation of extensive material deposits, resembling those observed in the Elbe River (Fig. 3). Conversely, diffusive transport processes led to the formation of levees. Since the main focus of this study lies on the analysis of levee formation due to diffusive transport, subsequent explanations and discussion refer exclusively to diffusive processes.

In all the experimental runs, the resulting levees were characterized by a narrow ribbon-like structure, with roughly constant width all along the channel. Transversally, toward the direction of the floodplain, their border was diffuse, while their height reached at most the height of the artificial grass. Hence, a precise survey of the levee height and width was only to a certain extent possible. Since the artificial grass stems bent strongly according to the flow acting over them, during the experiments the height of the artificial grass decreased to a height of roughly 2 cm (see Fig. 6). Particles deposited above the height of the artificial grass remained in that position only for a short time, to be entrained again by the flow. This occurred even though the mean flow velocity on the floodplain was below the critical velocity of the particles.

The first experimental runs without bed forms (runs 1 and 2) led to the extensive material deposits mentioned above, which impeded the development of a levee. Due to the attachment of the mentioned sieve at the beginning of the model (see Fig 5b), and a slight adjustment of the discharge, in runs 6 and 7 a natural levee was formed. On average the levee's width was $\Delta y = 6.5$ cm in zone 1 and $\Delta y = 5.7$ cm in zone 2 (Fig. 7a). The maximum height of the levee reached roughly 2 cm (1 cm under the height of the artificial grass in dry conditions).

In runs 3 and 8, which were performed with bed forms, a significantly wider levee was developed. The bed forms exhibited on average a height of 0.06 m and a length of 2 m. In zone 1, the levee had a width of $\Delta y = 11.4$ cm on average. The maximal

thickness was estimated to be 2.2 cm. In zone 2, the levees showed a width similar to zone 1, of roughly $\Delta y = 11.8$ cm (Fig. 7b).

The reduction of the water stage by 1 cm (run 4) led to halving of the levee width in zone 1 ($\Delta y = 5.9$ cm). This result agrees with observations by Cazanacli & Smith (1998) in the Saskatchewan River in Canada. These authors described the formation of smaller natural levees in areas where the water stage hardly exceeded the elevation of the floodplains. They assumed this trend was related to the limited area of interaction between the main channel and the floodplain.

Doubling the experimental time, from 19h to 38h (run 9), caused an increase of the levee width up to a maximum increment of 1 cm. Therefore, such increments in y-direction were within the measuring accuracy. This low dependency on time correlates with observations of Smith & Pérez-Arlucea (2008), who found that the duration of flooding has only a minor impact on levee size.

Levee formation occurred also for a low bed slope of $I_S = 0.01\%$ (run 5) and the associated low flow velocities. With an average levee width of $\Delta y = 9.8$ cm in zone 1, and $\Delta y = 9.1$ cm in zone 2, the resulting levees were wider than levees in runs 6 and 7, but narrower than in runs 3 and 8. Despite very low flow velocities in run 5, the levees maximum height reached the top of the artificial grass.

The assessment of the effect on the geometry of the levee, of the pebbles arrangement laid on the floodplain border, turned out to be rather obscure, since this effect was negligible in most runs. Only run 4, with a 1 cm lower water stage, led to a 3.5 cm widening of the levee in the zone of pebbles. This striking outcome might be related to the fact that the pebbles in this run were not completely submerged, due to the low water depths.
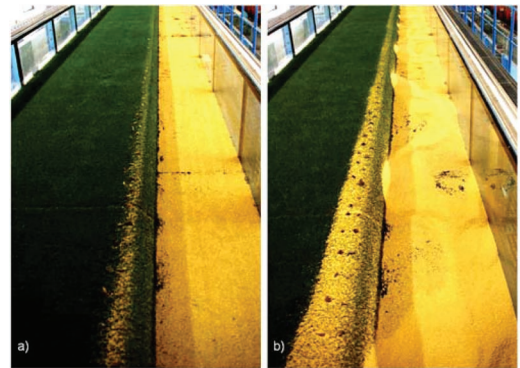

Figure 7. Developed levee in experimental runs a) without bed forms in the main channel (run 7) b) with bed forms (run 3).

4 DISCUSSION

4.1 Turbulent structures observed

During the experiments, in the transition area between the main channel and the floodplain, a multitude of different flow structures were observed. Figure 8 shows a schematic representation of the observed structures. In this figure, the open arrow indicates the direction of flow.

In the whole channel, horizontal eddies (dotted circle in Fig. 8b) were observed in the area of the upper border of the bank, as long the floodplain was underwater. Such eddies were stronger, the lower the water stage on the floodplain was. The roughness of the channel-boundaries induced further eddy-structures with a lateral axis that was parallel to the associated part of the boundary (drawn through cylinders in Fig. 8a and 8b). In addition, all runs with bed forms showed a prominent longitudinal turbulence, strengthening existing eddies and intensifying sediment transport onto the floodplain (dashed, filled arrow in Fig. 8a). The longitudinal turbulence occurred periodically at the toe of the bank-slope in the main channel. It skewed existing roughness induced eddies into the flow direction (dashed funnel structure in Fig. 8a).

4.2 Development of levees as a natural cyclical process

Mobility of the polystyrene particles used in the experiments exhibited a striking sensibility to flow velocity fluctuations. This behavior, related to the low-density of the polystyrene with respect to natural sediment, caused sediment transport pulses on the floodplain, induced by horizontal eddies. Besides, high mobility of the granular material enabled that large amounts of particles were set in suspension in the main channel. Nonetheless, one disadvantage of the light-weight particles used was their uniform grain size distribution, while natural levees are normally composed of material with different grain size fractions. This distortion, as well as the shape of the artificial material, may have affected the stability, final height and geometry of the experimental levees to a certain extend.
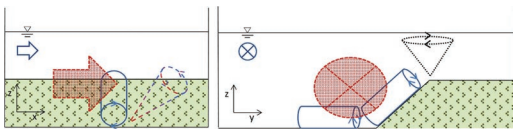

Figure 8. Schematic representation of flow structures observed in the area of interaction a) view in y-direction b) view in x-direction.
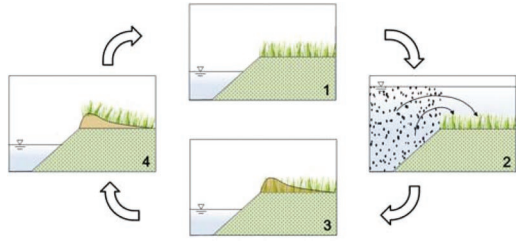

Figure 9. Conceptual model of the cyclical genesis of a natural levee.

Nevertheless, it is likely that in nature the height of the levees could be limited by the height of the existing vegetation, similarly as it occurred in our experiments. The annual growth rate of natural levees was determined by Klasz et al. (2014), in the Danube in Austria, to reach up to 11 mm/year, while Rommel (2013) found in the River Elbe in Germany an average growth rate of 6.4 mm/year. Thus, the growing rate of a levee is normally within a fraction of centimeter per year, which means that the time scale of levee formation spans several years. Low bank vegetation, like for instance, mown grass, lawn or reed, exhibits heights in the order of decimeters. Besides, this type of vegetation can grow in less than one year. If levee formation is conceived as a process with a strong interaction between sediment deposition and vegetation growth, as observed in the experiments, the genesis of a natural levee can be conceptualized as a cyclical process of gradual succession, as represented schematically in Figure 9, and described below.

In (1), the edge of a stream bank, or an old levee, is covered with low vegetation. When floodwaters spill onto the floodplain, the described diffusive transport of suspended sediment might occur, conveying sediment from the main channel to the floodplain (2). Sheltered from flow attack by e.g. grassy vegetation, the sediment settles along the edge of the bank and silts up to the upper border of the grass (3). A while after flooding, new grass grows over the sediment deposit. This new grass puts down roots in the deposit and holds firmly (4). Finally, the cycle starts over again.

5 SUMMARY

In this work, the formation of natural levees through diffusive sediment transport onto the floodplain was studied. The process was investigated by means of experimental runs, where the required flow conditions for the formation of levees were achieved. The levee morphologies produced in laboratory were basically in good agree-

ment with the descriptions found in published literature.

In the experiments, the significance of the different factors involved in the development of levees was identified. Bed forms and water stage had the most important influence on the formation of levees, while the beds' longitudinal slope exhibited a marginal influence. Similarly, the duration of the runs had only a secondary effect. The influence of bank vegetation on the formation of levees was evaluated only for uniform distributed vegetation on space, like mown grass, lawn or reed. The experimental runs showed that vegetation gives a sheltering effect to particles, so that they cannot be further entrained by the flow, and thus low vegetation encourages levee formation. The experimental runs provided information for conceiving a conceptual model, to describe the formation of natural levees as a cyclical process dependent not only on the stream flow conditions, but also on vegetation growing at the edge of the banks.

Future developments to study levee formation will try to develop a practical criterion to quantify the observed process. Also, runs with different patterns of bank vegetation will be carried out, to study their influence on the characteristics of the levees.

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