BANK PROTECTION AT THE OUTER SIDE OF CURVED CHANNELS BY AN UNDULATED MACROROUGH CONCRETE WALL

A. Vela Giró[1] and A.J. Schleiss[2]

[1] INGENI SA, Lausanne, Switzerland, alexandre.velagiro@ingeni.ch
[2] Laboratoire de Constructions Hydrauliques (LCH), EPFL, Lausanne, Switzerland
anton.schleiss@epfl.ch

Abstract: Systematic hydraulic model tests were performed in a 90° curved channel with an undulated wall at the outer bank. The outer wall consisted of trapezoidal elements of 0.1 m depth and 0.33 m length. Three discharges (150, 180 and 210 l/s) and three bed slopes (0.35, 0.5 and 0.7%) with a wide grain size distribution of the bed sediments (d_m = 8.7mm) were tested. The following parameters for subcritical flow conditions were studied: bed morphology, water level, sediment transport, longitudinal water velocities and grain sorting across the bend.

Based on the experiments, two principal scour holes could be identified. Compared to the case of a smooth wall (without undulations) the depth of the two scour holes was significantly reduced. The reduction was about 20% at the first hole and 40% at the second one. The scour location was also influenced by the undulations. Compared to the smooth wall the two scour holes were shifted by 10° in downstream direction.

Keywords: channel bend, outer bank scour, bank protection, bed morphology.

INTRODUCTION

In valleys of the Alps and Pyrenees, rivers often pass through villages and cities. The lack of space between the river and the infrastructures requires protection by walls against floods and bank erosion. Due to bend effects, bend scour occurs near the outer bank. An extreme flood can erode the bank foundations and results in wall failure. Subsequently, uncontrolled erosion can propagate behind the failed wall and cause serious damages at buildings and infrastructures.

The construction of an undulated concrete wall (Fig. 1) along the outer bank of a bend has the following advantages:

1. The undulations can reduce considerably the scour depth along the wall toe.
2. The undulations increase the constructional rigidity and stability of the wall. Even if there is scouring along the foundation, the wall undulations increase resistance against overturning by earth and water pressure behind the wall.
3. Without reducing the width of the river, the undulated wall can increase space for public use and favor architectural integration.

Scour in bends has been investigated since a long time. Fargue, as one of the first researchers established a scour formula for river bends (Hager 2003). Later, Williams (1899) developed a theory on Fargue's laws. This theory allowed calculating the scour depth but also the position of the scour holes. Van Bendegom (1947) established an equation based on the equilibrium of the grains on an inclined plan. Engelund (1974) also proposed a formula based on the equilibrium of the grains.

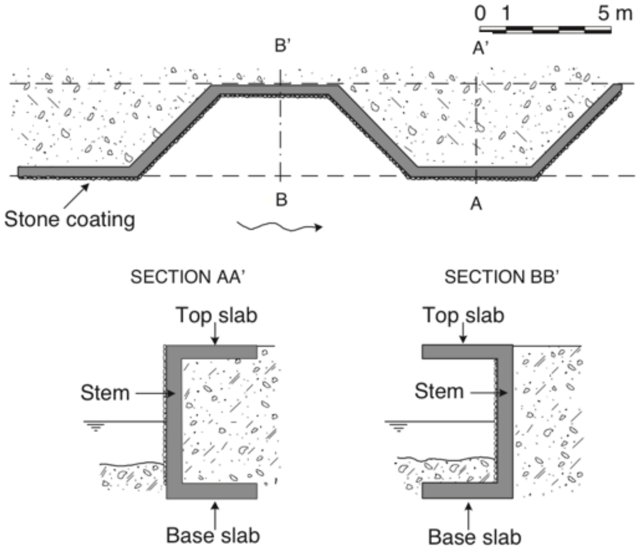

Fig. 1 – Schema of an undulated protection wall with stone coating

Falkon & Kennedy (1983) proposed an equation as a function of the porosity, the particle Froude number and the dimensionless shear stress. Odgaard (1984) established an equation as a function of the densimetric Froude number and the dimensionless shear stress. Peter (1986) made some systematic tests using a wide grain size distribution and suggested some empirical relationships. Reindl (1994) considered in his formula the equilibrium of the forces on a grain. Thorne (Hoffmans & Verheij 1997) based his equation on prototype and flume experiments in which the grain size diameter varied from 0.3 to 63 mm. Hersberger (2002), using also a wide grain size distribution, which takes into account the influence of vertical ribs on the wall acting as macro-roughness elements.

EXPERIMENTAL SET UP AND DATA AQUISITION

The 1 m wide channel was composed of a 7.5 m long inlet reach, followed by a 90° bend of 6 m centreline radius and an outlet reach of 6 m (Fig. 2).

To achieve continuous sediment supply, a conic tank stored 0.5 m^3 of sediments. The sediments were dropped into the channel at about 1 m downstream of the beginning of inlet reach. The other elements of the experimental set-up are shown in Fig. 2. The granulometry of the sediments was chosen similar to the grain size distribution used by Hersberger (2002), which is a poorly sorted, wide grain size distribution. This allowed comparing the present tests with the tests conducted by Hersberger (2002) at the same installation with a smooth wall. This coarse sediment mixture was selected similar to typical granulometry (made dimensionless with mean diameter) of Alpine rivers in Switzerland. The minimum diameter was d_{min} = 2 mm, the maximum d_{max} = 32 mm and the mean diameter d_m = 8.7 mm. The width of the grain size distribution was defined by $\sigma = (d_{84}/d_{16})^{0.5} = 1.65$. The geometry of the wall was created by trapezoidal ribs made of steel sheets. They were placed vertically, with a spacing of 46 cm (corresponds to 4° in the bend) along the outer side of the channel (Fig. 3).

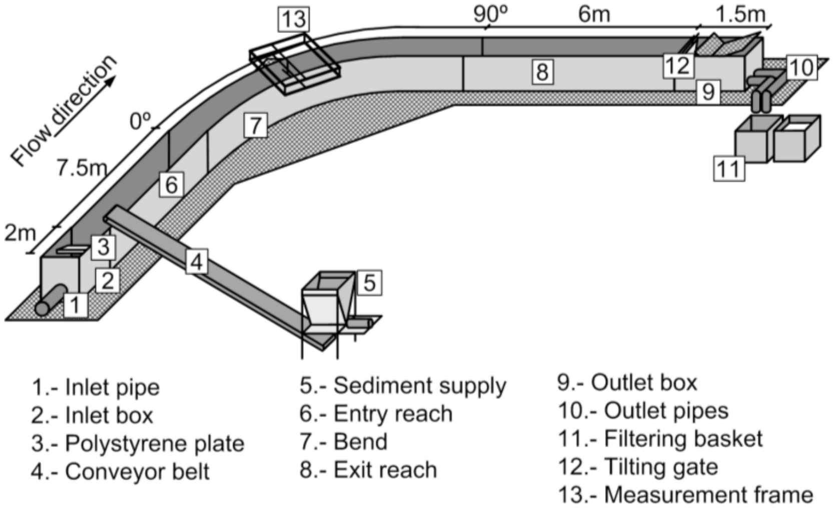

Fig. 2 - Schematic view of the experimental installation

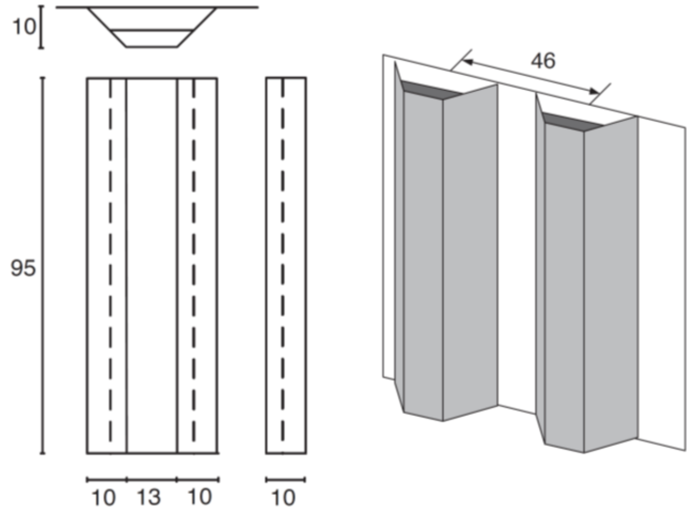

Fig. 3 - Trapezoidal wall ribs (units in cm) fixed at the outer vertical wall of the flume

A total of 10 experiments were performed with three different initial bed slopes. For the slopes of 0.5% and 0.7% the tested discharges were 150, 180 and 210 l/s. For the tests with a slope of 0.35% the discharges were 150, 170, 190 and 210 l/s. For the tests with a slope of 0.35% and 150 l/s the solid transport was very low. Therefore one discharge was added between 150 and 210 l/s to guarantee that for 3 of the 4 tests the scour phenomenon was fully developed. The principal measured parameters for each test are summarized in Table 1.

Before each test the bed was levelled to fit the wished initial longitudinal slope. During the test, the sediment supply was adjusted for each discharge in order to keep the longitudinal bed in the straight inlet reach as constant as possible. The flow was subcritical with Froude numbers in the range of 0.69 and 0.95 for the tested discharges.

The water and bed level was measured with 3 ultrasonic sensors (UNAM 30I9001) mounted on a probe support. The accuracy of the ultrasonic sensors is 0.3 mm. The levels were measured at about 900 points along the channel. The automatic measurements were complemented with manual level recordings in the straight reaches with a precision of 1 mm. The evolution of water and bed levels was also measured along the outer bank of the channel across the transparent wall. The measures were taken between the vertical ribs (approximately every 30 cm).

Table 1 – Summary of the principal measured parameters for each test: Discharge Q_w; initial slope S_o; mean water depth h_m; water depth at first and second scour hole h_1, h_2; location of first and second scour hole S_{L1}, S_{L2}.

ID	Q_w	S_o	h_m	h_1	h_2	S_{L1}	S_{L2}
	m^3/s	%	m	m	m	angle	angle
B2b	0.15	0.5	-	-	-	43	100
B2c	0.18	0.5	0.178	0.331	0.292	39	97
B2d	0.21	0.5	0.222	0.356	0.295	57	97
C2b	0.15	0.7	0.160	0.301	0.281	43	92
C2c	0.18	0.7	0.190	0.351	0.337	43	97
C2d	0.21	0.7	0.213	0.374	0.312	39	101
D2b	0.15	0.35	0.178	0.329	0.248	43	97
D2c	0.17	0.35	0.198	0.338	0.299	49	96
D2d	0.19	0.35	0.213	0.369	0.332	43	99
D2d	0.21	0.35	0.226	0.369	0.337	43	96

* The water level measurements at test B2b are not available.

The longitudinal velocity was measured manually with an electromagnetic flow sensor NAUTILUS C 2000, at six cross-sections along the channel. The longitudinal velocities were recorded for all points of a 10 cm × 2.5 cm grid over the entire cross section.

At the end of each test, the sediments accumulated in the filtering basket were weighted. Furthermore, after each test, samples of the armour layer were taken at 45° and 90°, near the inner and the outer side of the bend. To extract the samples of the armouring layer, a zone of 10 × 30 cm was coloured with a spray. Then, the coloured stones were manually removed. Later the samples were sieved in order to obtain the grain size distribution.

The measurements of the water level and longitudinal velocities were performed when the bed morphology was considered in equilibrium. The situation was considered stable when there were no changes of the water level on the outer side wall of the bend and the solid transport at the outlet was approximately equal to the sediment feeding into the flume. Typically this was the case after about 7 hours.

RESULTS

Depth and evolution of scour

The analysis of the final bed topography revealed that two scour holes are formed in the bend with the deepest part at about 45° and 100° (see Table 1) during the tests with the undulated wall. In the tests with the smooth wall they were located about 10° further upstream. The discharge and the bed slope are two parameters that influence the maximum scour depth. Fig. 4 shows that with an increase of the discharge the relative scour depth h_{max}/h_m decreases. The first hole was always between 5% and 32% deeper than the second hole.

The influence of the velocity on the scour depth is of particular interest. In the case of a smooth outer wall, the relative maximum scour depth increases if the densimetric Froude number becomes larger (see Fig. 5).

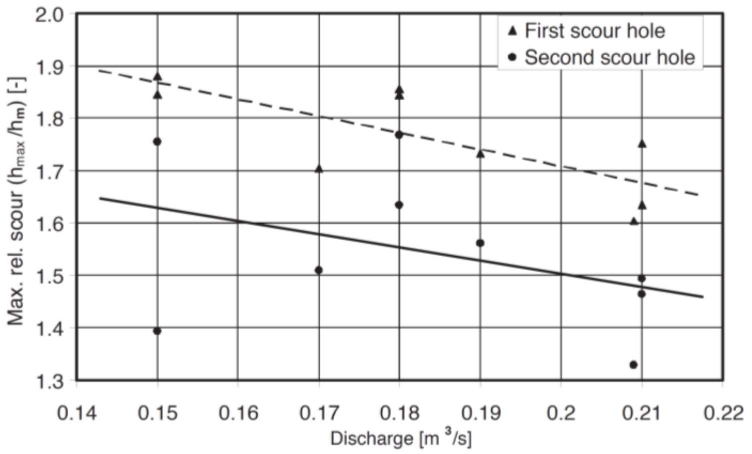

Fig. 4 - Maximum relative scour depth h_{max}/h_m as a function of the discharge for an undulated wall at the outer side of the bend

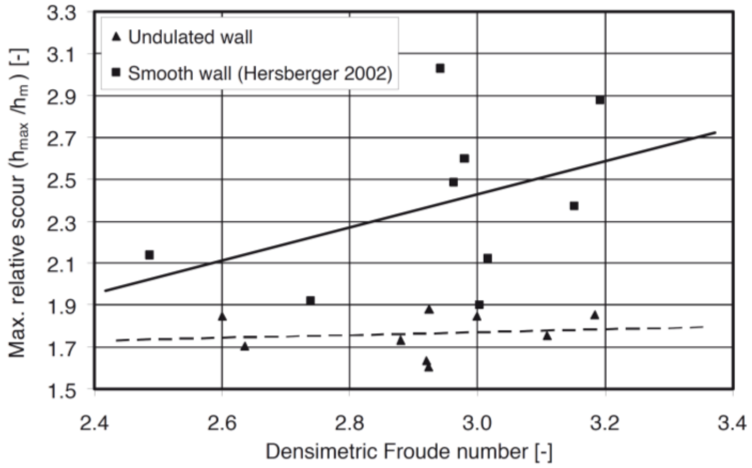

Fig. 5 - Maximum relative scour depth h_{max}/h_m as a function of the densimetric Froude number F_{rd}

For the undulated wall, the relative maximum scour depth h_{max}/h_m is very low and almost independent of the densimetric Froude number F_{rd}. Since the sediment density coefficient and the granulometry we kept constant, the relative scour depth h_{max}/h_m is independent of the velocity.

Compared to a smooth wall, the undulated wall can reduce significantly the scour depth, especially at the second scour hole. At the first hole, the scour depth is reduced between 5 to 35% (mean value 17%) and 0 to 60% (mean value 39%) at the second hole (see Fig. 6).

The scour reduction is more significant at the second hole because the effect of the wall undulations is fully present after the first hole (along the bend). The flow approaches the first scour hole directly from the inlet reach with almost no effect of the bend and the wall undulations. The latter become only important at the second hole, where the flow has passed the entire bend with the wall roughness.

Hersberger (2002) proposed a modified Bridge equation to estimate the scour depth. This equation takes into account the bend Radius and width (R_c, B), the mean flow depth (h_m) and the friction angle of the bed material (tanø). The local lateral bed slope is given by:

$$\sin\beta = 0.394\left(11 - 23\frac{h_m}{B}\right)\cdot\frac{R_c}{B}\cdot\tan\emptyset\cdot\frac{h_s}{r} \qquad (1)$$

For the test with an undulated wall, Eq. 1 was adapted to fit the data as follows:

$$\sin\beta = 0.3\left(11-21\frac{h_m}{B}\right)\cdot\frac{R_c}{B}\cdot\tan\emptyset\cdot\frac{h_s}{r} \tag{2}$$

The coefficient of determination between the observed data and the computed values with Eq. 2 is $R^2 = 0.924$.

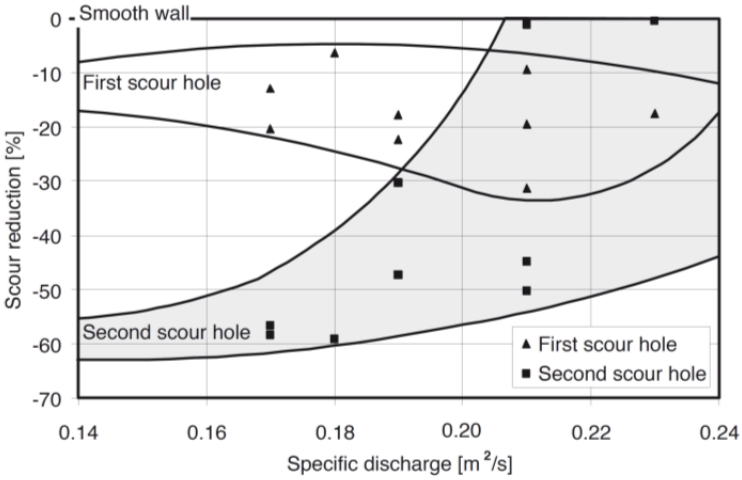

Fig. 6 - Reduction of the scour depth by the undulated wall with vertical trapezoidal ribs spaced 4° (spacing 46 cm) compared to a smooth wall

The time evolution of the scour with the undulated wall was observed during the tests, along the outer side wall. The erosion for the tests with $S_0 = 0.5\%$ starts at the end of the bend (second hole). The formation of the scour hole is fast (from 1h to 1h30'). The formation of the first scour hole begins when the second one has reached almost the maximum depth, at about 1 hour after the beginning of the tests. The formation of the first scour hole is slower than the second one.

During the erosion of the first scour hole the second one is filled up with a layer of 1.5 d_{max} (see Fig. 7). A possible explanation could be that the transport capacity at the first hole is more important than in the second hole (see Section 3.4). The sediments eroded at the first hole are transported along the bend and deposited in the second hole as an armouring layer.

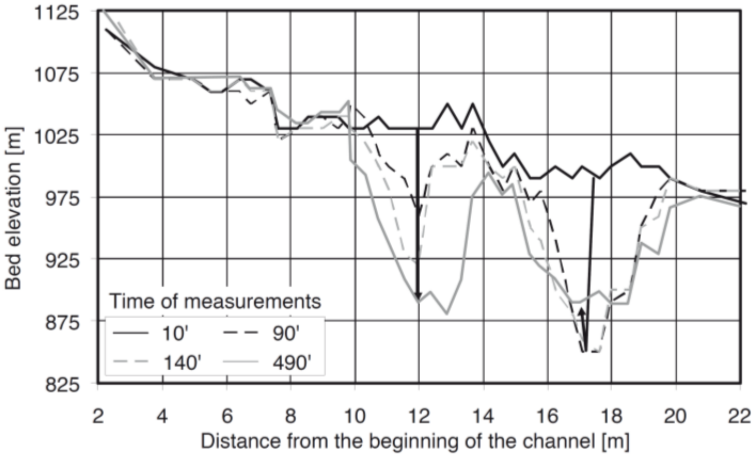

Fig. 7 - Evolution of the bed erosion with two scour holes ("1" at 12 m and "2" at 17 m) along the outer channel wall for the test with $S_0 = 0.5\%$ (test B2c). Bed elevation in [mm]

Analysis of sediment transport

The mean sediment transport was calculated as the ratio between the weight of all sediments collected in the filtering baskets and the total test duration. Some assumptions had to be made in order to compare all tests:

1. The mean bed slope is constant at the end of the test.
2. The sediment feeding is constant during the test and equal to the sediment transport capacity in the straight approach stretch upstream of the bend.
3. The volume of sediments eroded at the beginning of the test to form the final bed morphology in the bend is mainly transported to the inner side of the bend.

It can be seen in Fig. 8 that the relationship between solid discharge and liquid discharge is linear (R^2 between 0.91 and 0.99). As expected, the initial bed slope has an important influence on the sediment transport: an increase of the bed slope causes an increase of the linear regression slope. The wall undulations have also an influence on the solid discharge. It can be noted, that depending on the initial bed slope and the water discharge, the solid discharge is sometimes higher with the undulated wall and sometimes with the smooth wall. This may be explained by the fact that the solid transport is the result of the combination of two effects:

1. The undulations cause an increase of the water depth. Therefore, the shear stress increases at the channel bed and consequently the sediment discharge increases.
2. The undulations produce additional roughness and turbulence, which probably decrease the solid transport.

Thus depending on which effect is more important, the solid transport is higher with the undulated than with the smooth wall.

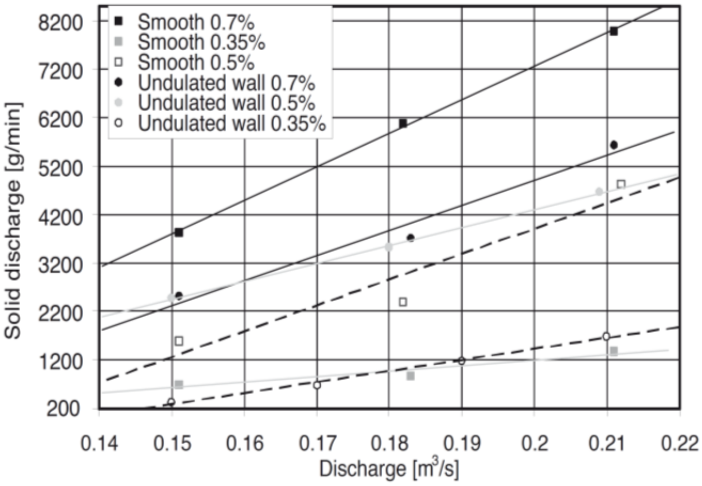

Fig. 8 - Mean sediment discharge during the entire test duration as a function of water discharge

Analysis of the granulometry of the armouring layer

For some tests, 4 samples of the armouring layer were taken across the section (see Section 2.2.6). The analysis of the grain size distribution of those samples shows that, as expected, the grains are much coarser at the outer bank. The difference of the d_m between the outer and the inner bank is 14 mm (1.6 d_m) at 45° and 11.3 mm (1.3 d_m) at 90°. At the outer bank the grain size is always coarser at 45° (see Fig. 9).

According to Section 3.1.2 some of the grains eroded in the first hole are transported and deposited in the second hole. Furthermore, the grains are coarser in the first than in the second hole. This means that at 45° the sediment transport and the scour potential is more important than at the second hole. At the inner bank, the smallest grains are observed at 45° where the transport capacity is lower due to the shallow water depth.

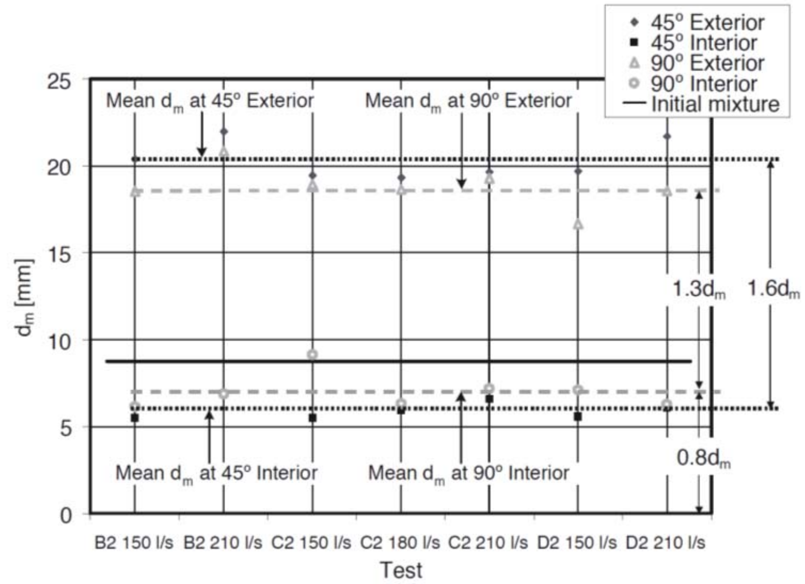

Fig. 9 - Mean diameter of the armouring layer at the inner and outer side of the bend for different tests with the undulated wall

CONCLUSIONS

The influence of an undulated macro-roughness wall at the outer bank on scour along the bend was studied. The undulated wall geometry tested in the experiments revealed the following:

- The tests demonstrated that the undulated wall affects the bed topography, the water surface, the flow velocities and the sediment transport.
- Compared to the smooth wall, with the same specific discharge and bed slope, the undulated wall reduces the scour depth by 5 to 35% (mean value 17%) at the first hole and by 0 to 65% (mean value 39%) at the second one. The higher slopes indicate the most important scour reductions.
- The modified equation of Bridge proposed by Hersberger (2002) for the scour depth estimation for the smooth wall was modified to fit the data of the undulated wall.
- Due to the wall undulations the position of the scour holes and the point bars were shifted by about 10° in downstream direction.
- The transversal grain sorting process at the bend is significant. At the outer bank, the mean diameter is at about 2.5dm and at the inner bank about 0.8dm.

It may be concluded that the undulated wall is a promising bank protection measure which reduces scour potential and thus can be a more economical solution than a traditional smooth protection wall.

REFERENCES

Engelund, F. (1974). Flow and bed topography in channel bends, *J. Hydr. Div.*, Vol. 100, No. 11.

Falcon, A.M. and Kennedy, J.F. (1983). Flow in alluvial-river curves, *J. Fluid Mech.*, Vol. 133, pp. 1-16.

Hager, W.H. (2003). Fargue, founder of experimental river engineering, *J. Hydr. Res.*, IAHR, Vol. 41, No. 3, pp. 227−233.

Hersberger, D. (2002).*Wall Roughness Effects on Flow and Scouring in Curved Channels with Gravel Bed.*

PhD thesis, No 2632 and Communication No 14, Laboratory of Hydraulic Constructions (LCH), Ed. A. Schleiss. École Polytechnique Fédérale de Lausanne.

Hoffmans, G.J.C.M. and Verheij, H.J. (1997). *Scour Manual*. Rotterdam, Balkema.

Odgaard, A.J. (1984). Flow and bed topography in alluvial channel bend, *J. Hydr. Eng.*, ASCE, Vol. 110, No. 4, pp. 521-536.

Peter, W. (1986). Kurvenkolk - Untersuchungen über Sohlenausbildung in Flusskrümmungen. Mitteilung Nr. 85 der Versuchsanstalt für Wasserbau, Hydrologie und Glaziologie. (VAW), Eidgenössische Technische Hochschule (ETHZ).

Reindl, R. (1994). *Sohl- und Strömungsausbildung in einer Bodenfolge mit und ohne Rückstaueinfluss*. PhD thesis. Innsbruck: Institut für Wasserbau, Leopold-Franzens-Universität.

van Bendegom, L. (1947). Eenige beschouwingen over riviermorphologie en rivierbetering. De Ingenieur 59 (4).

Vela Giro, A. (2007). Bank protection at the outer side of curved channels by an undulated concrete wall. Communication No 28, Laboratory of Hydraulic Constructions (LCH), Ed. A. Schleiss. École Polytechnique Fédérale de Lausanne.

Williams, R. (1899). Flussbefestigungen erläutert an einer Flussstrecke der weissen Elster sowie Beispiele zur Nachprüfung der Fargue'schen Gesetze mit Hilfe der Stossflächen. Leipzig: Verlag Wilhelm Engelmann.