Effect of adjustable flaps on river surf waves at abrupt drops

EFFECT OF ADJUSTABLE FLAPS ON RIVER SURF WAVES AT ABRUPT DROPS

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ABSTRACT

Surfing is a popular water sport in regions with ocean access. In countries without ocean access, standing river waves occurring in flood situations are often employed for surfing. The hydraulic conditions involving high flow velocities and large recirculation zones then impose a risk of injury to the surfers. As an alternative, artificial surf wave conditions are provided at a number of river locations in Europe and worldwide. In most locations, a wave-type hydraulic jump is generated at a bottom drop. Based on the experiences with those engineered surf waves, adjustable installations demonstrate a positive effect on the surf wave characteristics.

Physical laboratory experiments were conducted to quantify the effect of adjustable flaps on the generated wave characteristics at abrupt bottom drops. Whereas the wave-jump at a plain bottom drop without flap is very sensitive to the tailwater flow depth, adjustable flaps prevent the change of flow type from the favored wave-jump to non-surfable conditions for a wider range of downstream flow depths. Depending on the approach flow conditions, flaps significantly increase the wave height. However, adjustable flaps may also implicate additional limitations to the parameter range. Flaps with a small angle led to a wave height reduction, as compared to the plain bottom drop without flap. This paper details the above descriptions, and selected wave-type flow features are discussed. The research thus contributes to the general process understanding of surfable river waves and safer surf conditions, as compared to the common use of standing waves in rivers at flood situations.

Keywords: Flow separation zone, Physical modelling, River surfing, Wave type flow, Wave-jump

1 INTRODUCTION

Surfing is a popular water sport in regions with ocean access. Windsurfers use a sail to convert kinetic wind energy into board motion on the water, for which favorable wind conditions are necessary. For wave riding, the local sea bathymetry is important in addition to wind conditions. The incoming ocean waves, usually generated in a distant wind region, propagate to the shore and are subject to shoaling, as the still water depth continuously reduces. The wavelength then decreases, whereas the wave height increases. The wave steepness as the ratio between wave height and wavelength therefore increases leading to wave breaking at the shore. Particularly spilling and plunging type breakers are favorable for ocean surfing. The optimum wave riding conditions depend on the combination of favorable incoming wave characteristics, and the local sea bottom features, such that worldwide surf spots are limited.

In landlocked countries without ocean access, surfers commonly use standing waves in rivers mostly during flood events. Due to the then high flow velocities and additional floating debris, this might be risky, especially for untrained beginners. Downstream of sills or drops, a dangerous plunging jet can establish, also known as a so-called ‘drowning machine’. The recirculation zone is difficult to detect by eye, can have a large expansion, and may drag objects and persons back toward the structure and thus into the plunging jet zone. Surfers may be trapped at the jet, as they are hardly able to rescue themselves by own effort. In addition, the strong air entrainment decreases the water buoyancy, thereby complicating the situation for victims. In June 2008, such a drowning machine caused a rubber boat to capsize at Kander River in Switzerland during a military exercise, thereby leading to five fatalities (Swiss Army, 2008).

At Eisbach River in Munich, Germany, a standing wave at a bottom drop is used intensively for river surfing since the 1980s (Fig. 1a). The standing wave occurs coincidentally due to the combination of given up- and downstream flow characteristics, and the riverbed geometry. The wave properties were further optimized by installing a flow deflector on the riverbed. Based on the successful surf wave at Eisbach River, a number of river surfing initiatives were established for other locations. In Switzerland, these initiatives concentrate on the Reuss River near Lucerne, the Limmat River near Zurich, the Aare River in Berne, or the Aare River in Bremgarten (Dietsche, 2015). Installations to the riverbed aim to create controlled surfable river waves available throughout the entire year without any risk for wave riders. Some projects such as the surf waves at Almkanal (Fig. 1b, c) in Salzburg, Austria, or at Cunovo, Slovakia, were successful. Their adjustable installations to control upstream flow conditions proved advantageous. In contrast, the surf wave planned at the river mouth of Sill River in Innsbruck, Austria, does not develop satisfying surf wave properties. The river mouth discharging into the Inn River in Innsbruck, Austria, was reconstructed in 2012 to generate a surf wave. The channel is divided into an ecologically valuable block ramp, and a concrete sill without flap or flow deflector, at which the surfable hydraulic jump was planned. At this location, the tailwater flow depth is directly controlled by the Inn River with natural flow depth fluctuations and fluctuations caused by downstream hydropower plant operation. For decreasing downstream flow depth, the designed wave-type hydraulic jump becomes unstable and collapses, thereby changing into a not-surfable plunging jet. The site access is restricted by local authorities due to dangerous hydraulic conditions.

In 2013, 2014, and 2016, the Bayerische Ingenieurekammer-Bau ("Bavarian Chamber of Civil Engineers") together with Workshop Wellentechnik ("Workshop wave engineering") organized a forum for ≈100 participants. With presentations and exhibitions, these events served as a platform for both responsible authorities and river wave initiatives to discuss various perspectives of planned European river surf waves.

In contrast to river surfing during flood events, artificial river waves can be utilized throughout the entire year and without particular risk for surfers. However, a number of hydraulic, ecologic, and legal constraints need to be respected. Due to the often vague legal situation, local authorities or owners of hydropower plants disclaim liability. In addition, usage restrictions may arise during fish migration periods, given the wave project is located in the main channel of a fish habitat. Transverse structures including sills or weirs may lead to sediment discontinuity with upstream deposition and downstream erosion. Changes in the sediment continuum may have negative effects on the hydraulics of river surf waves.

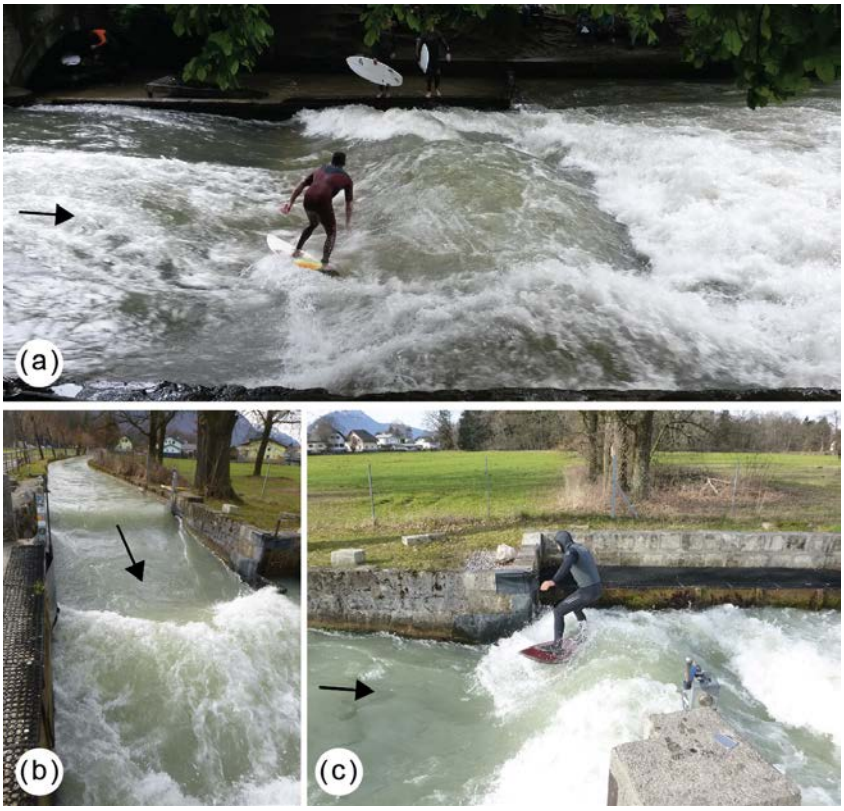

Figure 1. Surf wave at (a) Eisbach River in Munich, Germany (photo by author), (b) and (c) Almkanal in Salzburg; arrow indicates flow direction (photo by Ingenieurbüro Gostner & Aigner, Wals, Austria).

Surfable river waves are generated by four different basic hydraulic principles: (1) *sheet-flow* on a wave-like bathymetry, (2) generation of a spatial *wave-tube*, (3) plain hydraulic jump at bottom drops, and (4) plain hydraulic jump at bottom drops with additional adjustable installations. A sheet-flow on a wave-like bottom topography (1) is often used in water parks (e.g. Alpamare Pfäffikon, Switzerland), to offer mainly children surfing possibilities using small surfboards without fins on shallow flows (flow depth $h \approx 10$ cm). The Cunovo surf wave at the Danube River close to Bratislava, Slovakia, is based on this principle, but with larger flow depths of $h \approx 40$ cm, thereby compensating variations of the up- and downstream flow conditions (Bauer, 2015). The location is commercially used and a surfing day-pass is offered for ≈10 EUR. Surfers partially reported damaged surfboard fins caused by the small flow depth.

Spatial wave tubes (2) are similar to the collapsing free surface profile of a pronounced plunging wave breaker. They can be generated by relatively large flow deflectors installed at the channel bottom (Hornung and Killen, 1976; Oertel et al., 2012). Due to the increased injury risk and the relatively high installation effort, this wave type is not favored for river surf projects.

The plain hydraulic jump at bottom drops (3) is one of the classic hydraulic phenomena and was therefore widely investigated in the past (e.g. Moore and Morgan, 1957; Rajaratnam and Ortiz, 1977; Hager and Bretz, 1986; Kawagoshi and Hager, 1990; Ohtsu and Yasuda, 1991; Mossa et al., 2003). However, these studies mainly focus on fixing the hydraulic jump within a stilling basin, and to increase energy dissipation. As classified by Moore and Morgan (1957), an A-jump (jump upstream of bottom drop), wave-jump (pronounced wave crest directly downstream of bottom drop) or B-jump (jump downstream of bottom drop) occurs depending on both approach flow Froude number and tailwater flow depth. The wave jump, which is favorable for surf projects, occurs only for a specific combination of approach and tailwater flow conditions and transforms rapidly into a non-surfable A- or B-jump as the downstream flow depth changes.

A plain hydraulic jump involving adjustable installations (4) is a promising method to generate surfable river waves for a wide range of flow parameters. The above described wave characteristics are positively affected by regulating the approach flow conditions. For the surf wave at Almkanal in Salzburg, Austria, a l_k = 0.6 m long flap is installed, which can be adjusted to angles between 0-30° to the horizontal. The approach flow depth is $h_o \approx$ 0.4 m, and the drop height s = 0.725 m (Figs. 1b, c and 2). Similar to regulated gates, e.g. at spillways, the operating personnel needs to be responsible. The wave regulation mechanism can be combined with an adjustable upstream weir to further improve the approach flow conditions (Aufleger et al., 2015).

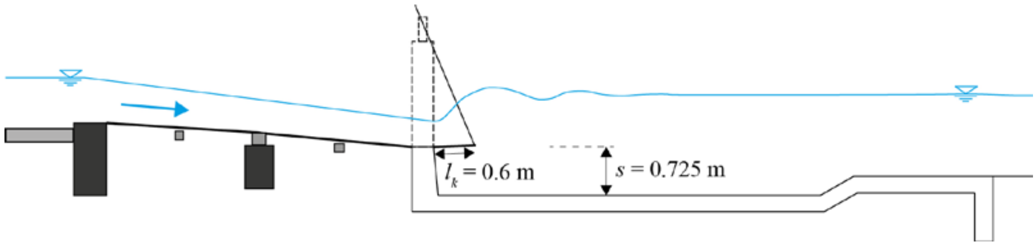

Figure 2. Cross-section of Almkanal surf wave in Salzburg, Austria (adapted from Gostner et al., 2010).

Adjustable flaps at abrupt drops appear promising to optimize existing structures with minimum structural adaptations to obtain surf wave conditions. The generated hydraulic jump is stabilized for varied tailwater flow conditions, thereby leading to safer surf conditions, as compared to the common use of standing waves in rivers at flood situations. Since literature on this configuration does not exist, hydraulic model tests were conducted, investigating the effect of flaps on the wave properties for various down- and upstream flow conditions. Selected experimental results are presented and discussed below.

2 EXPERIMENTAL SETUP

Physical model experiments were conducted in a 6 m long, 0.3 m wide and 0.5 m deep flow channel at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich. Whereas the back wall is made of steel, the channel bottom and front wall are made of glass to enable optical access. Fig. 3 shows a definition sketch with the governing parameters, namely: approach flow depth h_o, approach flow velocity V_o, drop height s, flap length l_k, flap angle κ, downstream flow depth h_u, wave height h_w, as well as wave crest height h_{wb}, and wave crest length L_{wb}. The origin of the horizontal and vertical coordinates (x ,z) is set at the drop toe.

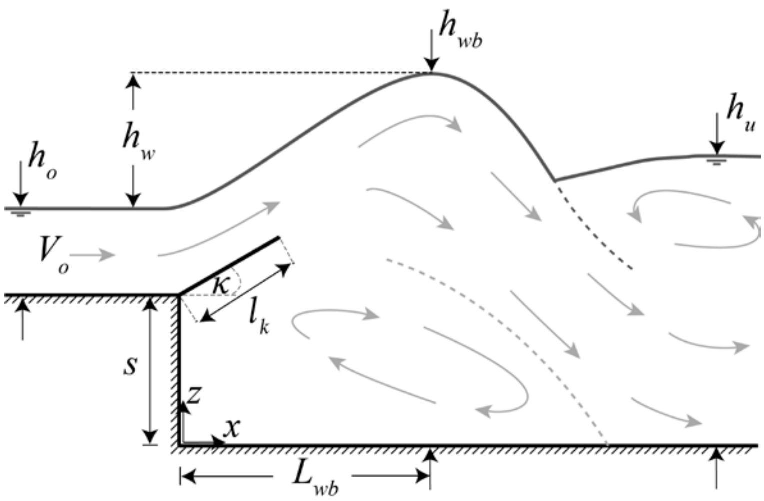

Figure 3. Definition sketch of surf wave at abrupt bottom drop with adjustable flap.

The investigated parameter range is specified in Tab. 1. A jetbox (Schwalt and Hager, 1992) was used to control the inflow conditions with approach flow Froude numbers $F_o = V_o/(gh_o)^{1/2}$ = 2.0 - 4.0, involving g as the gravity acceleration. The downstream flow depth was regulated with a weir at the channel end. Free surface profiles were measured to ±1 mm with a point gauge mounted on a traverse system. For selected parameter combinations, the wave-type flow field was recorded using Particle Image Velocimetry (PIV).

Table 1. Investigated parameter range.

Parameter	Range
Q	20 - 40 l/s
h_o	3.3 - 7.7 cm
F	2.0 - 4.0
s	5 cm, 10 cm
l_k	1.0, 2.5, 5.0 cm
κ	10°, 20°, 30°

3 RESULTS

Favorable surf wave properties are shown in Fig. 4 for Q = 30 l/s, F_o = 3.0, l_k = 2.5 cm, and κ = 30°. Flow features are separated into 4 reaches: (1) supercritical approach flow, (2) surf wave, (3) recirculation zone, and (4) subcritical tailwater. If air is entrained by a surface roller, the water buoyancy reduces, thereby complicating surf maneuvers. Waves with a smooth surface are therefore easier to surf. Based on existing river surf waves, a favorable prototype wave height is h_w = 0.5 - 1.2 m. The subsequent recirculation zone should be separated from the surf wave, and possibly short to diminish the risk of injury. Particularly for long recirculation zones, fallen surfers may be unable to rescue themselves. Again, aeration may lead to decreased buoyancy, and thus a complicated situation for victims to emerge from the water. In the subcritical tailwater region, the turbulence reduces, leading to air detrainment.

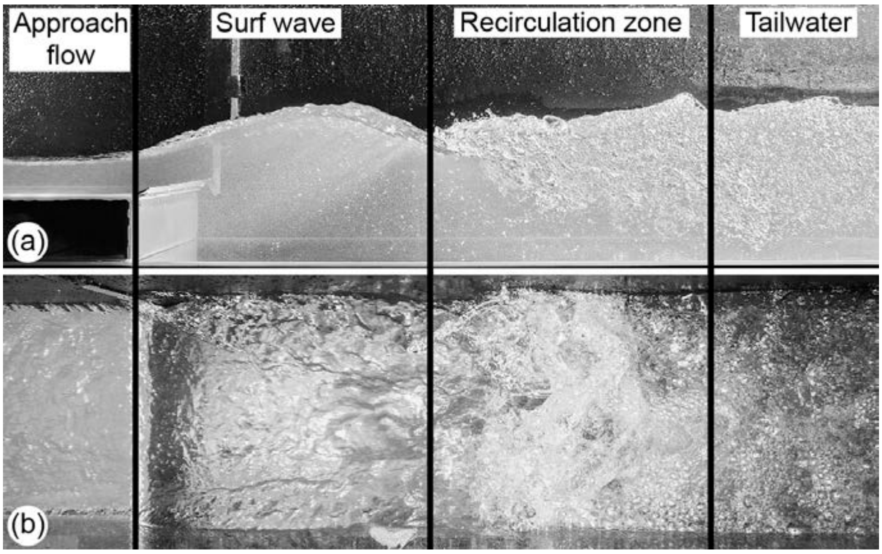

Figure 4. Favored surf wave properties for Q = 30 l/s, F_o = 3.0, l_k = 2.5 cm, with four characteristic reaches in (a) side view and (b) top view.

The maximum wave height occurred for Q = 40 l/s, F_o = 4.0, l_k = 5.0 cm, and κ = 30° (Fig. 5). This wave-type flow condition is considered unfavorable due to the strong air entrainment caused by high turbulence, and the large extension of the recirculation zone.

As a major benefit, adjustable flaps demonstrated a stabilizing effect on the surf wave for decreasing tailwater flow depths. Given a reference configuration of a bottom drop without flap and F = 2.5, the wave-type flow changes into a (non-surfable) undulating jump for a reduction of the downstream water depth by only 2.5%. In contrast, an installed flap of l_k = 2.5 cm and κ = 20° maintains a surfable wave-type flow.

Figure 5. Maximum wave height with $h_w \approx$ 23 cm for Q = 40 l/s, F_o = 4.0, l_k = 5.0 cm, and κ = 30°.

The free surface profiles of surf waves for Q = 30 l/s, F_o = 3.0, l_k = 5.0 cm are shown in Fig. 6 for different flap angles κ = 30°, 20°, 10°, and the reference geometry without a flap. The maximum wave height h_w = 0.18 m is generated if κ = 30°, and reduces to h_w = 0.15 m (κ = 20°), h_w = 0.126 m (κ = 10°), and h_w = 0.14 m (no flap), respectively. A long flap with a high angle therefore increases h_w by ≈29%, whereas for a flat angle the flow attaches to the flap and deflects downward, leading to wave height reduction by ≈−10%.

The effect of the flap length on the free surface profiles of the surf wave is shown in Fig. 7 for Q = 30 l/s, F_o = 3.0, and both κ = 10° and 30°. Given a flat angle of κ = 10°, the flap length has no significant effect on the free surface profile, however, wave heights generated at the drop with flap are smaller as compared to a simple drop without flap (Fig. 7a). Given a large flap angle of κ = 30°, h_w increases by ≈29% (l_k = 5.0 cm, h_w = 0.18 m) and ≈16% (l_k = 2.5 cm, h_w = 0.162 m) as compared to the plain drop without a flap. Note that the free surface profile generated for l_k = 1 cm is identical to those generated by the drop without a flap.

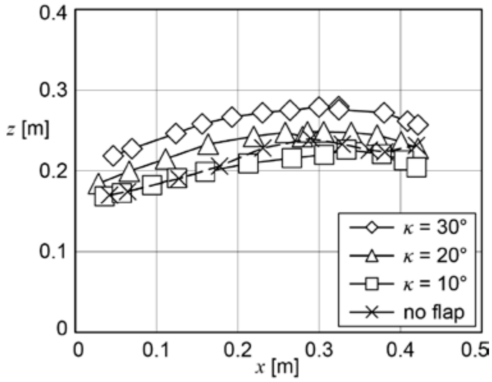

Figure 6. Free surface profiles $z(x)$ of surf wave for Q = 30 l/s, F_o = 3.0, and l_k = 5.0 cm.

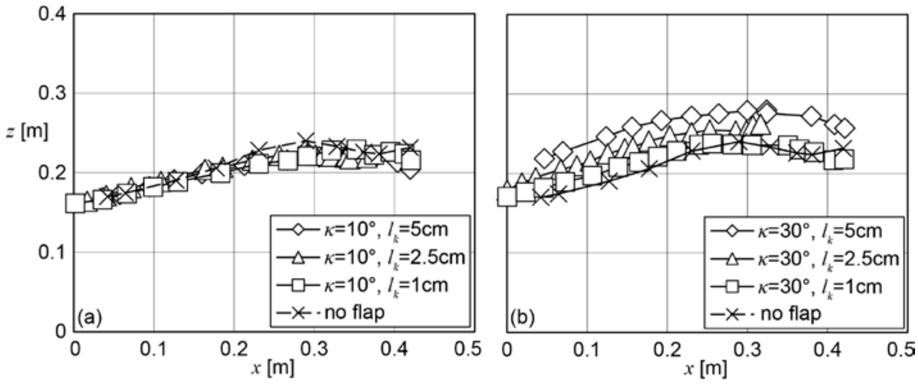

Figure 7. Free surface profiles $z(x)$ of surf wave for Q = 30 l/s, F_o = 3.0 with (a) κ = 10° and (b) κ = 30°.

4 PIV MEASUREMENTS

The flow field downstream of the bottom drop was recorded using Particle Image Velocimetry (PIV) for selected test conditions. Polyamide particles of 1.03 g/cm^3 density and a mean diameter of 5-35 µm were used as seeding material. The particles were illuminated using a Litron-DualPower 200-15 with a pulse rate of 15 Hz at a wavelength of 532 nm, and an energy per pulse of 2 x 200 mJ. The laser beam was coupled into a laser-guiding arm and led underneath the channel bottom. A cylinder lens was used to create the vertical light sheet along the flume axis. Images were captured using a Dantec 2 MP FlowSense camera of 1200 x 1600 pixels (V:H) resolution. The corresponding field of view was ≈ 300 mm x 400 mm (V:H). The correlation grid size of 32 x 32 pixels resulted in a spatial vector resolution of ≈ 4.15 mm x 4.15 mm.

The hydraulic jump generated at an abrupt bottom drop was characterized by strong turbulence and pronounced vortex formation, resulting in a continuously changing flow field. For a meaningful comparison of the flow field for different parameter combinations, the temporal average was created from 75 double frames, corresponding to 5 s of flow. The flow field at an abrupt bottom drop is shown in Fig. 8 for F_o = 3.0, h_o = 4.8 cm, and l_k = 5 cm with different flap angles (a) κ = 30°, (b) κ = 20°, (c) κ = 10° as well as (d) without flap. The main approach flow (dark grey) aligns to the flap and is deflected with the flap angle. For a large flap angle κ = 30°, the approach flow is significantly deflected upwards at x ≈ 50 mm, but orientates back downward to the channel bottom for x ≈ 250 mm (Fig. 8a). Given a small flap angle (Fig. 8c), the approach flow is deflected almost horizontally, resulting in a smaller wave height as compared to the plain bottom drop without flap (Fig. 8d). The corresponding free surface profile is therefore flat and not suitable for surfing.

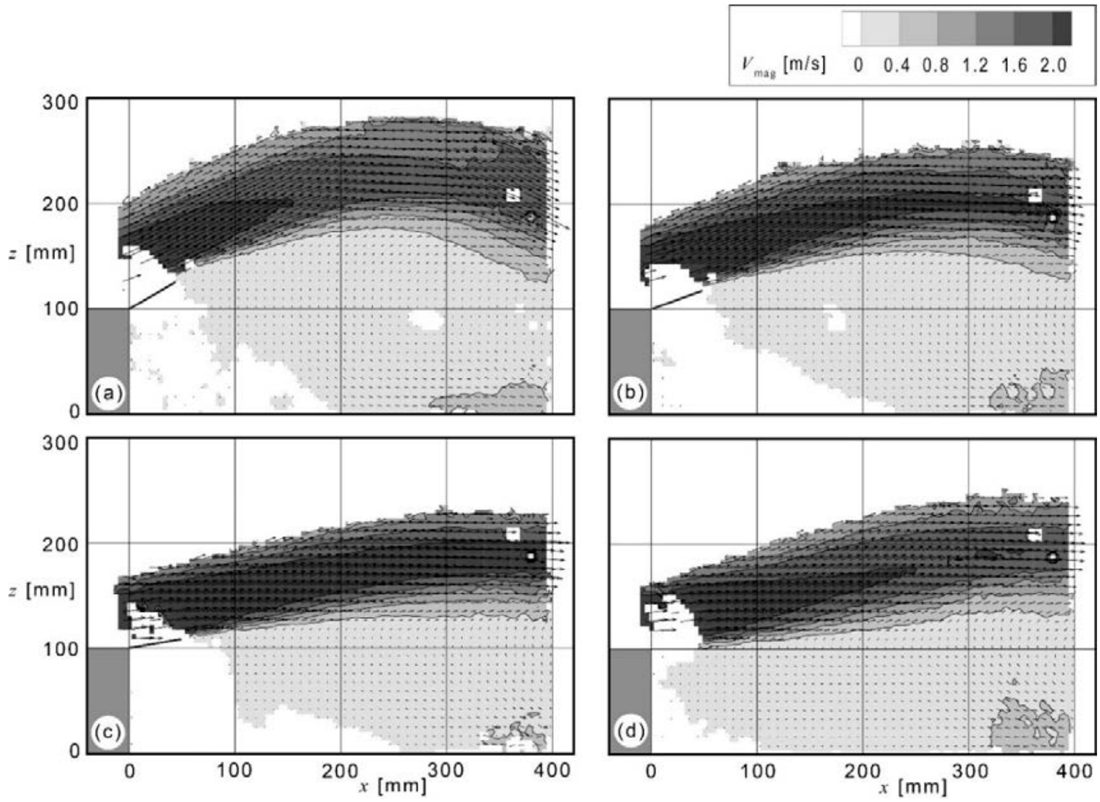

Figure 8. Flow field at abrupt bottom drop for F_o = 3.0, h_o = 4.8 cm, and l_k = 5 cm with (a) κ = 30°, (b) κ = 20°, (c) κ = 10°, and (d) without flap.

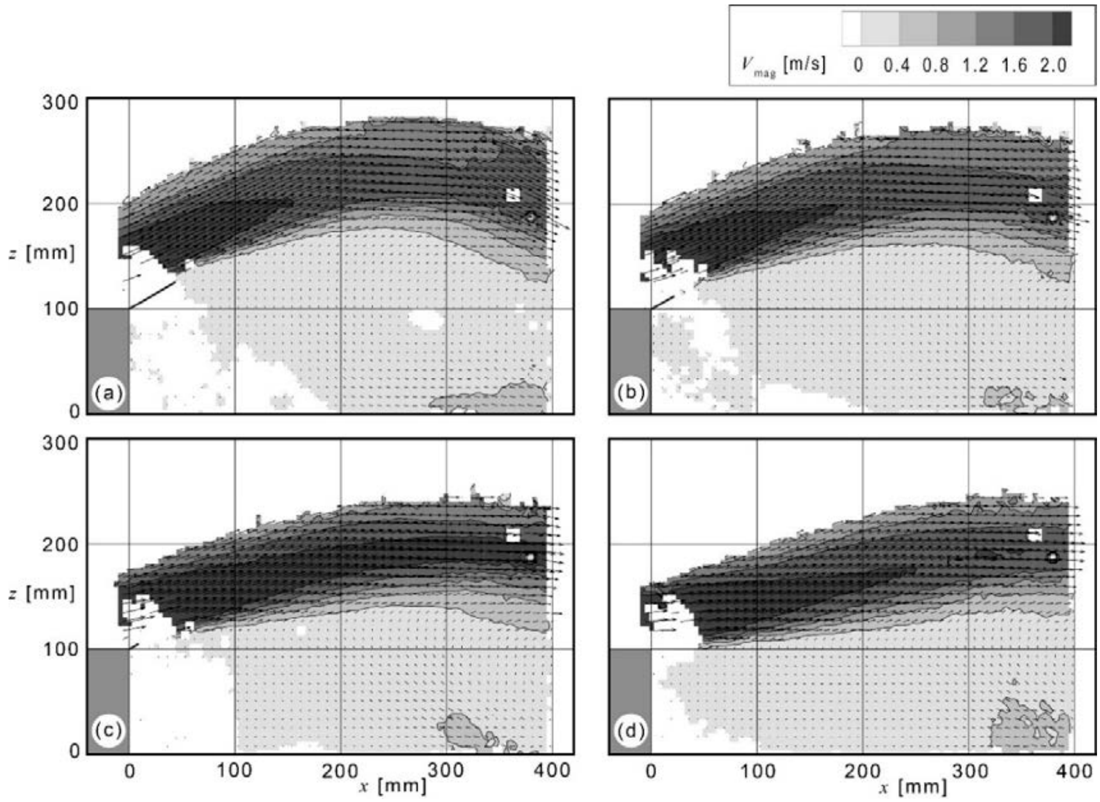

Figure 9. Flow field at abrupt bottom drop for F_o = 3.0, h_o = 4.8 cm, and κ = 30° with (a) l_k = 5 cm, (b) l_k = 2.5 cm, (c) l_k = 1 cm, and (d) without flap.

Fig. 9 shows the flow field at an abrupt bottom drop for F_o = 3.0, h_o = 4.8 cm, and κ = 30° with different flap lengths (a) l_k = 5 cm, (b) l_k = 2.5 cm, (c) l_k = 1 cm as well as (d) without flap. For all three configurations involving a flap, the main approach flow is deflected upwards at $x \approx 50$ mm. As described above, the flow orientates back downward to the channel bottom at $x \approx 250$ mm. Longer flap lengths thereby result in stronger flow deflection. A short flap with a large flap angle (l_k = 1 cm, κ = 30°) therefore generates a flatter free surface profile as compared to the plain bottom drop without flap (Figs. 9c,d).

5 CONCLUSIONS

Only sparse literature exists on the hydraulics of river surf waves at abrupt drops. However, experiences at existing river surf wave locations demonstrate a positive effect of adjustable installations on the generated wave characteristics. Physical model tests conducted at VAW laboratory confirmed that both wave height and steepness, as the important surf wave characteristics, are affected by a flap. Given an approach flow Froude Number of F_o = 3.0, the wave height can increase by ≈30% using a long flap with a large flap angle (κ = 30°), as compared to a plain bottom drop without a flap.

Longer flaps have their potentially positive effect on the surf wave characteristics for a wider range of approach flow and tailwater conditions. However, adjustable flaps also implicate potential limitations: on the one hand, a hydraulic jump can be generated upstream of the bottom drop (A-jump) given the approach flow Froude number is small. On the other hand, flaps with a small angle can deflect the main approach flow downwards, thereby decreasing the targeted wave height as compared to a plain bottom drop without flap. Given large approach flow Froude numbers, the long flaps with a large flap angle may have similarities to a ski-jump, leading to a pronounced wave-jump with large air entrainment, and thus an irregular surface profile. The wave is then difficult to surf and can be dangerous for fallen surfers due to the large recirculation zone.

Additional model tests are necessary to extensively quantify the effect of adjustable flaps on the surf wave characteristics. The effect of the bottom geometry is considered important, but not yet investigated. Therefore, in future experiments, the bottom drop height will be varied in a wider range, and a sloped bottom ramp will be involved instead of the abrupt vertical drop.

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