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Comparative study on the influence of trajectory bucket geometry on energy dissipation downstream of ski-jump spillways

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Ski-jump spillways redirect floodwater using a trajectory bucket to ensure the jet impinges the plunge pool at a predetermined impact location that avoids adverse loading on the dam foundation. While energy dissipation primarily occurs in the plunge pool, the high erosive power of a compact jet can induce significant scour damage to the pool bottom. To mitigate this, innovative trajectory bucket designs featuring splitter teeth or a central insert have been explored. A 1:25 scale model study was conducted to compare two trajectory bucket variations with a conventional design, assessing their impact on energy dissipation downstream of a ski-jump spillway. Both modified configurations outperformed the conventional design, with the splitter teeth design demonstrating superior performance in energy dissipation and reducing scour potential.

Keywords: trajectory bucket, energy dissipation, ski-jump spillway, jet trajectory geometry, dynamic impact pressures, impact velocities

INTRODUCTION

Ski-jump spillways as an energy dissipator

Ski-jump spillways provide an economical solution for energy dissipation on high-head dams. Originating in France, the design was originally developed to accommodate the installation of a spillway and hydroelectric power plant in deep and narrow rivers where space constraints precluded separate structures (Elevatorski 1959). The ski-jump conveys high-velocity flow from the reservoir down the spillway chute, where it is then deflected into the atmosphere by a trajectory bucket. This creates a free-trajectory jet that is projected away from the dam's foundation, eventually impacting the downstream plunge pool.

As the high-velocity jet travels through the atmosphere, it undergoes air entrainment and disintegration before impinging on the plunge pool water surface, where most of its energy is dissipated through jet diffusion (Khatsuria 2004). According

to Khatsuria (2004), air entrainment and jet disintegration have a minimal effect on the energy dissipation of ski-jump jets. Therefore, the jet may retain a compact core upon impact, preserving the erosive power of the jet and potentially causing significant scour in the plunge pool (Lewis *et al* 1999). A well-documented example of severe plunge pool scour occurred at the Wivenhoe Dam on the Brisbane River in Australia during the January 2011 flood event. Jet-induced erosion removed large volumes of rock from the plunge pool, generating boulders up to the size of a bus (1200 t), extending the scour hole by more than 40 m and to depths approaching one-third of the dam height, highlighting the potential risk to plunge pool stability and spillway safety (Bollaert *et al* 2015).

To enhance air entrainment and jet disintegration during the jet's free-fall, and thereby mitigate the scour potential, this research hypothesises that increasing the turbulence intensity at take-off is an effective strategy. This can be achieved by modifying the trajectory bucket design,

incorporating elements such as splitter teeth or an insert (Novak & Čábelka 1981).

Objective of the study

Understanding scour behaviour downstream of a dam's spillway and assessing the extent of scour hole formation is pivotal for ensuring dam safety and abutment stability (Bollaert 2002; Annandale 2006). This study investigated how the use of trajectory buckets, designed to enhance air entrainment during free fall, can effectively reduce dynamic impact pressures and impact velocities, thereby mitigating plunge pool scour while maintaining an optimal jet trajectory that safeguards the dam and its foundation.

The main objective of the study was to compare the energy dissipation performance of a conventional circular-shaped trajectory bucket with those incorporating splitter teeth or an insert. The scope of the investigation was therefore limited to the optimisation of trajectory (flip) bucket designs for high-head spillways where a free-falling jet and plunge pool are required as part of the energy dissipation strategy. A configuration without a trajectory bucket was not considered, as this would represent a fundamentally different spillway concept with distinct flow regimes and design objectives, such as hydraulic jump formation or stilling basin dissipation. To achieve this objective, physical hydraulic model tests were conducted in the hydraulic laboratory of the Civil Engineering Department of Stellenbosch University. The study assessed the geometric jet trajectory parameters, analysed the dynamic impact pressures and pressure distribution in the plunge pool, and evaluated the jet velocities at impact.

RELEVANT LITERATURE

Energy dissipation in ski-jump spillways

The energy dissipation process along a ski-jump spillway can be divided into five distinct phases, as illustrated in Figure 2. The first three phases – (1) self-aeration on the spillway chute, (2) air entrainment and jet disintegration during free fall, and (3) jet diffusion upon impact with the downstream plunge pool water surface – are the primary stages where energy dissipation occurs (Novak *et al* 2004). Among these, phase 1 contributes minimally to overall energy dissipation, and only about 12% of the total energy is dissipated within the

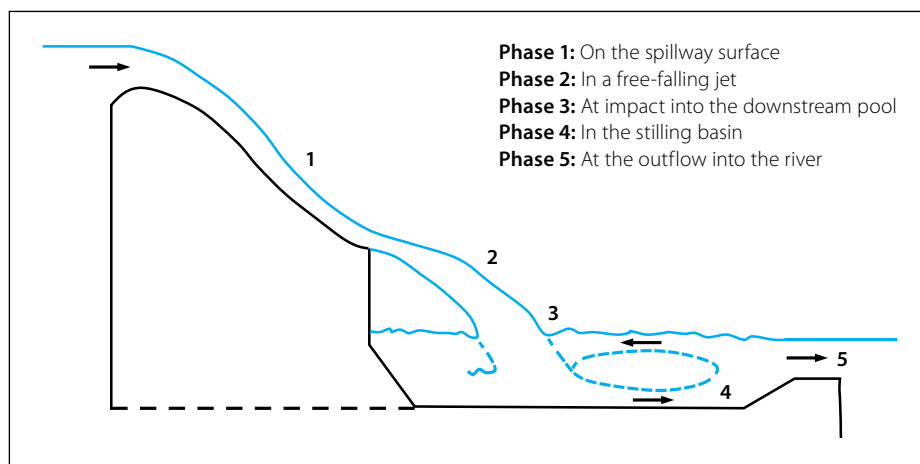


Figure 1 Energy dissipation phases on a spillway (adapted from Novak *et al* 2004)

free-falling jet during phase 2 (Novak *et al* 2004). Most energy dissipation occurs in phase 3, where the jet impacts the plunge pool water surface, leading to high turbulence and compression of air bubbles. Although phase 2 (free falling) contributes less to overall energy loss, its effectiveness can be enhanced by increasing jet dispersion and promoting greater aeration before the jet reaches the plunge pool. This, in turn, improves the dissipation efficiency upon impact.

Energy dissipation by air entrainment

As the water leaves the terminal structure of a ski-jump spillway, it forms a free-trajectory jet that travels through the atmosphere. During this flight, air resistance alters the jet's physical characteristics, promoting several important behaviours, such as lateral expansion, progressive deformation, and, with sufficient fall height, jet breakup (Ervine & Falvey 1987). A key factor in this process is the initial turbulence intensity of the jet, which governs both the rate of inner core decay and the degree of lateral spreading. As the inner core decays, the jet becomes increasingly aerated, eventually breaking apart into smaller, less cohesive masses of water (Ervine & Falvey 1987). To enhance air entrainment during phase 2 of the energy dissipation process (refer to Figure 1), the trajectory bucket can be modified with splitter teeth. These features subdivide the main jet into multiple coherent sub-jets, increasing surface area and promoting earlier and more effective aeration (Novak *et al* 2004).

Energy dissipation by jet disintegration

Jet disintegration occurs in two distinct forms: primary and secondary. Primary jet

disintegration results from the combined effects of turbulence and gravity on the jet itself, while secondary jet disintegration arises from the aerodynamic interactions that cause water bodies to separate from the main jet (Pfister *et al* 2014).

When a jet particle has sufficient kinetic energy to overcome the surface tension's restraining force, turbulent surface fluctuations can penetrate the jet core. This penetration accelerates jet breakup, transforming from a solid core of non-aerated water surrounded by a shell of aerated water, into a conglomeration of individual water droplets (Lewis *et al* 1999).

A jet plunging through the air can be categorised into an undeveloped jet region and developed jet region. Jets in the undeveloped region undergo primary jet disintegration under gravity and turbulence, while in the developed region, secondary disintegration occurs due to aerodynamic interactions, such as air drag. As the jet descends through the air, the density of the air-water mixture within it decreases while its interaction with the surrounding air increases. This results in a larger jet footprint upon impinging the plunge pool. The decreased density significantly reduces the erosive power of the jet on a loose riverbed (Pfister & Schleiss 2015).

Trajectory bucket types to enhance jet disintegration

To increase the initial turbulence intensity and enhance air entrainment and jet disintegration, the transversal geometry of the trajectory bucket can be modified. Two common modifications are the inclusion of a local central insert or splitter teeth at the take-off point (Pfister & Schleiss 2015). These design features have been successfully applied at various dams, including the Chastang Dam in France, and Slapy

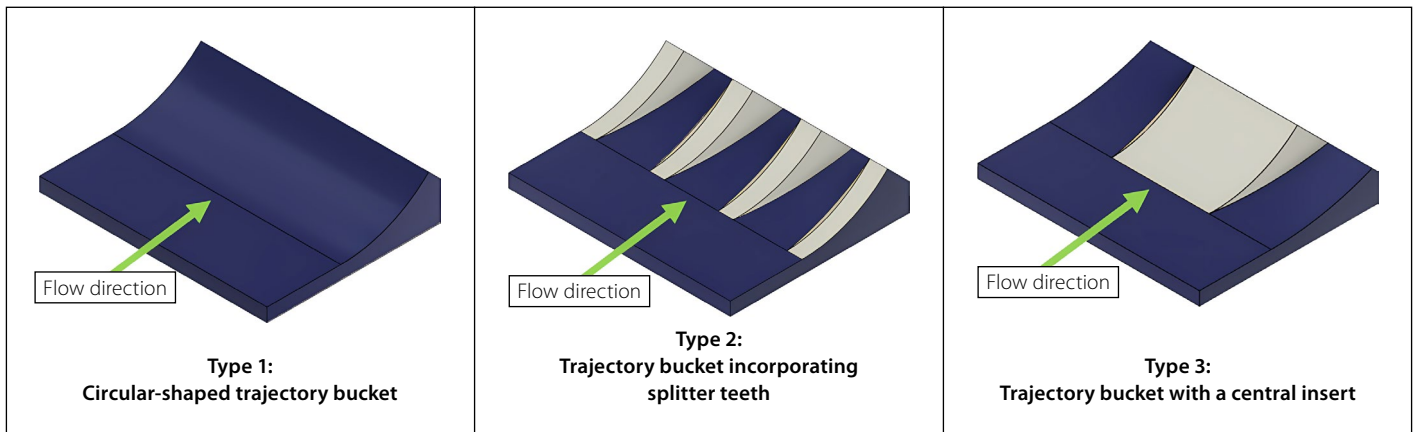


Figure 2 Trajectory bucket types used in the present study

and Orlik Dams in the Czech Republic, to improve energy dissipation performance (Vischer & Hager 1995).

Physical modelling has often been employed in previous studies to optimise the geometric design and configuration of the trajectory bucket. However, despite several case studies, there is still a lack of comprehensive design guidelines concerning trajectory buckets with splitter teeth or insert configurations. One of the few structured contributions is that of Chengyi (1988), who investigated a range of bucket types on overflow arch dams and proposed foundational design principles. These principles provide useful preliminary guidance for the design of splitter-tooth trajectory buckets but do not yet constitute a complete design framework for modern applications.

Based on the mechanisms identified in the literature – namely jet disintegration,

air entrainment, and pressure attenuation – a physical hydraulic model was developed to systematically evaluate how modifications to trajectory bucket geometry influence jet behaviour and plunge pool loading.

HYDRAULIC MODEL

Scope of hydraulic model

A physical hydraulic model of a ski-jump energy dissipator was constructed at a 1:25 scale. This scale was chosen to limit scaling-induced distortions while accommodating the practical limitations of various measurement instruments, as well as the available space in the laboratory. The physical model was designed using Froude similitude, because gravitational and inertial forces dominate the motion of the free

surface flow. Additionally, the Reynolds (viscosity) and Weber (surface tension) numbers were sufficiently large to mitigate any scale effects resulting from discrepancies between the model and prototype.

The model featured three configurations of trajectory buckets (Figure 2):

1. **Type 1:** A control model with a conventional circular-shaped trajectory bucket (Type 1), designed according to existing guidelines on ski-jump hydraulics.
2. **Type 2:** A trajectory bucket incorporating splitter teeth (Type 2), designed following guidelines recommended by Chengyi (1988).
3. **Type 3:** A trajectory bucket with a central insert that combines elements of both the Type 1 and Type 2 designs.

The general layout of the pipe system used to convey water to the hydraulic model is shown in Figure 3. To evaluate the

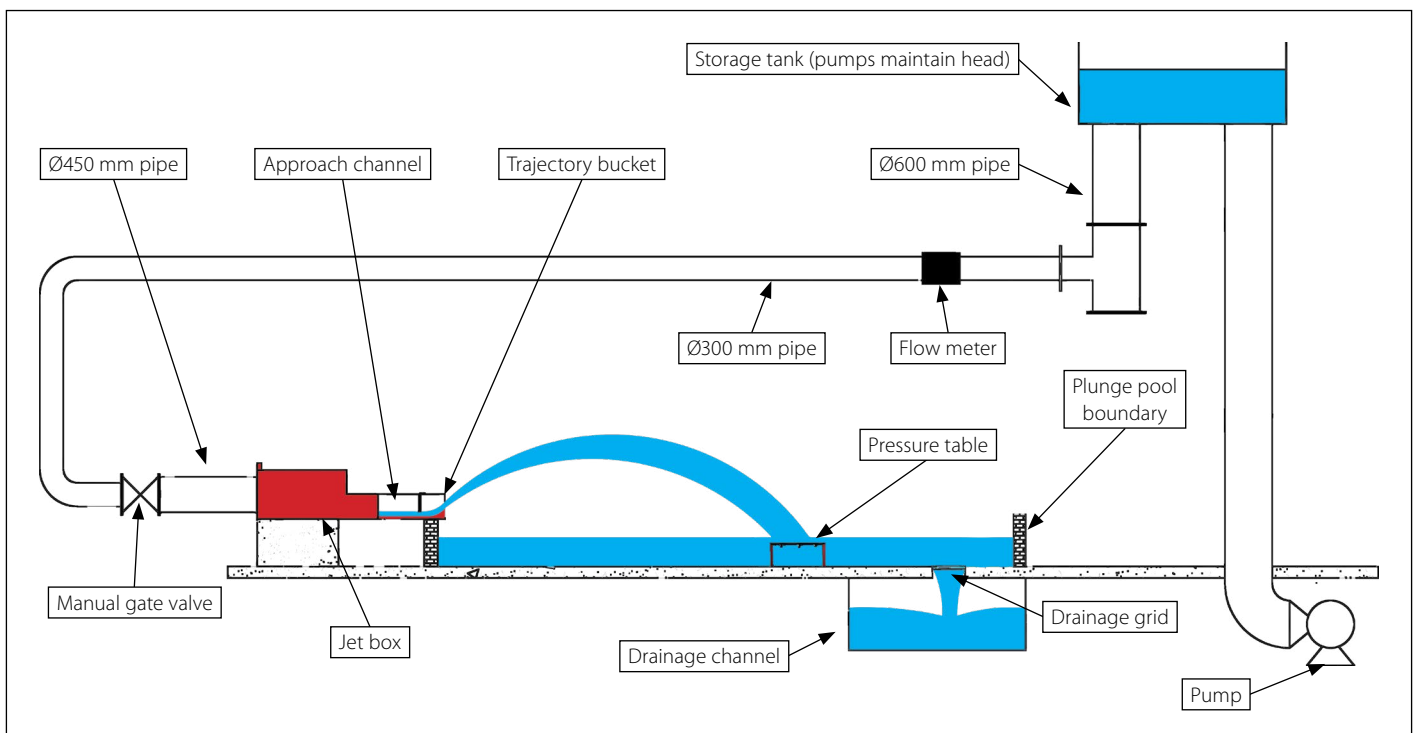


Figure 3 General layout of pipe system and hydraulic model

effectiveness of each bucket configuration in maximising energy dissipation, jet trajectory characteristics and dynamic impact pressures were measured and compared using a pressure table.

Design and construction

General parameters

The prototype was designed with a unit discharge (q_d) of 50 m³/s/m, based on Fraser’s (2016) recommendation for ski-jump spillways. An ogee spillway served as the control structure, with a total head above the ski-jump bucket invert (H_s) of 97 m and a crest length (L_c) of 12.5 m (as indicated on Figure 6). This setup yielded a prototype design discharge (Q_d) of 625 m³/s (model: 200 L/s) and flow depth over the spillway crest (H_o) of 8.24 m (model: 0.33 m), derived using the standard stage-discharge relationship. The difference between the initial velocity upstream of the crest (v_o) relative to the velocity at the bucket (v_b) was found to be negligible. Therefore, the velocity on the bucket (v_b) was calculated with reference to the ski-jump bucket invert, resulting in an approach flow velocity of 43.6 m/s and corresponding flow depth of 1.15 m.

To minimise surface tension effects and ensure the air-water interface of the jet and air entrainment in the downstream water body did not significantly influence the observed behaviour, a sluice-gate control structure (jet box, shown in Figure 3) was employed. This approach allowed a sufficiently large structure to be constructed, facilitating accurate reproduction of ski-jump flow conditions. The jet box with horizontal approach flow was used as a suitable

Table 1 General design parameters for hydraulic model

Parameter	Symbol	Unit	Prototype	Model
Design unit discharge	q_d	m ² /s	50	0.4
Design discharge	Q_d	m ³ /s	625	0.2
Crest length	L_c	m	12.5	0.5
Design flow depth over spillway	H_o	m	8.24	0.33
Head above bucket invert	H_s	m	97	3.88
Approach flow velocity on bucket	v_b	m/s	43.6	8.7
Approach flow depth on bucket	h_b	m	1.15	0.046

Table 2 Trajectory bucket design parameters

Parameter	Symbol	Type 1	Type 2		Type 3	
			Tooth	Slot	Central insert	Slot
Slope angle (°)	θ	0	0	0	0	0
Bucket angle (°)	α	45	45	22.5	45	22.5
Total deflection angle (°)	β	45	45	22.5	45	22.5
Lip termination angle (°)	ϵ	90	90	67.5	90	67.5
Expanding bottom angle of tooth (°)	γ	-	35	-	35	-

control structure to independently vary the approach flow velocities and flow depths for different Froude numbers. This layout was considered adequate for analysing key hydraulic parameters on ski-jump buckets as recommended by Heller *et al* (2005). The general design parameters of the hydraulic model are summarised in Table 1.

Trajectory bucket design

The Type 1 trajectory bucket was designed according to established guidelines for ski-jump hydraulics. The Type 2 trajectory bucket incorporated splitter teeth, following design recommendations of Chengyi (1988).

The Type 3 trajectory bucket integrated features from both Type 1 and Type 2, including a central insert flanked by side slots. Figure 5 illustrates the three trajectory bucket designs tested, while Table 2 summarises the key design parameters. Detailed dimensions of the three trajectory buckets are provided in the appendices.

Test conditions and schedule

The approach flow conditions were varied in terms of discharge and flow depth to model a broad range of flow scenarios expected on a ski-jump spillway. Flow Condition A constitutes the design flow

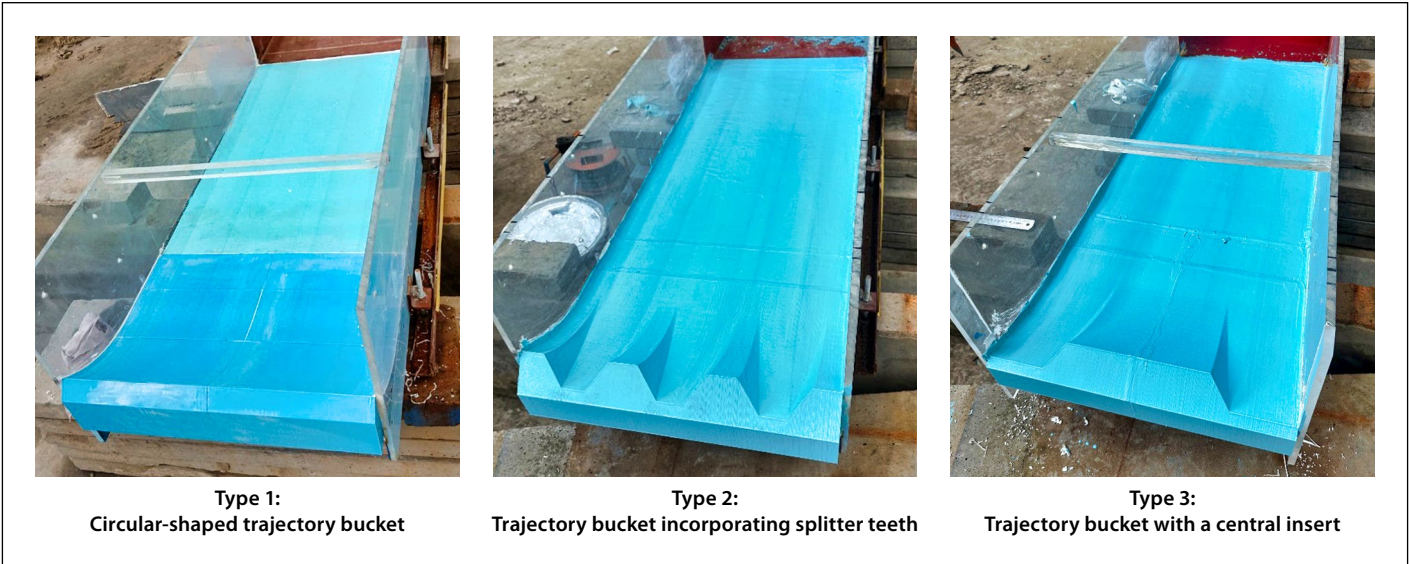


Figure 4 Physical model trajectory bucket designs

Table 3 Summary of flow conditions

Flow Condition	Model				Prototype			
	Fr	h_b (m)	Q (L/s)	v_b (m/s)	Fr	h_b (m)	Q (m ³ /s)	v_b (m/s)
A	13	0.046	200.0	8.7	13	1.15	625.00	43.6
B	8	0.046	123.1	5.4	8	1.15	384.69	26.9
C	10	0.046	153.8	6.7	10	1.15	480.63	33.6
D	8	0.063	200.0	6.3	8	1.59	625.00	31.6
E	10	0.055	200.0	7.3	10	1.37	625.00	36.6

Table 4 Longitudinal and transverse impact footprint characteristics for design flow conditions (prototype values)

Bucket type	Longitudinal impact length (m)	Transverse impact width (m)	Impact footprint area (m ²)
Type 1: Circular-shaped	217	53.49	1 416
Type 2: Splitter teeth	212.36	47.98	5 094.52
Type 3: Central insert	237.63	75.4	4 000

condition for the study, serving as the baseline for all trajectory buckets designed. It was used to evaluate scenarios with both variable discharge and approach flow depth. Flow Conditions B and C maintained a constant design flow depth while varying the discharge. In contrast, Flow Conditions D and E maintained a constant design flow discharge but varied the flow depth. Table 3 summarises the model and prototype values of the flow conditions tested with the trajectory buckets.

Measuring techniques and equipment

The jet trajectory and impact width were surveyed using a total station to determine their three-dimensional coordinates. Pressure transmitters were mounted on a pressure table equipped with small-diameter pipes placed on the model floor, enabling remote measurement of transient water and air pressures. Nine WIKA S-20 pressure transmitters were used to record the static pressures and pressure fluctuations in the plunge pool. The transmitters had a linear working range of –100 mbar to +500 mbar, an accuracy of ±0.2%, and a reading repeatability of ±0.1%. Pressure measurements at the point of impingement were recorded for 5 minutes at a sampling frequency of 100 Hz, yielding 30 000 readings per transmitter. Additional data collected included discharge, water level, and velocity vectors. Velocity measurements were performed using a Nortek Vectrino Acoustic Doppler Velocimeter

with Vectrino+ firmware, allowing collection rates up to 200 Hz. Measurement uncertainty of the various instruments was minimised by repeating tests, using multiple sampling points, utilising different physics to measure the same aspect, and using high-frequency data capture. Water levels were measured with a precision of 0.1 mm, and the velocity to ±1%. Further details regarding the model and its design, construction, setup, data capturing methodology, measurement accuracies, and scaling effects are described in Tessendorf (2024).

Visual observations

Visual observations of the model study helped identify flow patterns and assess hydraulic performance, which can be used to explain and justify the measured results. Figure 5 illustrates these observations, for the design flow condition (Flow Condition A), highlighting differences in flow patterns and hydraulic performance among the tested trajectory buckets.

For the Type 1 jet trajectory, the initial part of the jet exhibited both an upper and lower nappe. However, the jet lost coherence and developed a more aerated core upon impingement. The Type 2 jet, with its splitter teeth, experienced significant jet disintegration closer to the bucket lip, resulting in a highly aerated jet with greater thickness in the longitudinal direction. These splitter teeth also enhanced jet spray along the lower nappe, causing water

particles falling much closer to the bucket lip compared to the Type 1 jet. Notably, the Type 2 jet produced the longest trajectory length among the tested types. The Type 3 trajectory bucket displayed a distinctive jet profile. The larger geometric take-off angle of the central insert produced a longer and higher jet trajectory, while the flatter and shorter jet trajectory was created by the smaller take-off angle of the slots on either side of the insert. Upon impingement, the jet was divided into three well-defined trajectories. Comparing the lateral spread of the jets for the different trajectory buckets, the Type 2 trajectory bucket maintained a more compact transverse profile, whereas the Type 3 bucket exhibited a broader footprint due to the three distinct jet trajectories produced by the central insert. While visual observations (Figure 5) suggest effective breakup of the dense central jet for the Type 3 configuration, the assessment of jet spread in this study is based on measured impact footprint characteristics rather than visual uniformity alone. In the longitudinal direction, the Type 2 trajectory bucket produced the largest impact footprint (Figure 8), indicating a more distributed dissipation of momentum along the plunge pool floor. This increased longitudinal spread is hydraulically significant, as it reduces localised impact pressures and contributes to improved energy dissipation compared to the Type 1 and Type 3 buckets. A quantitative comparison of longitudinal and transverse impact footprint characteristics for the design flow condition is summarised in Table 4. The impact footprint areas were determined from the surveyed footprint perimeters using polygon area calculations, rather than assuming idealised geometric shapes.

Jet trajectories

Calculating the jet trajectory determines the impingement location of the jet in the plunge pool. The relevant parameters used to describe the trajectory geometry are presented in Figure 6.

A limitation of this study was the inability to measure the lower nappe trajectory profile due to safety regulations imposed by the hydraulics laboratory. As a result, only the upper nappe trajectory profiles were recorded, using measurements along the centreline of the jet to capture the maximum trajectory dimensions. The take-off elevation and plunge pool water level were kept constant for all trajectory bucket tests, ensuring consistent



Type 1: Trajectory bucket



Type 2: Trajectory bucket



Type 3: Trajectory bucket

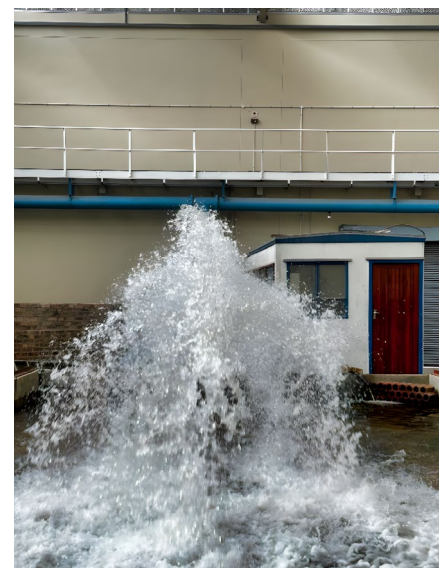


Figure 5 Jet trajectory profile (left) and lateral spread (right) for each trajectory bucket under design flow conditions (Flow Condition A)

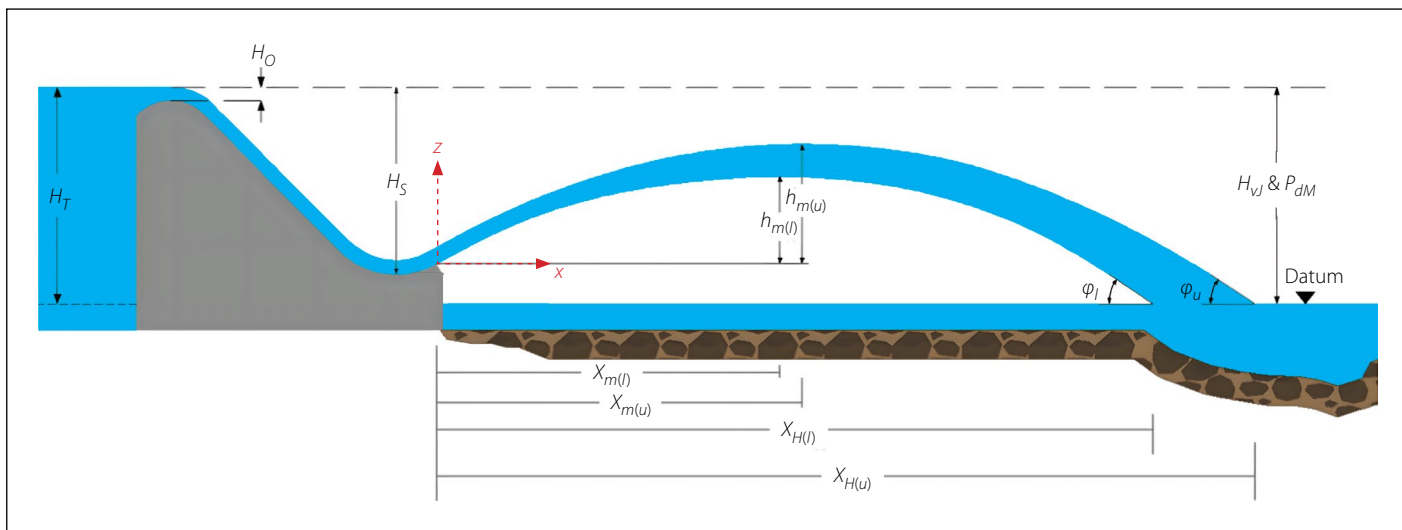


Figure 6 Jet trajectory geometry parameters (adapted from Fraser 2016)

boundary conditions across trajectory bucket types.

Figure 7 demonstrates the jet trajectories of the various bucket types for the design flow condition (Flow Condition A). When comparing the Type 1 and Type 2 jet trajectories under design flow conditions, the results indicate a substantial alteration in jet behaviour. Specifically, the maximum horizontal throw distance decreased by 8.11%, the vertical throw distance decreased by 24.68%, and the impact angle reduced by 14.49%. These reductions indicate that the splitter teeth markedly enhanced breakup and dispersion of the jet, resulting in a shorter and flatter trajectory with a lower impingement angle.

In contrast, the trajectory produced by the Type 3 bucket closely resembled that of Type 1, with only marginal differences. The maximum horizontal throw distance increased slightly by 1.90%, whereas the maximum vertical throw distance decreased by 1.41%. The jet impact angle decreased by 1.81%. This indicates that although the central insert of the Type 3 design altered the jet geometry, its overall trajectory remained similar to the conventional design.

These findings show that Type 2 (splitter teeth) introduced the most substantial changes to the jet trajectory, reducing both the horizontal distance and impact angle, whereas Type 3 (central slot) produced only minor alterations relative to the control. Although longer jet trajectories generally allow increased air entrainment during free fall, in the present study the breakup of the jet core for Type 1 and Type 3 occurred primarily due to air interaction alone, resulting in relatively coherent jets that travelled further but had smaller impact

footprints. In contrast, the splitter teeth of the Type 2 bucket actively disrupted the jet at take-off, promoting early jet disintegration in combination with air entrainment, which produced a substantially larger impact footprint (Figure 8), lower impact pressures, and consequently reduced downstream scour potential.

Jet impact widths

A limitation of this study was that the jet footprint could only be measured at the plunge pool bottom and not at the tailwater level, due to practical constraints. The footprint geometry was surveyed using a calibrated total station by recording the three-dimensional coordinates of the wetted impact perimeter at the plunge pool floor. For consistency, the take-off elevation was kept constant across all tests,

meaning the elevation difference between the bucket invert and the plunge pool bottom was kept constant for each trajectory bucket configuration. To characterise the impact geometry of the jets, the following parameters were measured and analysed:

- X_B : The minimum horizontal distance between bucket lip and the point of jet impact on the plunge pool bottom
- W_j : The longitudinal impact length of the jet footprint (i.e. spread in the direction of flow)
- B_j : The transverse impact width of the jet footprint (i.e. spread perpendicular to the direction of flow)
- γ : transverse jet expansion angle, representing the rate of lateral jet spread during flight.

These parameters provided key insights into how each trajectory bucket design

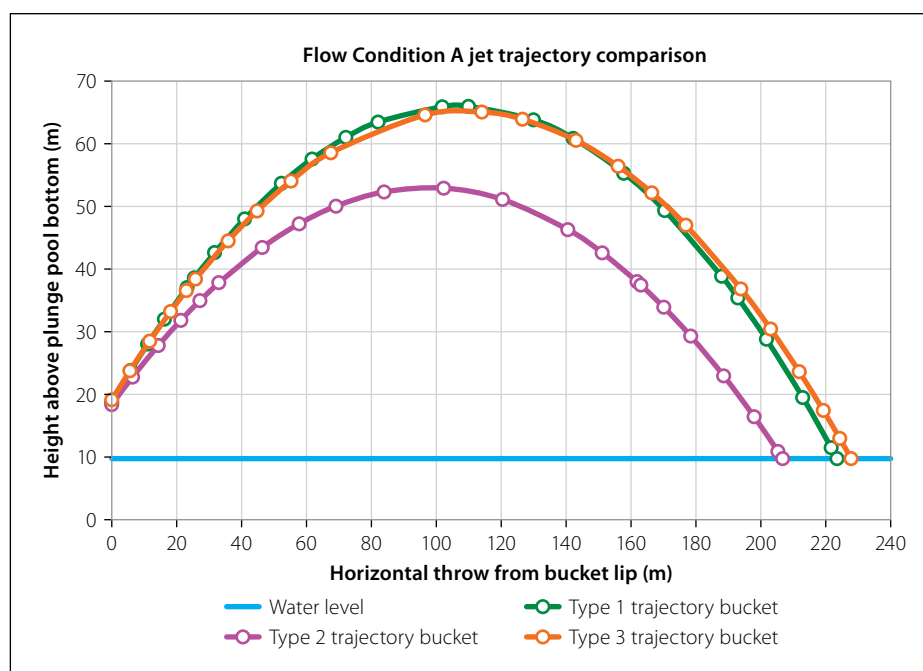


Figure 7 Jet trajectory comparison for Flow Condition A (prototype values)

affected the jet's spread and footprint upon impact, which in turn influences the dynamic pressures and scour potential.

Comparison of jet footprints under design flow condition

The impact jet footprints for the Type 1, Type 2 and Type 3 trajectory buckets were compared under the design flow condition (Flow Condition A). The design flow condition was selected as baseline for evaluating the optimal performance of each bucket in terms of impact footprint characteristics. The respective footprints of the different trajectory buckets for the design flow condition are depicted in Figure 8.

When comparing Type 1 and Type 2, distinct differences in footprint shape and size were observed. The Type 1 bucket produced a compact horseshoe-shaped footprint, while the Type 2 bucket created an elongated diamond shaped footprint. In terms of key parameters, the minimum horizontal distance between the bucket lip and the impact area was 119.57 m for Type 1 and 67.49 m for Type 2. This reduction is consistent with the reduced take-off angle, as the lower take-off angle of the slots along the centreline for Type 2 caused the lower nappe to fall closer to the structure. The longitudinal spread of the jet footprint increased by 48.58% for Type 2 compared to Type 1, indicating a more distributed impact zone in the downstream direction. However, this was accompanied by a 10.08% reduction in the transverse spread, meaning the Type 2 jet remained more confined laterally.

When comparing Type 1 and Type 3 trajectory buckets, both produced a horseshoe-shaped footprint, but the Type 3 trajectory bucket resulted in a significantly larger footprint overall. The jet footprint of the Type 3 trajectory bucket increased in both the longitudinal and transverse directions. The longitudinal and transverse impact widths increased by 74.73% and 41.21%, respectively. While the minimum horizontal distance to the impact area decreased by 43.67%, this did not reduce structural safety margins. The lateral spread of the jet from the side slots ensured that the bucket lip foundation remained protected.

Notably, although the Type 3 footprint had greater width in both directions compared to Type 2, its total surface area was smaller. This is attributed to the horseshoe shape of the Type 3 footprint versus the diamond shape of the Type 2 footprint.

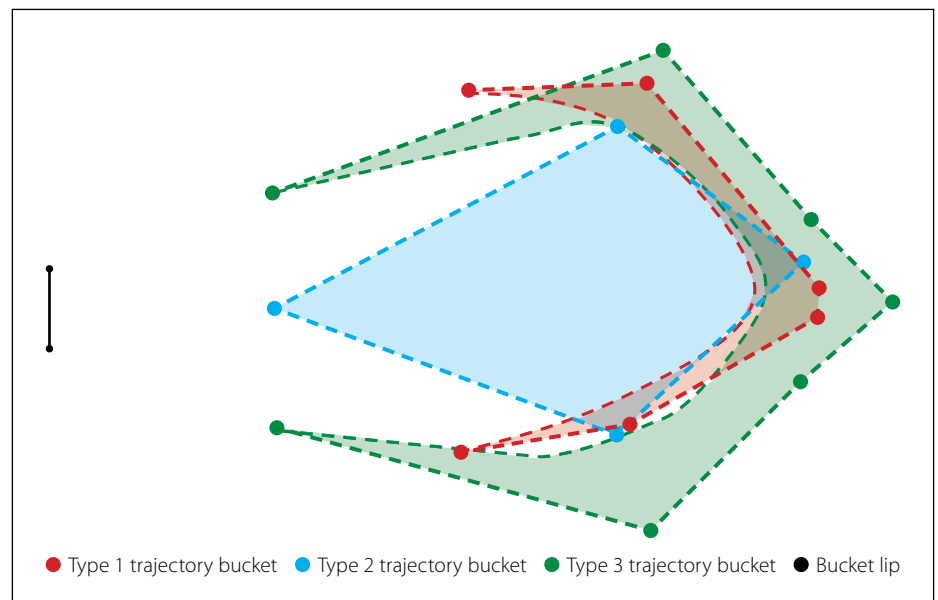


Figure 8 Comparisons of prototype jet footprints for Flow Condition A

The larger surface area of the Type 2 jet footprint suggests that it would result in lower dynamic impact pressures, making it more effective for energy dissipation and scour reduction.

Analysis of transverse jet expansion angle

According to Vischer and Hager (1995), the transverse jet expansion is primarily influenced by two hydraulic factors, namely the bucket flow depth (h_b) relative to the head above the bucket invert (H_s), and the relative unit discharge (q). Figure 9 relates the bucket flow depth relative to the head above the bucket invert (h_b/H_s) to the transverse impact width (B_j) and Figure 10 shows the relationship between

unit discharge (q) and transverse impact width (B_j). Because Flow Conditions B and D share the same Froude number, their relative unit discharge (h_b/H_s) equals 0.031, while Flow Condition C and E share a relative unit discharge, h_b/H_s , of 0.020. From Figure 9, it can be seen that for all three trajectory bucket types, the transverse impact width decreases as the flow depth ratio (h_b/H_s) increased. This indicates that flow depth suppresses lateral jet expansion. Conversely, Figure 10 shows that the transverse impact width increased with increasing relative unit discharge. Additionally, for conditions with equal relative unit discharge values, a lower flow depth ratio (h_b/H_s) still results in wider lateral jet spread.

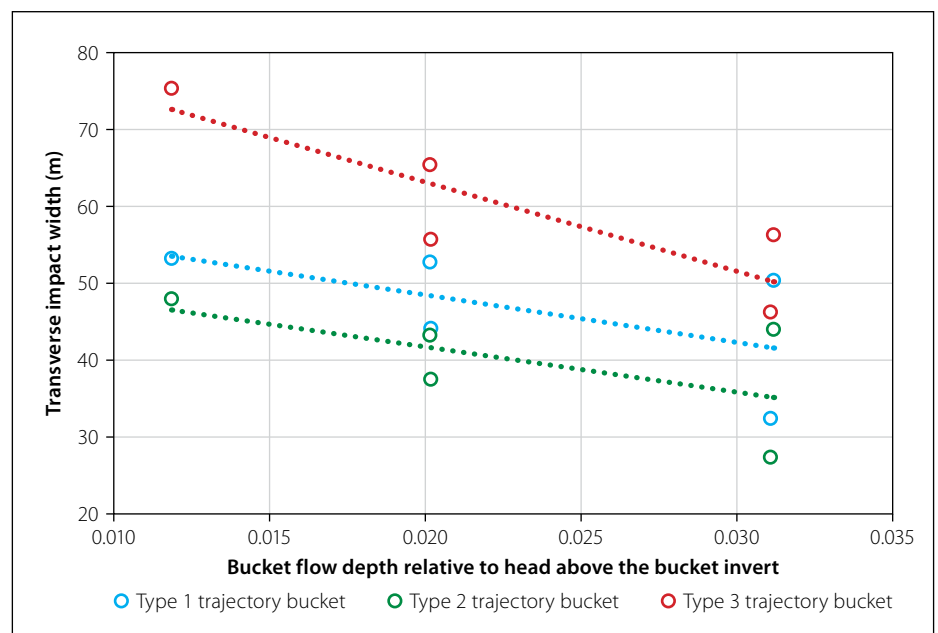


Figure 9 Influence of the bucket flow depth relative to bucket invert head on transverse impact width

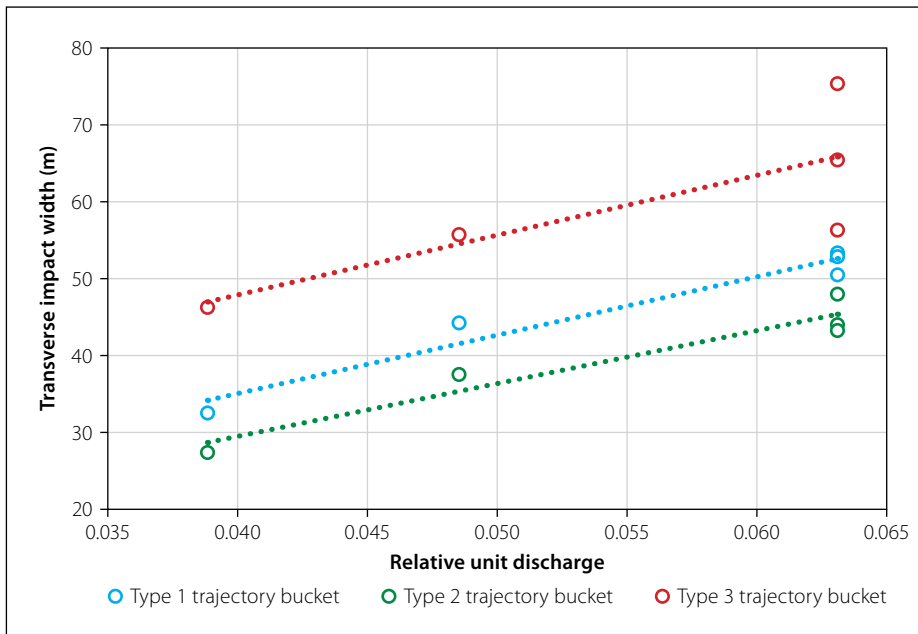


Figure 10 Influence of the relative unit discharge on transverse impact width

In summary, the following trends were observed:

1. For varying flow depth with constant discharge, the transverse impact width (B_j) was governed by the bucket flow depth ratio (h_b/H_s).
2. For equal Froude numbers, the transverse impact width (B_j) was governed by the relative unit discharge (q).
3. For flow conditions with varying discharge and constant flow depth, both the bucket flow depth ratio (h_b/H_s) and the relative unit discharge (q) influenced the transverse impact expansion (B_j).

These findings reinforce the influence of both geometric and hydraulic parameters on the lateral spread of the jet and support the observations made in earlier sections of the study.

Dynamic impact pressures

The dynamic impact pressure heads for the different flow conditions were obtained by converting the recorded voltage readings using Equation 1. This conversion allowed direct comparison of impact pressures across the three trajectory bucket types. The pressure head was derived using the standard linear conversion method, which accounts for the transmitter's operating range and electrical characteristics as follows:

$$H_{out} = \frac{H_{max} - H_{min}}{I_{max} - I_{min}} \times \frac{1000}{R} (x_{total} - x_{static}) \quad (1)$$

For analytical consistency, the 99th percentile (1% exceedance) pressure head

was used as the representative value for comparison, as recommended by Lopardo (1988, as cited in Castillo *et al* 2018). H_{max} and H_{min} represent the maximum and minimum pressure head limits of the transmitter, typically +1 m and -1 m, respectively. The corresponding maximum and minimum current outputs are $I_{max} = 20$ mA and $I_{min} = 4$ mA, while the transmitter resistance, R , was 120 Ω . The variable, x_{total} , represents the measured total pressure voltage reading, and x_{sta} is the voltage reading associated with the static tailwater depth.

The dynamic impact pressure heads for the Type 1, 2, and 3 trajectory buckets were compared under the design flow condition

(Flow Condition A). The Type 1 trajectory bucket served as the control for evaluating the performance of the alternative geometries. The comparison was done by determining the change in maximum dynamic impact pressure heads recorded for the different pressure sensors. The percentage difference in maximum dynamic pressure heads, as recorded by the pressure sensors, are presented in Figure 11. The results demonstrate that the Type 2 trajectory bucket significantly reduced the dynamic impact pressure head compared to Type 1, with an average reduction of 62.5% for Flow Condition A. A similar trend was observed for the Type 3 bucket, although the reduction was less pronounced, with an average decrease of 20.88%. One outlier was observed at pressure sensor 3, which recorded a slight increase in pressure for the Type 3 configuration relative to Type 1. This anomaly was likely due to the jet's position during impact, where a large portion of the flow may have directly impinged on the area covered by sensor 3 during the Type 3 test.

Further spatial insights are provided by the 2D contour plots shown in Figure 12, which illustrate the distribution of dynamic impact pressure heads across the plunge pool floor for Flow Condition A. These contour plots confirm that the Type 1 bucket produced the highest pressure magnitudes, with significantly more concentrated pressure zones. Both Type 2 and Type 3 geometries were effective at reducing pressure intensity due to improved jet breakup and

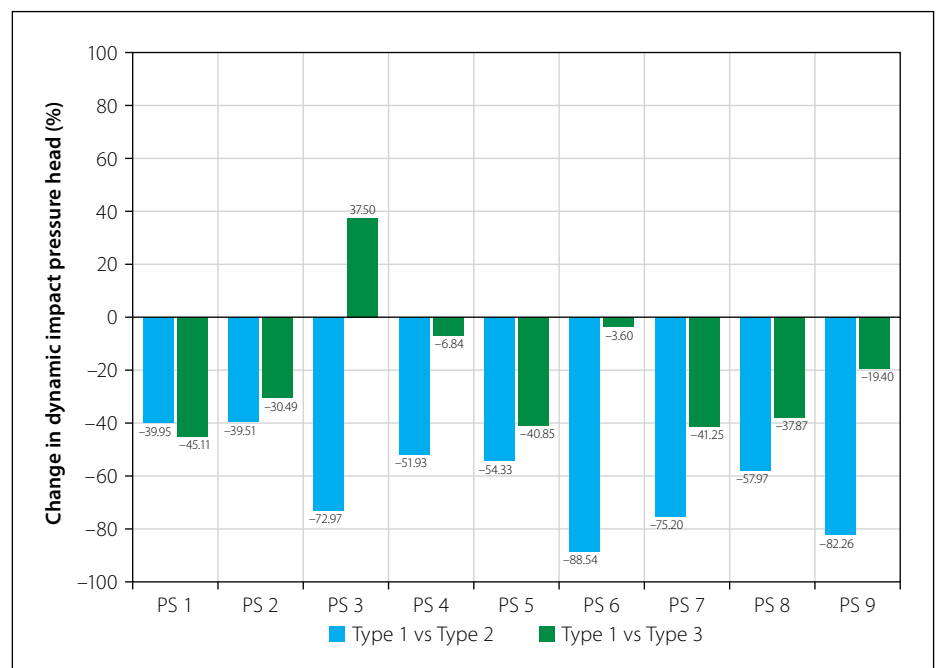


Figure 11 Percentage difference in dynamic impact pressure head for design flow condition

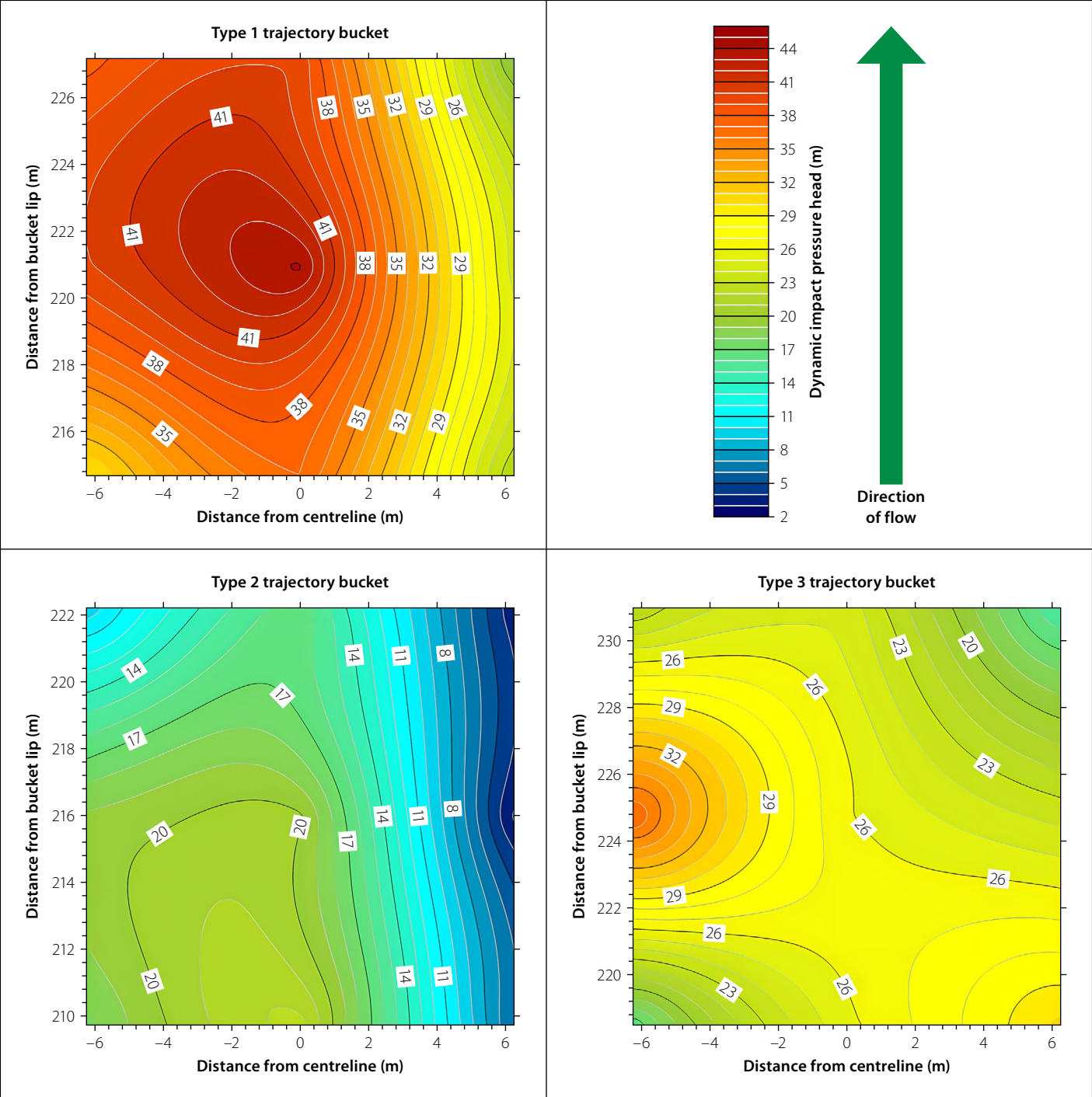


Figure 12 Comparison of spatial pressure distributions for Design Flow Condition A (prototype values)

dispersion. However, the Type 2 configuration demonstrated the most significant reduction, suggesting it is most effective at lowering scour potential through pressure attenuation.

While impact pressure measurements provide insight into local scour-driving mechanisms, an assessment of overall energy dissipation is required to place these observations within a broader hydraulic performance context.

Energy loss comparison

The dynamic impact pressures and impact velocities recorded for each test condition were used to calculate the maximum

dynamic impact pressure head (P_{dM}) and maximum impact velocity head ($H_{vj} = v_j^2 / 2g$) for each flow trajectory bucket configuration. A summary of these

values is presented in Table 5 and Table 6, respectively.

To quantify the energy dissipation efficiency of each trajectory bucket design,

Table 5 Summary of maximum dynamic impact pressure heads (prototype values)

Flow	Dynamic impact pressure head (m)		
	Type 1	Type 2	Type 3
B	25.48	10.86	15.55
C	33.37	20.95	29.16
A	44.14	22.37	37.12
E	30.40	16.81	16.64
D	33.98	15.86	26.36

Table 6 Summary of impact velocity heads (prototype values)

Flow	Impact velocity head (m)		
	Type 1	Type 2	Type 3
B	25.98	20.92	25.23
C	68.61	46.37	56.14
A	61.47	30.68	35.93
E	61.55	50.88	51.98
D	66.19	48.64	64.40

Table 7 Summary of initial total head for the different flow conditions tested (prototype values)

	Flow B	Flow C	Flow A	Flow E	Flow D
H_S (m)	37	57	97	68	51
Y_p (m)	11	11	11	11	11
H_T (m)	48	68	108	79	62

the initial total head (H_T) was compared with the energy level at the point of impact (E_2). The initial total head was calculated by summing the head above the bucket invert (H_S) to the vertical distance between the bucket invert and point of impact (Y_p). The calculation of the initial total head was based on a theoretical approach, considering the static dam level. Furthermore, the datum level of the point of impact for measuring the dynamic impact pressures and impact velocities was kept constant for all tests ensuring consistency when comparing relative energy losses. The bucket invert head (H_S), the elevation difference between bucket invert and point of impact (Y_p), and the initial total head (H_T) are summarised in Table 7.

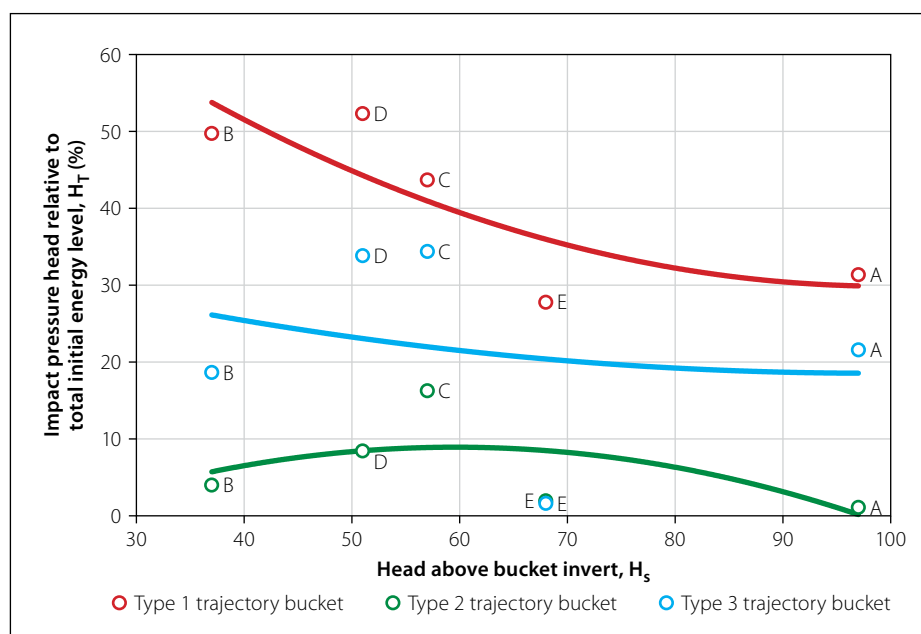
Two approaches were used to assess the relative energy loss between the initial total head and the energy level at the point of impact. By comparing the values from Table 5 and 7, the relative energy loss was determined as the difference between the initial head and the dynamic impact pressure head. These results are visualised in Figure 13. A clear trend was observed for the Type 1 and Type 3 trajectory buckets: as the bucket invert head increased (H_S), the relative dynamic impact pressure head decreased and, consequently, energy loss increased. For the Type 2 trajectory bucket, however, energy losses were more consistent across flow conditions. At lower bucket invert heads, the relative pressure head was higher, resulting in slightly lower energy

losses. At higher heads, pressure heads decreased more sharply, increasing energy losses significantly. When comparing the trajectory bucket types individually, the following observations were made with these results visually presented in Figure 14:

1. The Type 1 trajectory bucket showed the lowest relative dynamic impact pressure heads (and therefore highest energy losses) under Flow Conditions E and A (61% and 60% loss, respectively).
2. The Type 2 trajectory bucket consistently achieved relative dynamic impact pressure heads below 26% across Flow Conditions B, D, E, and A, translating to energy losses above 74%.
3. The Type 3 trajectory bucket also showed strong dissipation, with energy losses of 58%, 79%, and 66% for Flow Conditions B, E, and A, respectively.

Overall, the Type 2 trajectory bucket exhibited the highest energy dissipation, with losses exceeding 69% for all conditions tested. The Type 3 bucket also performed well, dissipating between 57% and 79% of the available energy. In contrast, the Type 1 bucket was the least effective, with energy losses ranging from 45% to 62%.

It should be noted that there is no single threshold value of energy dissipation that guarantees a safe design, as scour development is highly site-specific and depends on the resistance of the foundation material. In plunge pool environments, scour initiation and progression are governed primarily by whether the dynamic pressures generated by the impinging jet exceed the critical pressure of the rock mass. Consequently, increasing overall energy dissipation is beneficial insofar as

**Figure 13** Dynamic impact pressure heads expressed as a percentage of the initial total energy head

it reduces jet coherence, impact pressures, and momentum concentration at the pool bottom. The higher energy dissipation achieved by the Type 2 bucket is therefore interpreted as indicative of reduced scour potential through attenuation of dynamic pressures, rather than compliance with a fixed energy dissipation criterion.

The results from Figures 13 to 15 demonstrate a clear link between jet footprint expansion, pressure attenuation, and downstream scour mitigation. Trajectory buckets that promoted early jet breakup and produced broader, more uniformly wetted impact footprints resulted in significantly lower peak dynamic pressures at the plunge pool bottom. In particular, the splitter-teeth bucket (Type 2) achieved the greatest pressure attenuation by distributing jet momentum over a larger effective footprint, thereby reducing pressure concentrations that are critical for scour initiation. From a prototype design perspective, this behaviour is particularly advantageous in narrow valleys or constrained plunge pools, where lateral footprint expansion is limited and pressure reduction must be achieved primarily through longitudinal spreading and enhanced jet disintegration.

By comparing the values from Table 6 and 7, the relative energy loss was determined as the difference between the initial head and the impact velocity head. These results are visualised in Figure 15.

A consistent trend was observed for the Type 1, 2, and 3 trajectory buckets. For smaller bucket invert heads (H_s), relative impact velocity heads increased, and energy losses decreased. For larger bucket invert heads, the relative impact velocity head significantly reduced leading to substantial energy losses. When comparing the trajectory bucket types individually, the following observations were made with these results visually presented in Figure 16:

1. The Type 1 trajectory bucket showed the lowest relative impact velocity heads (and therefore highest energy losses) under Flow Conditions B and A (46% and 43% loss, respectively).
2. The Type 2 trajectory bucket showed the lowest relative impact velocity heads (and therefore highest energy losses) under Flow Conditions B and A (56% and 77% loss, respectively).
3. The Type 3 trajectory bucket showed the lowest relative impact velocity heads (and therefore highest energy losses) under Flow Conditions B and A (47% and 61% loss, respectively).

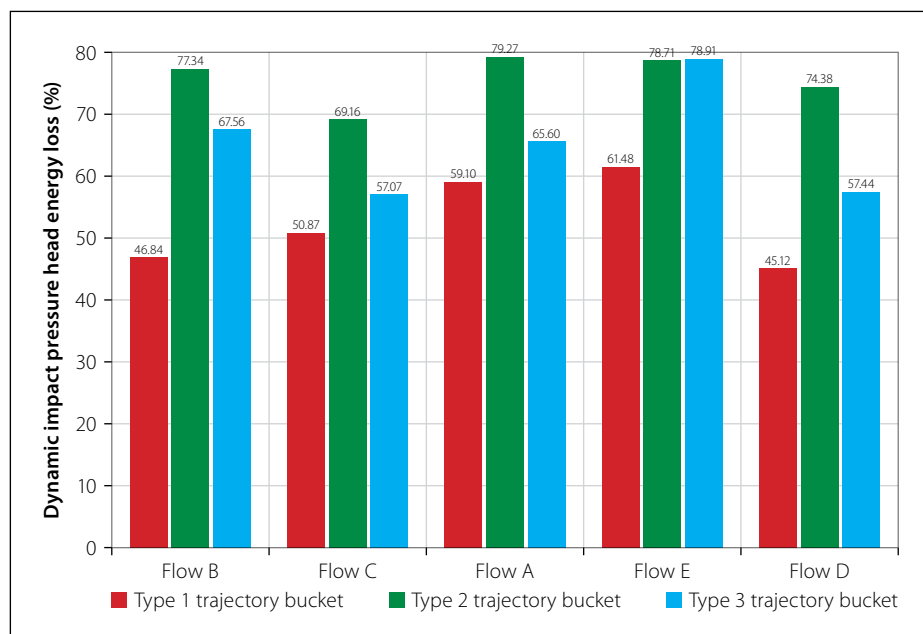


Figure 14 Relative dynamic impact pressure head energy loss for each trajectory bucket and flow condition

For the Type 1 trajectory bucket, small negative values of relative impact velocity head loss were observed for Flow Conditions C and D (Figure 16). These values indicate that the measured impact velocity head marginally exceeded the reference velocity head used for normalisation. This behaviour is attributed to jet focusing effects associated with the smooth bucket geometry, which allows the jet to remain coherent and undergo local contraction during take-off. As a result, limited initial turbulence and diffusion can lead to locally increased impact velocities for certain combinations of discharge and flow depth. This phenomenon does not imply an energy gain but

rather highlights the sensitivity of smooth trajectory buckets to flow–geometry interactions. The absence of such behaviour for the Type 2 and Type 3 buckets confirms the effectiveness of active jet disruption at take-off.

Overall, when the relative impact velocity head losses are averaged over the four flow conditions investigated (Flow Conditions A to D), the Type 2 trajectory bucket exhibited the highest energy dissipation, with a mean loss of approximately 43%. The Type 3 bucket performed moderately, with an average loss of about 32%, while the Type 1 bucket was the least effective, with an average energy loss only approximately 20%.

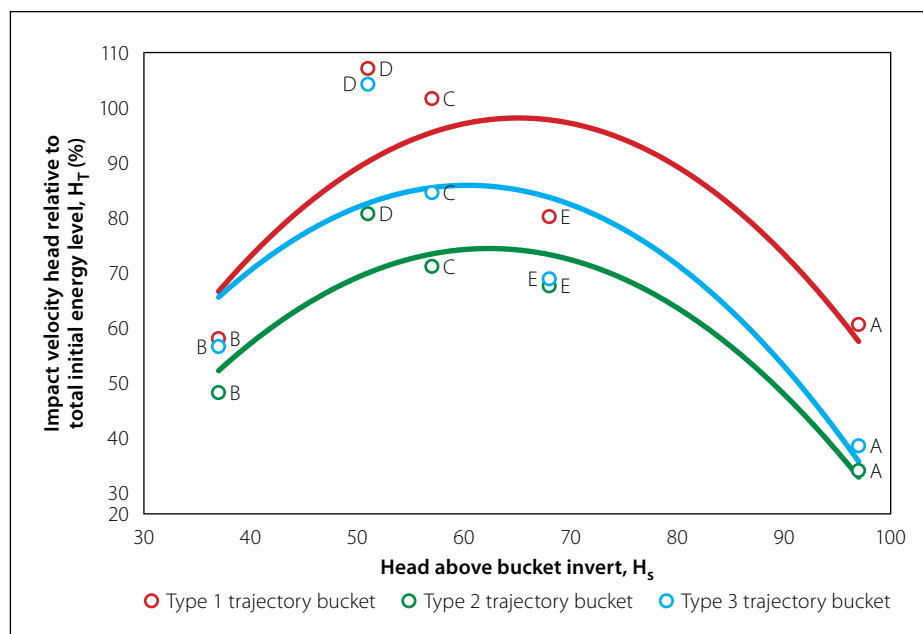


Figure 15 Impact velocity head expressed as a percentage of the initial total energy head

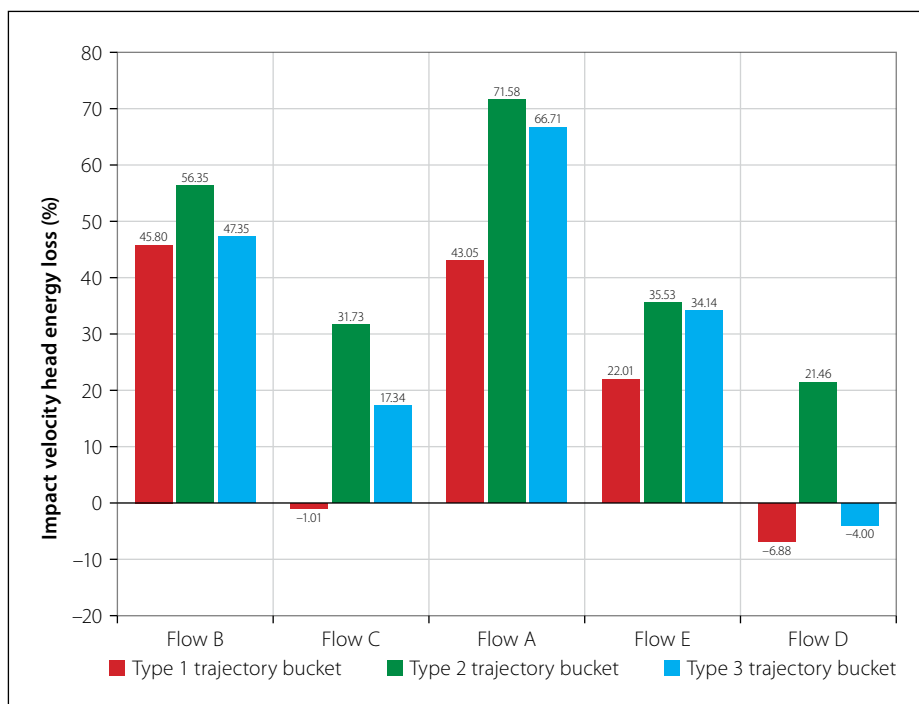


Figure 16 Relative impact velocity head energy loss for each trajectory bucket and flow condition

To synthesise the key geometric and hydraulic performance differences between the three trajectory bucket configurations, and to support practical interpretation, Table 8 provides a comparative summary of the principal design-relevant metrics under the design flow condition.

These findings further validate the effectiveness of splitter teeth in enhancing jet disintegration and distributing impact energy. The larger jet footprint and reduced dynamic pressures and impact velocity heads associated with the Type 2 bucket make it especially effective at reducing scour potential downstream of a ski-jump spillway.

CONCLUSIONS

Summary of findings

This study investigated the influence of trajectory bucket geometry on jet disintegration and energy dissipation in ski-jump spillways, focusing on three configurations: a conventional bucket (Type 1), a bucket with splitter teeth (Type 2), and a bucket with a central insert (Type 3). Based on experimental results from the physical model study, several conclusions were drawn. Experimental results showed that bucket geometry significantly affected jet behaviour, including disintegration, flight characteristics, footprint shape, and dynamic impact pressures – all of which contributed to energy dissipation performance. The analysis of transverse jet impact width supported findings by Vischer and

Hager (1995), confirming that both the flow depth relative to the bucket head (h_b/H_s) and the relative unit discharge ($\bar{q}$) influence the jet expansion angle, while this study further demonstrated that bucket geometry itself plays a critical role in transverse spread.

Jet trajectory increased with higher discharge and decreased with increased flow depth, but in all cases, the horizontal throw distance remained sufficient to protect the dam structure relative to the conventional trajectory bucket design. The Type 2 and Type 3 buckets produced broader impact footprints compared to the conventional design, with Type 2 more effective in narrow valleys with long plunge pools, and Type 3 suited to wide valleys with available pool width. The 1% exceedance pressure heads, derived from spatial contour plots, showed substantial reductions in dynamic

impact pressures for modified buckets: 62.5% lower for Type 2 and 20.9% lower for Type 3, relative to Type 1. Although not as substantial, reductions in impact velocities were also observed for modified buckets: 16.15% lower for Type 2 and 8.8% lower for Type 3, relative to Type 1.

Among the configurations, the Type 2 bucket proved most effective, enhancing jet breakup and aeration while distributing impact energy over a larger footprint, both longitudinally and transversely. The Type 3 bucket also offered performance benefits but to a lesser degree. In contrast, the Type 1 bucket produced a more coherent, concentrated jet with higher impact pressures and a smaller footprint, resulting in reduced energy dissipation and increased scour potential. Overall, the splitter teeth configuration (Type 2) offered the greatest improvement in energy dissipation and should be prioritised in future ski-jump spillway designs where jet-induced scour poses a concern.

Practical recommendations

The Type 2 trajectory bucket was the most effective at dissipating the jet's energy under all flow conditions tested in this study. It achieved high energy losses while maintaining safe and efficient jet trajectories. The following flow condition ranges were tested (model and prototype values):

- Discharge: 123.1 l/s and 200 l/s (384.69 m³/s and 625 m³/s prototype)
- Unit discharge: 0.246 m²/s and 0.4 m²/s (30.78 m²/s and 50 m²/s prototype)
- Flow depth on bucket: 0.046 m and 0.063 m (1.15 m and 1.59 m prototype)
- Flow velocity on bucket: 5.4 m/s and 8.7 m/s (26.9 m/s and 43.6 m/s prototype)

If a proposed project's prototype operating conditions fall outside these tested

Table 8 Comparative performance summary of trajectory bucket configurations (design flow condition)

Performance metric	Type 1: Conventional	Type 2: Splitter teeth	Type 3: Central insert
Throw distance	Baseline	Reduced	Slightly increased
Longitudinal footprint extent	Smaller	Largest	Large
Transverse footprint extent	Moderate	Moderate	Largest
Impact footprint area (m ²)	≈1 416	5 095	≈4 000
Reduction in 1% exceedance pressure head at pool bottom	–	62.5%	20.9%
Reduction in impact velocity	–	16.2%	8.8%
Overall scour mitigation effectiveness	Low	High	Moderate

hydraulic envelopes, the performance characteristics of the Type 2 trajectory bucket should be applied with engineering judgement. The following updated design recommendations for splitter teeth trajectory buckets are proposed, building on previous guidelines by Chengyi (1988):

1. The bucket's width may equal the spillway crest length, L_c .
2. Tooth radius (r_t) should be $\geq 6h_b$, where h_b is the flow depth on the bucket. This refines Chengyi's (1988) original recommendation of $r_t \geq 8h_b$.
3. The tooth width at the upstream section (b_1) is equal to $0.125 r_t$.
4. The bottom expanding angle of the tooth (γ) equal to 35° , as per Chengyi (1988).
5. The tooth side slope is equal to 1:1, as recommended by Chengyi (1988), resulting in an angle of 45° .
6. The ratio of slot width to tooth width (b_2/b_1) should range from 0.75 to 0.86, expanding on Chengyi's (1988) recommended 0.75.

7. Chengyi (1988) recommended a tooth take-off angle of 30° and a slot angle of 0° or a negative value. Based on this study, the tooth take-off angle may be increased to 45° , and the slot angle to 22.5° .

Based on the take-off angle of the slot and tooth, the radius (r_s and r_t), lip height (w_s and w_t), and length (l_s and l_t) of the slot and tooth may continue to follow standard design guidelines for circular trajectory buckets.

Future research

The conducted physical model tests on trajectory buckets to enhance jet disintegration can be improved to contribute to the aspects not addressed in this study. The following recommendations are made for future research on trajectory buckets to enhance jet disintegration:

- Research into pressure distribution within the bucket is recommended to understand potential issues such as cavitation, especially near splitter teeth and central inserts.

- A scour model study should be conducted to examine how the modified trajectory buckets influence erosion patterns and plunge pool morphology.
- Integration of numerical simulations (e.g. CFD) with physical models could help visualise internal flow mechanisms and improve design optimisation.
- The long-term structural impact of jet impingement, including potential fatigue or wear on reinforced concrete components, could be evaluated to inform maintenance planning and lifespan assessments.
- Future research could incorporate complementary CFD modelling to extend the findings of the physical model. High-resolution numerical simulations would allow detailed investigation of air–water interaction, jet breakup processes, and pressure fluctuations at spatial and temporal scales that are difficult to capture experimentally, particularly under prototype-scale conditions.

APPENDICES: TRAJECTORY BUCKET DESIGNS

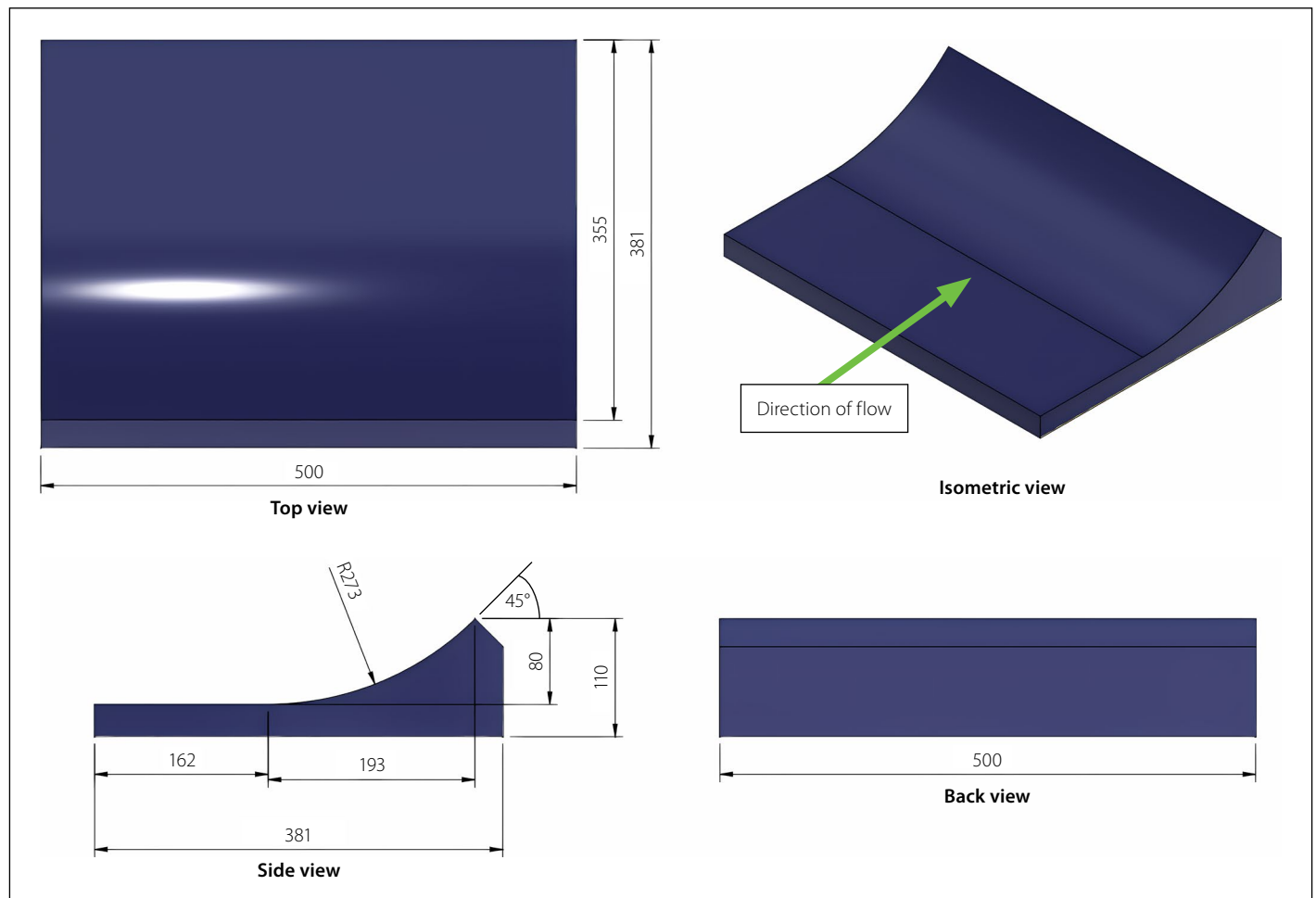


Figure 17 Design of Type 1 trajectory bucket (model dimensions in mm)

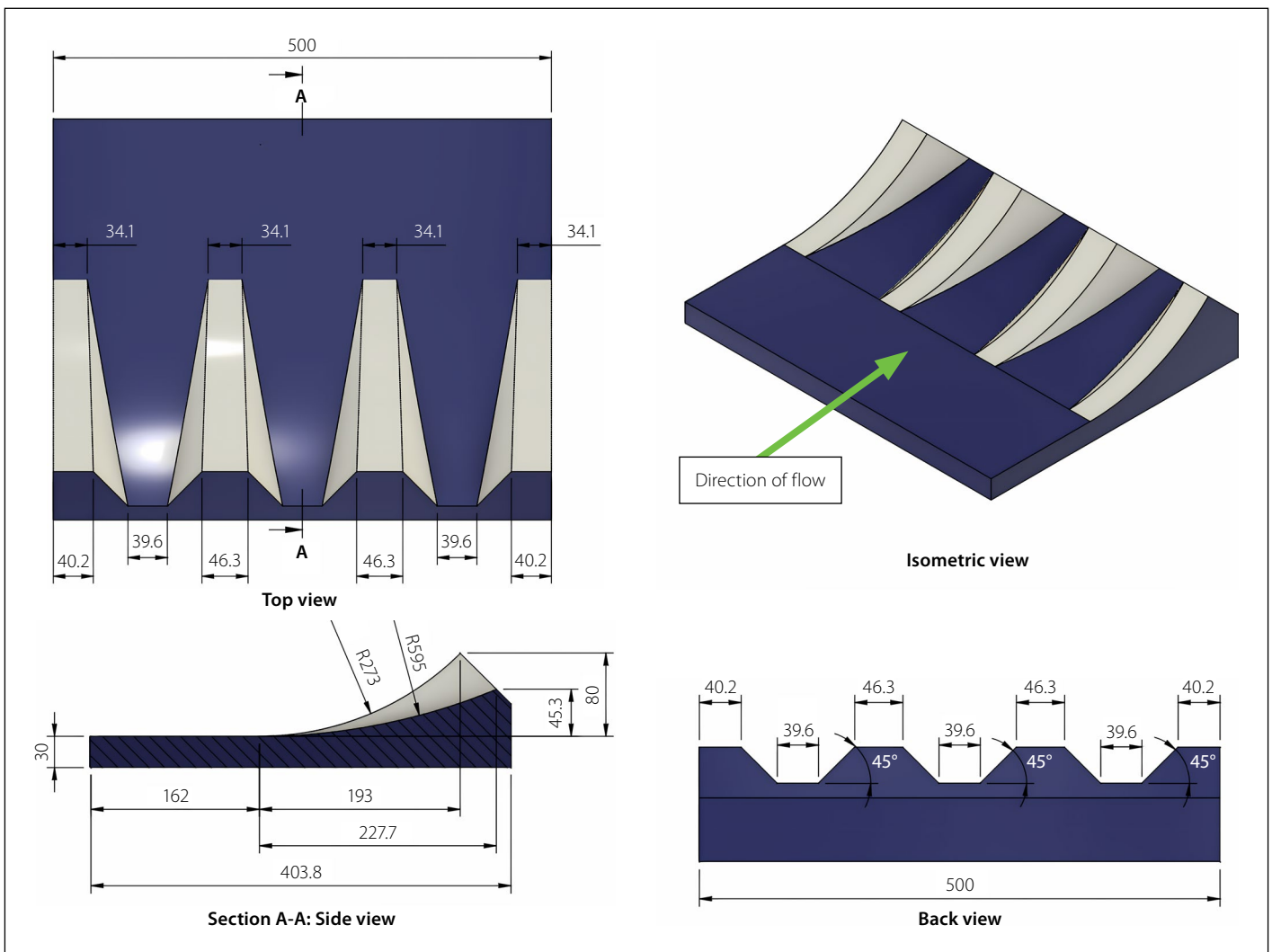


Figure 18 Design of Type 2 trajectory bucket (model dimensions in mm)

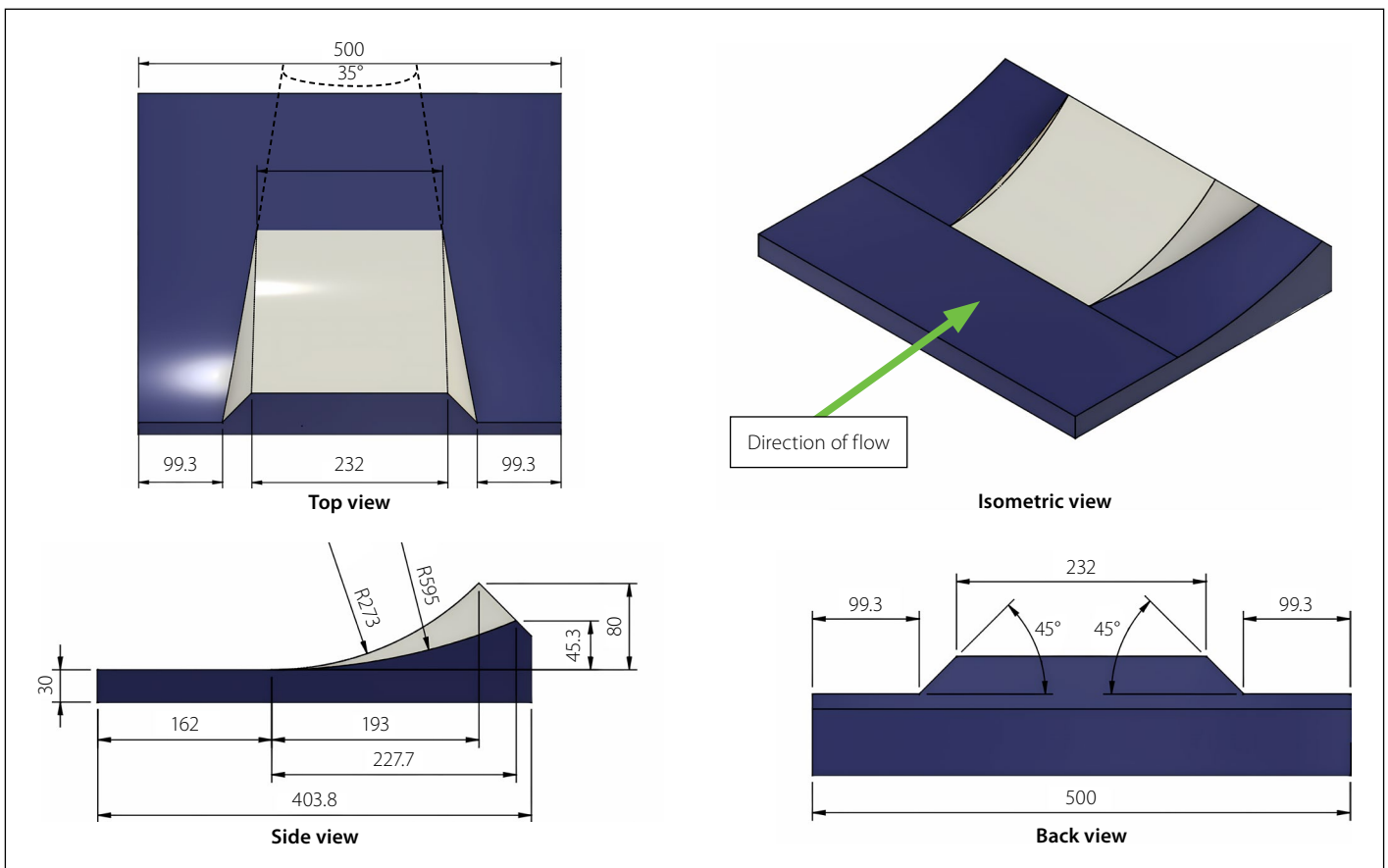


Figure 19 Design of Type 3 trajectory bucket (model dimensions in mm)

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