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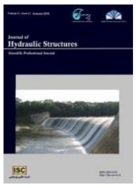

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Investigating and predicting hydraulic jump energy loss with threshold (Experimental and regression analysis)

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Abstract

The present investigation delves into the intricate dynamics surrounding the incorporation of thresholds and their consequential impact on parameters associated with hydraulic jumps—a phenomenon critical to the efficient functioning of the gates. In the pursuit of a comprehensive understanding, the study employed experimental models of thresholds crafted from polyethylene. These models underwent meticulous examination, encompassing variations in dimensions, widths, and positions relative to the gate. The positions explored included beneath the gate, tangent to the gate upstream, and downstream, each contributing unique insights into the behavior of water flow and energy dissipation. An intriguing outcome emerged as thresholds were introduced at different locations. The energy dissipation for a given gate opening exhibited a discernible increase, shedding light on the intricate relationship between threshold placement and hydraulic performance. Notably, as the initial depth relative to the secondary depth increased, a consequential decrease in the $\Delta E_{AB}/y_A$ was observed, signaling a convergence between the initial and secondary depths. Further illuminating the findings, a comparative analysis of energy loss was conducted across all three threshold positions—beneath the gate, tangent to the gate upstream, and downstream. This scrutiny uncovered a distinct pattern, indicating a heightened energy dissipation in scenarios where the threshold was submerged, setting it apart from conditions where the threshold was positioned otherwise. In essence, the investigation not only accentuates the intricate interplay between sluice gates, thresholds, and hydraulic parameters but also underscores the importance of considering the placement of thresholds in optimizing the energy dissipation efficiency of these hydraulic structures.

Keywords: Gate, Hydraulic Jump, Threshold, Regression Equation.

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1. Introduction

The gates represent hydraulic structures where water movement occurs beneath the gate. Among the common types is the vertical lift gate, adjusting its opening vertically in the flow path for precise control of upstream water level, discharge regulation, and estimation of the gate discharge coefficient. The influx of water velocity into channels induces oscillatory waves, causing erosion of the channel bed downstream. Consequently, designing stilling basins becomes crucial to prevent excessive energy dissipation while maintaining downstream water depth above the secondary depth to mitigate jumps. Understanding flow behavior in diverse threshold positions enhances hydraulic performance and water distribution efficiency in irrigation networks. The use of a combined gate-threshold structure reduces upstream water depth, diminishing the force on the gate and increasing the flow coefficient. Hydraulic jump is a fundamental phenomenon in the field of open-channel hydraulics that necessitates precise management and control. Various factors, including water flow velocity, irregularities, and geometric changes in the channel, can have a significant impact on the occurrence of this phenomenon. Considering these factors in the design and management of open channels can enhance the performance of irrigation systems and prevent sudden issues associated with the hydraulic jump phenomenon.

The understanding of hydraulic and geometric parameters associated with gates has been the subject of numerous analytical and laboratory studies, as documented in a range of scholarly works [1-11]. Among these investigations, Abdelmonem et al. [12] made notable contributions by focusing on energy dissipation downstream of flap gates, particularly in the presence of a submerged threshold. Their findings revealed a remarkable 20% increase in hydraulic jump efficiency under these conditions, emphasizing the potential benefits of incorporating submerged thresholds in hydraulic structures equipped with flap gates.

In a related study, Habibzadeh et al. [13] delved into the hydraulic jump characteristics downstream of flap gates. Their scrutiny unveiled a correlation between an increases in the Froude number and escalated surface wave oscillations. This observation highlights the sensitivity of hydraulic jump dynamics to flow parameters, with implications for the overall efficiency and stability of hydraulic systems featuring flap gates.

Another significant contribution comes from Abbaszadeh et al. [14], who investigated hydraulic jump characteristics with a threshold. Their study underscored the role of the threshold in enhancing energy dissipation, providing valuable insights into the design considerations for hydraulic structures. The incorporation of thresholds in such systems can contribute to optimizing energy dissipation processes and improving overall hydraulic performance.

Furthermore, Abbaszadeh et al. [15] conducted experimental research to explore the impact of a threshold on flow characteristics. Their findings revealed a reduction in hydrodynamic force exerted on the gate, suggesting that the presence of a threshold not only influences energy dissipation but also has implications for the structural forces experienced by the hydraulic components.

In summary, these studies collectively contribute to advancing our understanding of flap gates and their interactions with hydraulic jumps. The insights gained from these investigations have implications for the design and optimization of hydraulic structures, with the potential to enhance energy dissipation efficiency and overall system performance.

As part of efforts to improve the hydraulic performance and increase the efficiency of water distribution in irrigation networks and channels, a comprehensive study was undertaken. The study focused on exploring the use of a gate-threshold structure in various locations, with the aim of determining the most effective placement to enhance the distribution of water in irrigation networks and channels. The gate-threshold structure was tested in three different locations, namely below the gate, tangent to the gate upstream, and tangent to the gate downstream. The effectiveness of the structure was examined in each location, and data was collected to determine its impact on the hydraulic performance and efficiency of the overall system. The study aimed to provide valuable insights into the optimal location for the gate-threshold structure to be placed in order to achieve the best results for water distribution in irrigation networks and channels. The findings of the study will be useful in improving the efficiency of irrigation systems and ensuring that resources are utilized optimally.

2. Materials and Methods

Experiments in this study were conducted in a laboratory flume featuring a rectangular cross-section (length: 5 meters, width: 0.3 meters, height: 0.5 meters) constructed with transparent Plexiglas walls and floor, facilitating precise observation of flow details. The channel bed slope was adjustable, set at zero for experimentation. Two pumps with a nominal power of 450 liters per minute provided inflow to the flume. Rotameters installed on the flume measured the inflow discharge. To mitigate turbulence from the inlet, several parallel calmers were employed at the beginning of the flume. A point depth gauge mounted on a movable rail measured water depth in the flume. Depths were measured at four points across the width of the cross-section, with their average considered the final depth. Experiments were conducted in two conditions: without a threshold and with a threshold at various gate openings. Thresholds made of polyethylene, with a thickness of 5 centimeters, height of 3 centimeters, and width (B) ranging from 2.5 to 30 centimeters, were positioned beneath the gate, tangent to the gate upstream, and tangent to the gate downstream. Figures (1) and (2) illustrate the flume and thresholds, respectively.

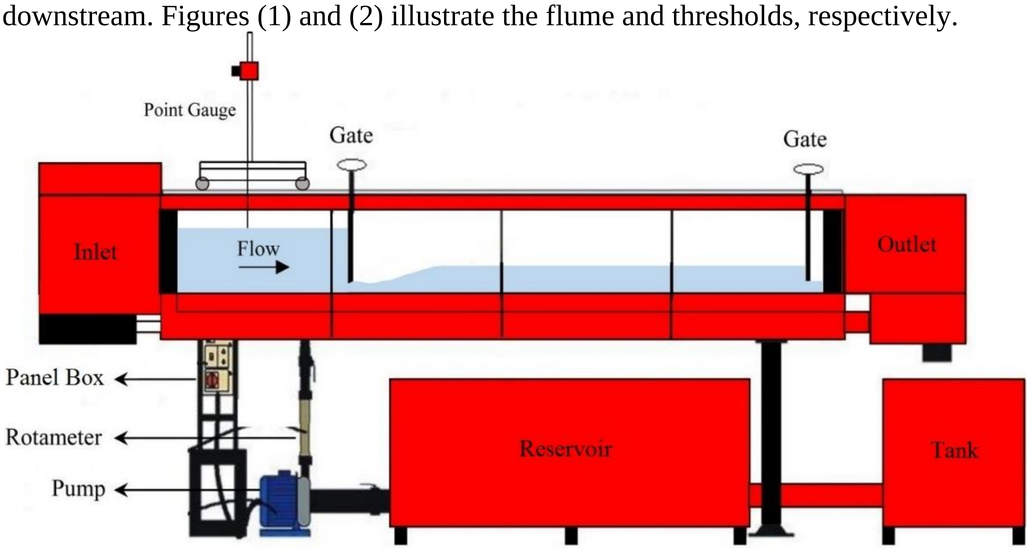

Figure 1. Schematic view of the flume

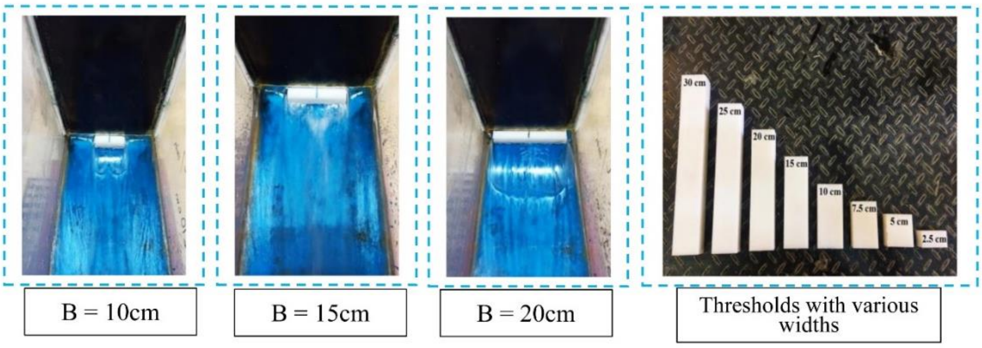

Figure 2. The view (x-y section) of the threshold with different placement relative to the gate

3. Results and Discussion

The relationship between the energy loss relative to initial depth ($\Delta E_{AB}/y_A$) and the ratio of initial depth to hydraulic jump secondary depth (y_A/y_B) is a crucial aspect in understanding the hydraulic behavior of flow through openings. As depicted in Figure (3a and b), the total openings of 4 and 5 centimeters provide insights into the dynamics of energy dissipation. The variation in $\Delta E_{AB}/y_A$ with changing y_A/y_B ratios reveals intriguing patterns.

An intriguing observation is the consistent decrease in the $\Delta E_{AB}/y_A$ value with an increase in the y_A/y_B ratio. This trend suggests a convergence of initial and secondary depths, culminating in the formation of a weak hydraulic jump with minimal energy loss. The interplay between these parameters highlights the intricate balance governing the efficiency of energy dissipation in hydraulic systems.

Furthermore, the influence of the y_A value on the Froude number and subsequent energy loss is noteworthy. An increase in y_A corresponds to a decrease in the Froude number, contributing to an overall reduction in energy loss. This relationship underscores the importance of threshold width in modulating the hydraulic characteristics of the flow. The findings in Figure (3) illuminate the trade-off between threshold width and energy dissipation efficiency.

Interestingly, the highest energy loss is pinpointed at the y_A/y_B=0.1 ratio, as indicated in Figure (3). This particular ratio signifies a critical point where, at a constant discharge, an increase in threshold width leads to a reduction in secondary depth, consequently amplifying energy loss. This observation provides valuable insights for optimizing hydraulic structures, emphasizing the significance of maintaining a delicate balance between opening dimensions and energy dissipation efficiency.

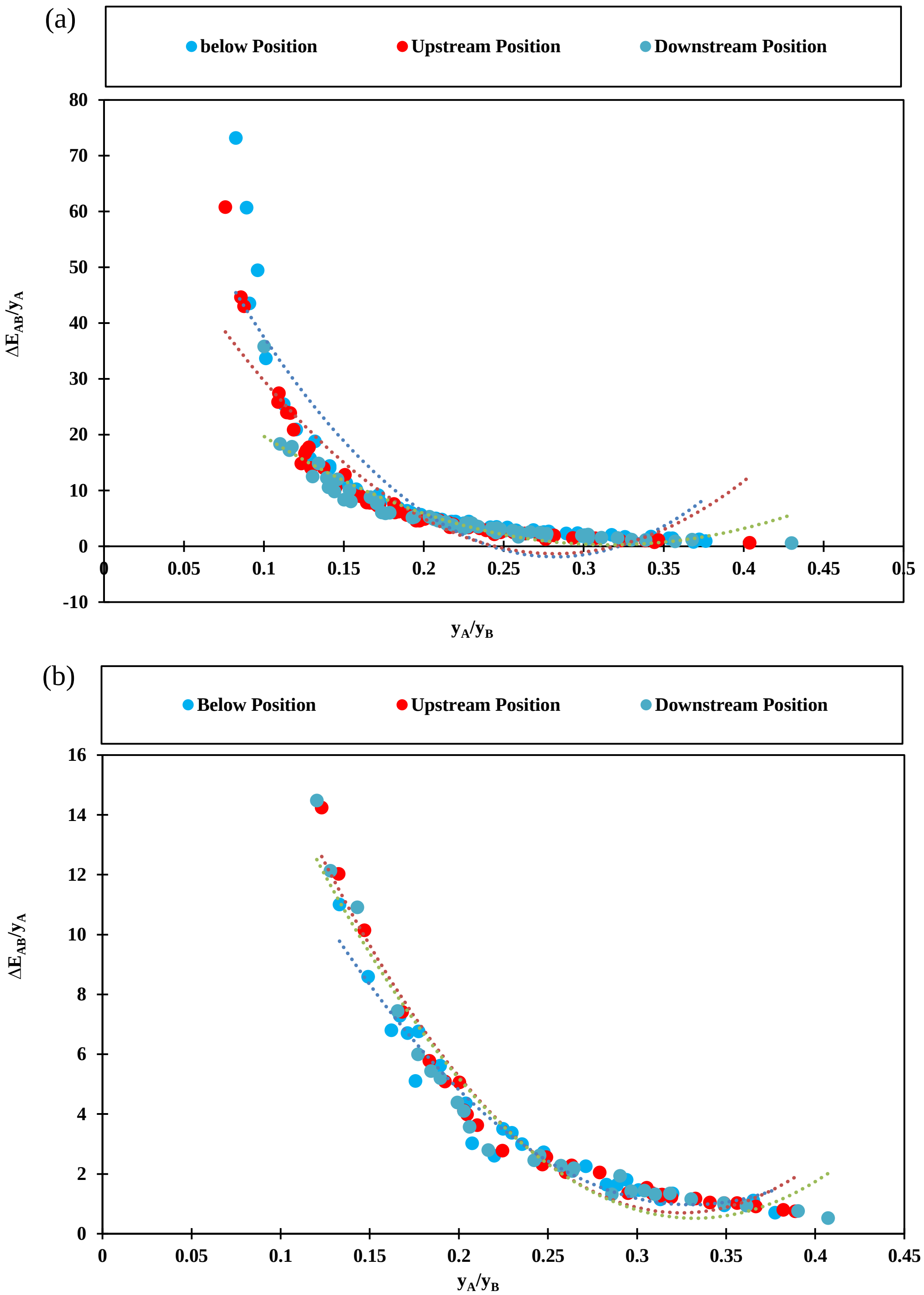

Figure 3. The value of $\Delta E_{AB}/y_A$ and y_A/y_B for various locations of the threshold placement a) 4 cm opening, b) 5 cm opening

To predict energy loss relative to specific energy at the upstream and downstream in the presence of a threshold, Equations (1) and (2) have been proposed.

In conclusion, the introduction of Equations (1) and (2) enhances our ability to model and understand energy dissipation in hydraulic jump scenarios. These equations provide a practical and accurate framework for predicting energy losses relative to specific energy, thereby contributing to the optimization and design of hydraulic structures for improved performance in the presence of thresholds.

$$\frac{\Delta E_{AB}}{E_A} = -3.067 Fr_A^{-0.778} + 1.692\left(\frac{y_B}{y_A}\right)^{-1.073} + 0.004\left(\frac{B}{y_A}\right)^{-9.083} + 1.161\left(\frac{B}{y_B}\right)^{0.001} \quad (1)$$

$$\frac{\Delta E_{AB}}{E_B} = 0.486 Fr_A^{1.180} - 0.175\left(\frac{y_B}{y_A}\right)^{1.228} + 0.012\left(\frac{B}{y_A}\right)^{-6.197} - 0.537\left(\frac{B}{y_B}\right)^{0.008} \quad (2)$$

The statistical indexes of percentage relative error (RE%), root mean square error (RMSE), and Kling Gupta efficiency (KGE) were used to evaluate the equations.

$$RE\% = \frac{X_{Obs} - X_{cal}}{X_{Obs}} \times 100 \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{Obs} - X_{Cal})_i^2}{n}} \quad (4)$$

$$KGE = 1 - \sqrt{(R-1)^2 + (\beta-1)^2 + (\gamma-1)^2}$$
$$\beta = \frac{\overline{X_{Cal}}}{\overline{X_{Obs}}}, \gamma = \frac{CV_{Cal}}{CV_{Obs}} = \frac{\sigma_{Cal}/\overline{X_{Cal}}}{\sigma_{Cal}/\overline{X_{Obs}}}$$
$$R = \frac{[\sum_{i=1}^{n}(X_{Obs\,i} - \overline{X_{Obs}}) \times (X_{Cal\,i} - \overline{X_{Cal}})]}{\sum_{i=1}^{n}(X_{Obs\,i} - \overline{X_{Obs}}) \sum_{i=1}^{n}(X_{Cal\,i} - \overline{X_{Cal}})} \quad (5)$$

$0.7 < KGE < 1$ "Very good"
$0.6 < KGE < 0.7$ "Good"
$0.5 < KGE \leq 0.6$ "Satisfactory"
$0.4 < KGE \leq 0.5$ "Acceptable"
$KGE \leq 0.4$ "Unsatisfactory"

Equations (3) and (4), both approaching zero, are indicative of a high level of accuracy in the solutions. This is consistent with the common practice where smaller differences between observational (Obs) and computational (Cal) results signify a closer match and, consequently, a more accurate representation of the observed phenomena [16].

Equation (5) involves several parameters: R (coefficient of correlation), β (average of calculated values to observed values), and γ (standard deviation of calculated values to observed values). The correlation coefficient provides a measure of the linear relationship between the two datasets. A value close to 1 indicates a strong positive correlation, reinforcing the reliability of the computational results.

The ratios β and γ offer insights into the central tendency and variability of the data, respectively. A β ratio close to 1 suggests that the average of the calculated values aligns well with the average of the observed data. Similarly, a γ ratio close to 1 implies that the standard deviation of the calculated values is in good agreement with the standard deviation of the observed values [5].

The KGE (Kling-Gupta Efficiency) statistical index, mentioned in relation to Equation (5) and categorized into levels such as very good, good, satisfactory, acceptable, and unsatisfactory, serves as an overarching measure of the accuracy of the solutions [17]. A higher KGE index suggests a more accurate representation of the observed data by the computational model.

In conclusion, these equations collectively provide a comprehensive framework for evaluating the accuracy of computational results relative to observational data. The emphasis on correlation, central tendency, variability, and the KGE index underscores the multifaceted nature of accuracy assessment, enabling a nuanced understanding of the reliability of the computational solutions.

Figure (4) presents a comprehensive comparison between experimental results and computational simulations, shedding light on the accuracy and reliability of the models in predicting energy dissipation relative to both upstream and downstream conditions. The juxtaposition of experimental and computational data allows for a nuanced evaluation of the predictive performance.

The statistical evaluation of the computational models against the experimental data is instrumental in assessing their fidelity. For Equation (1), the statistical indices reveal a maximum relative error of 8.53%, an average relative error of 0.78%, and a root mean square error of 0.004. Notably, the KGE for relation (1) falls within the "very good". These metrics collectively affirm the robustness of the computational model in accurately capturing the energy dissipation dynamics relative to upstream and downstream parameters.

Similarly, for Equation (2), the statistical indices exhibit a maximum relative error of 12.15%, an average relative error of 0.87%, and a root mean square error of 0.009. The KGE for Equation (2) also falls into the "very good" category. These results underscore the efficacy of the computational approach in providing reliable predictions, with a minor increase in error compared to Equation (1). The overall "very good" categorization indicates a high level of agreement between the computational simulations and experimental observations.

In summary, the comparative analysis in Figure (4) and the associated statistical indices validate the accuracy of both Equation (1) and Equation (2) in predicting energy dissipation. The "very good" categorization of the KGE index further enhances the credibility of the computational models, offering confidence in their application for understanding and predicting energy dissipation phenomena in hydraulic systems.

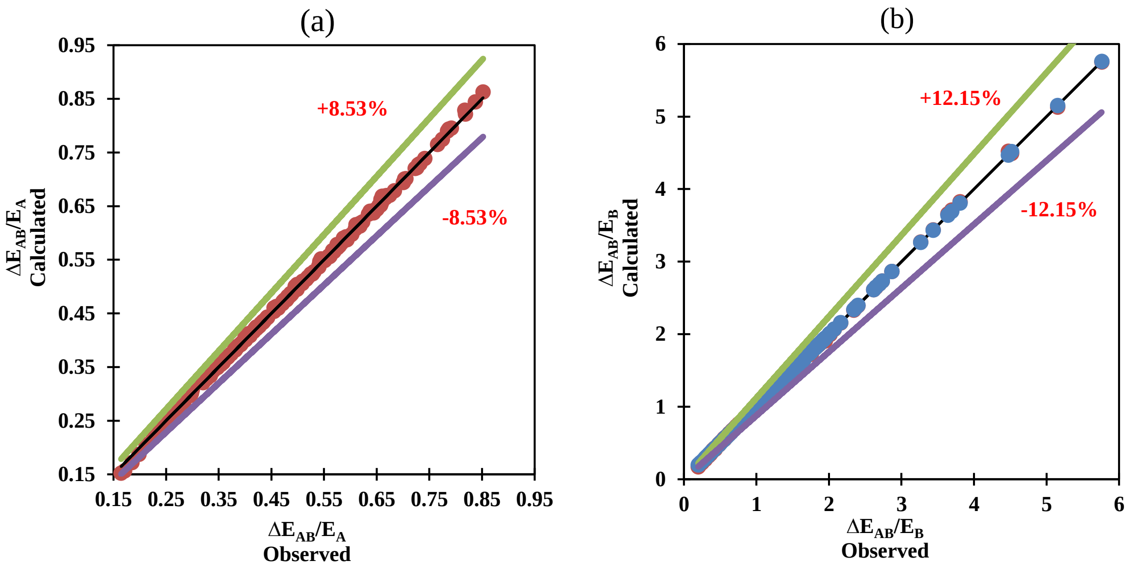

Figure 4. The values of calculated energy loss against observed data

4. Conclusion

This study examined the hydraulic jumps at varying gate openings, considering both threshold and non-threshold conditions, and accounting for various widths and positions relative to the gate. The experimental investigation encompassed a discharge range spanning from 150 to 850 liters per minute. The findings highlight that, in the absence of a threshold, downstream hydraulic jumps exhibit a decrease in relative energy loss as the gate opening increases.

Within specific gate openings, the introduction of a threshold, positioned both below the gate and tangent to the gate upstream and downstream, correlates with heightened energy dissipation. A notable observation is the decrease in the $\Delta E_{AB}/y_A$ value with an increasing ratio of initial depth to secondary depth. This decrease signifies the convergence of initial and secondary depths, leading to the formation of a weak jump characterized by minimal energy loss. Comparative analysis across all three threshold conditions—below the gate and tangent to the gate upstream and downstream—reveals a higher energy dissipation in the sub-threshold condition compared to other threshold scenarios.

In this current investigation, the study also derived general equations for calculating energy loss under threshold conditions. The accuracy of these equations was rigorously assessed using various statistical indices, including Relative Error, Root Mean Square Error, and Kling Gupta Efficiency. The results affirm the high precision of the presented equation, endorsing its utility in predicting relative energy loss with confidence.

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