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Numerical Analysis of Different Slit-Check Dams

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Keywords
Slit check dam, OpenFOAM, Horizontal openings, Vertical openings, Angled openings, CFD

Abstract: Check dam designs have attracted attention recently due to the clogging of classical check dam structures with sediment and wooden material carried during the flood quickly. These structures regulate flow characteristics and debris flow. However, until now, the impacts of these structures on flow characteristics have received little attention in the literature. Therefore, it is necessary to develop new models to increase these structures' trapping capacity or extend the clogging time. In this study, the flow characteristics of check dams with horizontal, vertical, and angled openings were numerically analyzed for two-phase (water and air) flow. The numerical model was validated using experimental results in the literature. For the study in which twelve analyses were performed, four different check dam models (i.e., check dam with the classical, the narrow horizontal opening, the vertical openings, and angled openings) and three different unit flows (0.04, 0.03, and 0.02 m^3 s^{-1} m^{-1}) were used in the analysis. The open-source software OpenFOAM and the k-ω SST turbulence model were used for the numerical analysis using the Computational Fluid Dynamics (CFD) method. At maximum unit flow, the highest energy dissipation rate among slit check dam models was seen in Model-3, which has vertical openings. At minimum unit flow, the highest energy dissipation rate was attained in Model 2, which has horizontal openings. There is no difference in the energy dissipation rate at low unit flows whether the openings are positioned vertically or angled; nevertheless, the vertical model (Model-3) is observed to be more efficient at maximum unit flow.

Farklı Geçirgen Kontrol Barajlarının Sayısal Analizi

Anahtar Kelimeler
Geçirgen kontrol barajı, OpenFOAM, Yatay açıklıklı kontrol barajı, Düşey açıklıklı kontrol barajı, Açılı açıklıklı kontrol barajı, HAD

Öz: Klasik kontrol barajları, taşkın sırasında taşınan tortu ve ahşap malzeme sebebiyle kısa sürede tıkanmaktadır. Bu nedenle klasik kontrol barajların tutma kapasitesini artırmak veya tıkanma süresini uzatmak için yeni modellerin geliştirilmesi gerekmektedir. Araştırmacılar, son yıllarda alternatif modeller üzerinde çalışmışlardır. Ancak bugüne kadar bu yapıların akış üzerindeki etkileri literatürde çok az ilgi görmüştür. Bu çalışmada; yatay, dikey ve açılı açıklıklı kontrol barajların akış özellikleri iki fazlı (su ve hava) akış için sayısal olarak incelenmiştir. Sayısal modelde kullanılan sınır şartları ve çözüm ağı, literatürdeki deneysel sonuçlar kullanılarak doğrulanmıştır. Toplamda 12 analizin gerçekleştirildiği bu çalışma için dört farklı baraj modeli (klasik, yatay açıklıklı, dikey açıklıklı ve açılı açıklıklı) ve üç farklı birim debi (0,04; 0,03 ve 0,02 m^3 s^{-1} m^{-1}) kullanılmıştır. Sayısal analizler için açık kaynak kodlu OpenFOAM yazılımı ve k-ω SST türbülans modeli kullanılmıştır. Elde edilen sonuçlara göre, geçirgen kontrol baraj modelleri arasında en yüksek enerji sönümleme oranı maksimum birim debide, düşey açıklıklı model olan Model-3'te gözlenirken; minimum birim debide, yatay açıklıklı model olan Model-2'de gözlenmiştir. Açıklıkların dikey veya açılı konumlandırılmasının düşük birim debide enerji sönümleme oranına bir etkisi olmazken, maksimum birim debide dikey modelin (Model-3) daha verimli olduğu gözlenmiştir.

1. INTRODUCTION

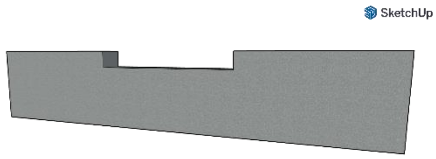
Global warming is an issue that has attracted the world's attention in recent years. While drought is observed in some regions due to climate change, loss of life and property occurs due to excessive rainfall in some regions. In recent years, researchers have made suggestions to reduce the impact of these losses by making regional risk assessments [1–3]. The clogging of the bridge and culvert, frequently seen especially in flood regions, increases the losses. For this reason, check dams are used to keep these transported materials.

Check dams are important water structures commonly used to prevent soil and water loss in stream beds or sloping lands to control water flow (Fig. 1a). These structures are designed to prevent erosion and ensure the sustainability of agricultural lands and can be constructed from various materials such as stone, logs, bricks, and cement. The history of the check dams is based on the information that the first example was made of wood for flood protection in Italy in 1537, and their number increased in the following years [4]. These structures are also known as control dams and offer various ecological benefits, such as improving water quality, recharge of groundwater, and development of coastal ecosystems [4].

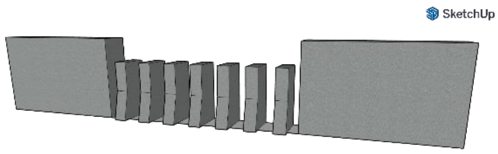
Check dams cause a decrease in the channel slope and flow rate of the sediment accumulated during the flood, thus increasing the flow depth [5]. This situation can cause significant problems when the natural material in the stream bed and the woody material around the canal during floods cause blockages [6]. Conventional control structures, especially those built of stone walls, may be poor at providing adequate resistance to the dynamic effects of debris flows and can cause damage in the downstream region [7]. Therefore, permeable slopes have been investigated to control the transport of sediment and woody material more effectively [8,9].

Conventional control dams, especially those built of stone walls, may be poor at providing adequate resistance to the dynamic effects of debris flows, and the downstream region may suffer due to the "hungry water effect" [7]. According to the studies, approximately 65% of such structures are destroyed due to the increase in the bed depth of the sediment [10,11]. For this reason, experimental studies have been carried out using slit check dam to control the transport of sediment and woody material [8,9]. The use of slit check dams has the potential to prevent the accumulation of sediment and woody material and offers a more effective solution in stream management. These experimental studies provide important guidance in the design and implementation processes to improve weirs' performance and effectively control sediment and woody material transport.

Slit check dams (see Fig. 1b) protect the ecosystem balance and prevent downstream scours by keeping the sediment and wood materials transported during the flood under control [12]. These structures keep the sedimentary material behind the dam, thanks to the openings that allow the passage of sediment of a certain diameter (Fig. 1b). This situation helps to reduce the possible damages of flood by preventing the clogging of downstream structures such as bridges and culverts [8]. In addition, thanks to the self-cleaning feature of the slit dams [13], it contributes to the cleaning of the accumulated sediment over time. However, due to the sediment accumulating in their gratings during a severe flood, these structures may also become clogged and inoperable, like classical dams [12]. For this reason, these structures should be used and developed more effectively to minimize the possible damages, especially in flood areas. Researches and experimental studies provide important clues for increasing the performance of slit check dams and minimizing the flood effect. In this way, it aims to use water structures as more durable, efficient structures and maintain the ecosystem balance.



(a)



(b)

Figure 1. a) Classical check dam, b) Slit check dam

Literature studies reveal that many models related to slit check dams have been proposed, but no effective results have been reached yet [14]. The study by Piton and Recking [14] provides a comprehensive review of the design of slit check dams and discusses the applications of these structures in flood hazard mitigation. They introduced the general context and functions of these structures, and the shape of the openings and hydraulic design criteria for different types are summarized in detail. In addition, the dynamics of sediment deposition were also studied in depth. As a result of their study, the researchers emphasized that the behavior of slit check dams can be significantly affected by the presence of woody material. That is, the presence of woody material can significantly affect the performance and effectiveness of structures. Therefore, the containment and management of woody material is essential to operate slit check dams successfully. In another study prepared by the same researchers [15], models used to control residual materials were examined. They explained how slit check dams are designed and used to hold the sedimentary material effectively. Different design models and structures of slit check dams offer alternative solutions for residual material control, and the need for further research and development in this regard has been emphasized. Aydin et al. [16] worked on the hydraulics of the slit-check dam for subcritical flow regimes. The hydraulic characteristics of slit-check dams were studied using the numerical and experimental determination of the flow's energy dissipation performances and water surface profiles. According to the findings, a slit-check dam with blocks causes hydraulic jumps and important energy losses in a subcritical flow. These findings demonstrated the effectiveness of slit-check dams with blocks for debris breaking, energy dissipation, and flow management in flood and normal flow situations.

As seen in the literature review, many researchers have conducted different studies on slit check dams in recent years and emphasized that more studies are needed to eliminate the uncertainties on this subject. In this study, the flow characterisrics of the check dams for four different geometries were numerically investigated for water flow condition. It is aimed to provide preliminary information for future studies by comparing the results obtained.

2. METHODOLOGY

In this study, the flow characteristics of classical and slit check dams with different openings were compared numerically. The analyses were carried out for a channel with a length of 4.80 m, a width of 0.52 m, and a height of 0.75 m. The check dam was located 1.50 m away from the upstream part of the channel, and a 0.10 m high threshold was added to the end of the channel (Fig. 2). The height of the dams is 0.50 m and their thickness is 0.05 m.

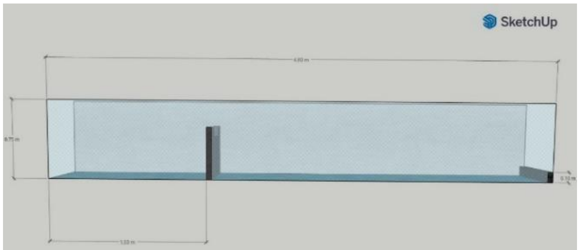


Figure 2. Longitudinal section of the channel

Within the scope of the study, a total of twelve analyses were conducted for three different unit flow rates (0.04-0.03-0.02 $m^3 s^{-1} m^{-1}$) and four check dam models. One of these models is the classic check dam, while the other models are designed using openings placed in different directions (horizontal, vertical, and angled) on the body of the classic check dam (Fig. 3). The dimensions of these openings are the same, and the ratio of the area of the filled part to the area of the empty part is equal for all slit check dams.

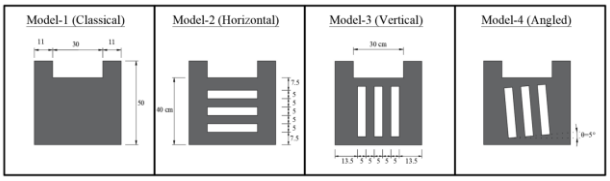


Figure 3. Check dam models considered in the study

Numerical analyses were carried out using the interFoam solver, which can solve two-phase (water and air) flow in the OpenFOAM software (v7). Previous studies [17,18] were validated mesh domain and boundary conditions for stepped spillway using the snappyHexMesh mesh generation method and the k-ω SST turbulence method (Table 1). In this study, the maximum cell dimensions are 0.05 m, and the minimum cell dimensions are gradually reduced to 0.001 m, as in the mentioned studies [17,18] (Fig. 4). Analyzes to determine the solution time were continued for 80 seconds. Although the flow reached a steady state after the 30th second, all analyses were continued for an additional 50 seconds (Fig. 5).

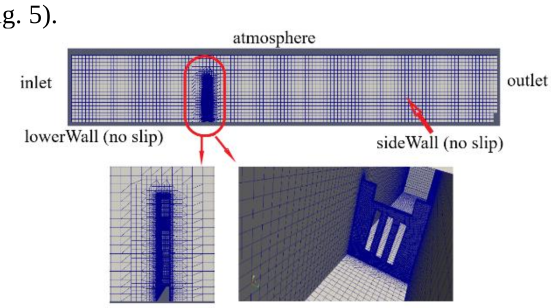


Figure 4. Mesh domain and boundary conditions

Table 1. Parameters in the boundary conditions [17,18]

	inlet	*outlet*	*lowerWall-sideWall*	*atmosphere*
U	variableHeightFlowRateInletVelocity	zeroGradient	noSlip	pressureInletOutletVelocity
omega	fixedValue	inletOutlet	omegaWallFunction	inletOutlet
k	fixedValue	inletOutlet	kqRWallFunction	inletOutlet
nut	calculated	calculated	nutkWallFunction	calculated
p_rgh	zeroGradient	zeroGradient	fixedFluxPressure	totalPressure
Alpha. water	variableHeightFlowRate	zeroGradient	zeroGradient	inletOutlet

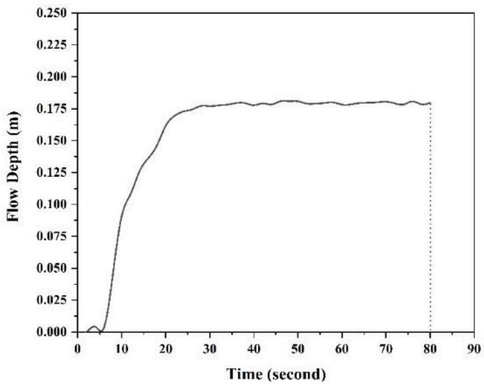
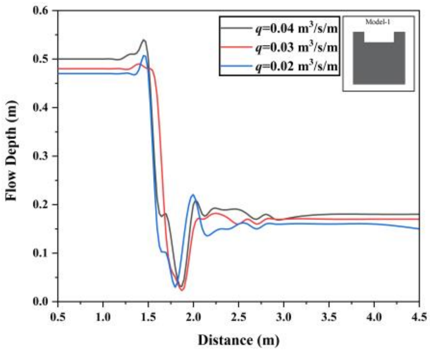
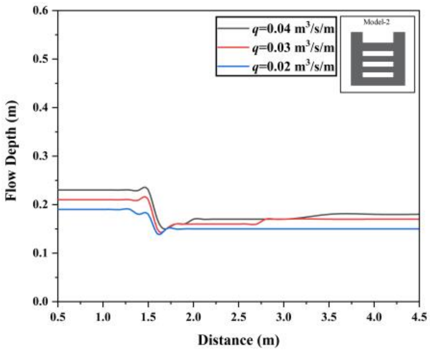


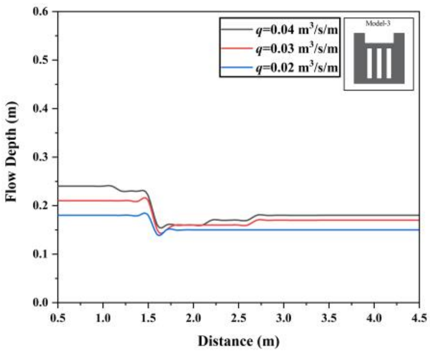
Figure 5. Variation of flow depth throughout the analysis time

3. RESULTS AND DISCUSSION

According to the results, an increase in water heights is observed as the unit flow increases. Due to the increased momentum, the hydraulic jump's length also increases in all models. Although the water height upstream of the classic check dam is considerably higher than in other models, no significant difference was observed between the downstream water heights (Fig. 6). However, since the height of the water surface in the region where the water falls in the classic check dam decrease due to the impact, it is thought that the amount of scour in this region will be higher compared to other models [19].







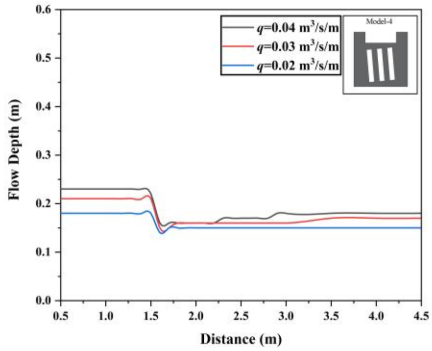
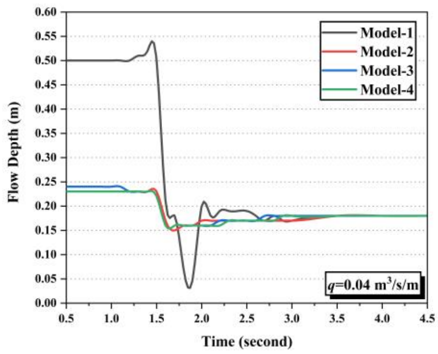
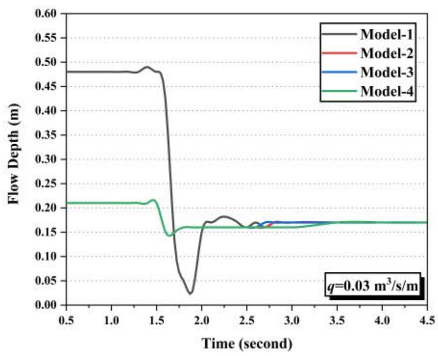


Figure 6. Water surface profiles

Figure 7 compares the water surface profiles of check dam types for three different flow discharges. Generally, water surface levels rise upstream of check dams and begin to fall downstream due to increased flow velocity. Larger discharges have visible effects on the surface profiles (Fig. 7a), whereas small discharges have a negligible effect on the water surface profiles (Fig. 7c). The model with the longest hydraulic jump length at maximum unit flow is Model-2, while at medium unit flow it is Model-4. The model with the shortest hydraulic jump length is Model-3.



(a)



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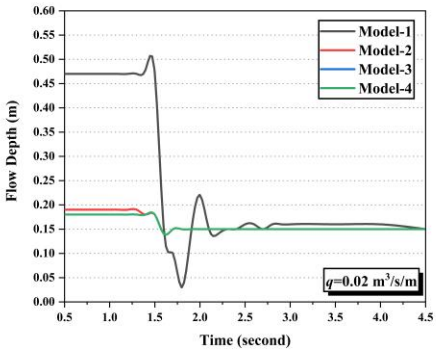

(c)

Figure 7. Comparision of the water surface profile for: a) q=0.04 m^3 s^{-1} m^{-1}, b) q=0.03 m^3 s^{-1} m^{-1}, and c) q=0.02 m^3 s^{-1} m^{-1}

The subcritical upstream flow condition (Fr<1) was used for all numerical simulations. The flow's depth decreases, and velocity increases throughout the slit models. Thus, the supercritical flow regime is observed downstream of the slit models. Then, the flow energy is dissipated due to the hydraulic jump, and the flow regime returns to the subcritical flow regime. This situation is important for stream regulation and flood control, particularly during high discharge during floods. The energy dissipation ratio was calculated using the following equations.

$$E = \frac{V^2}{2g} + h \tag{1}$$

$$\Delta E(\%) = \frac{E_1 - E_2}{E_1} \tag{2}$$

where, E_1 and E_2 are the specific energy at the upstream and downstream of the check dam, respectively. V is the mean velocity, and h is the flow depth.

The energy dissipation rates of the models are given in Table 2. The upstream Froude number (Fr_1) defines the subcritical flow regime, which ranges from 0.02 to 0.12. According to the results, while the energy dissipation rate increases as the unit flow rate increases in slit check dam models, the situation is the opposite for classical check dams. The energy dissipation rate varies between 63.5-65.8% for Model-1, 18.7-21.2% for Model-2, 16.5-24.4% for Model-3, and 16.5-21.2% for Model-4. According to these results, the highest energy dissipation rate among slit check dam models was observed in Model-3 at maximum flow rate, while it was obtained for Model-2 at minimum flow rate. As for the vertical or angled placement of the openings, no difference in energy dissipation rate is observed at low flow rates, while the vertical model (Model-3) is seen to be more effective at maximum flow rate.

Table 2. Energy dissipation rates

	q	h_1	h_2	V_1	Fr_1	V_2	E_1	E_2	$\%\Delta E$
Model-1	0.04	0.50	0.18	0.08	0.04	0.22	0.50	0.18	63.5
	0.03	0.48	0.17	0.06	0.03	0.18	0.48	0.17	64.3
	0.02	0.47	0.16	0.04	0.02	0.13	0.47	0.16	65.8
Model-2	0.04	0.23	0.18	0.17	0.12	0.22	0.23	0.18	21.2
	0.03	0.21	0.17	0.14	0.10	0.18	0.21	0.17	18.7
	0.02	0.19	0.15	0.11	0.08	0.13	0.19	0.15	20.8
Model-3	0.04	0.24	0.18	0.17	0.11	0.22	0.24	0.18	24.4
	0.03	0.21	0.17	0.14	0.10	0.18	0.21	0.17	18.7
	0.02	0.18	0.15	0.11	0.08	0.13	0.18	0.15	16.5
Model-4	0.04	0.23	0.18	0.17	0.12	0.22	0.23	0.18	21.2
	0.03	0.21	0.17	0.14	0.10	0.18	0.21	0.17	18.7
	0.02	0.18	0.15	0.11	0.08	0.13	0.18	0.15	16.5

4. CONCLUSION

In this study, the flow characteristics of the classical check dam and three different slit check dam models were compared, and 12 analyses were conducted for the subcritical flow regime (Fr<1) using OpenFOAM software and k-ω SST turbulence method. The results obtained are listed below.

- While the highest energy dissipation rate was observed in the classical check dam, the risk of scouring the downstream of these structures may be higher than in the slit check dams.
- Among the slit check dam models, the highest energy dissipation rate was obtained in Model-3 at maximum unit flow and Model-2 at minimum unit flow.
- While the energy dissipation ratios of model 2 and model 4 for maximum unit flow are equal to each other, for medium unit flow rate, the energy dissipation rates of all slit check dam models were equal.
- The model with the longest hydraulic jump length is Model-2.
- It has been observed that placing the openings vertically or at an angle does not change the energy dissipation rate at low unit flow, and the vertical model is more effective at high unit flow.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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