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Experimental and Numerical Investigations of the Hydraulic Characteristics of the Makhool Dam in Iraq: A Review

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Abstract

The hydraulic characteristics of dams can be predicted with high precision and reliability of physical and numerical models depending on accurate hydraulic data. The model is operated and simulated to get a more efficient, optimized utilization of the dam. This research included a comprehensive overview and literature examination of the Makhool Dam which is considered one of the most important dams under construction in Iraq. Previous studies of the dam focused on different topics in the operation of the dam and analyses of its properties, part of which focused on the dam ability to manage flood and how it works best with other dams in critical times, and another part studied the properties of the stilling basin, velocity in the dam reservoir, pressure, seepage and other characteristics that affect the operating the dam. Despite this research and the variety of topics discussed, there is no well-established research on the operation of the bottom and emergency spillway of the dam by using computational fluid dynamics (CFD) simulation software. CFD is considered an essential tech because it has an important influence in determining the hydraulic properties of a spillway and studying its effectiveness under different operating conditions. Because the spillway is an important element in the dam body, the research highlighted the necessity of performing a simulation using appropriate CFD software for this part. This research has also reviewed previous research on CFD software and their ability to simulate previously constructed or under-construction dams to analysis of its hydraulic properties.

Keywords: Makhool Dam, Computational Fluid Dynamics (CFD), FLOW-3D, Spillway.

التحقيقات التجريبية والعددية للخصائص الهيدروليكية لسد مكحول في العراق: مراجعة

فاطمة علي صادق ، هيثم علاء حسين ، محمد ريمي رزيني محمد عارف زينل

الخلاصة:

يمكن تحديد الخصائص الهيدروليكية للسدود بدقة وموثوقية عالية من خلال استخدام النماذج الفيزيائية أو العددية التي تعتمد على معلومات هيدروليكية دقيقة. يتم تشغيل النموذج ومحاكاته للحصول على كفاءة أكبر واستغلال أمثل للسد. تضمن هذا البحث نظرة عامة شاملة ودراسة أدبية لسد مكحول الذي يعتبر من أهم السدود قيد الإنشاء في العراق. وركزت الدراسات السابقة للسد على مواضيع مختلفة في تشغيل السد وتحليلات لخصائصه، جزء منها ركز على قدرة السد على إدارة الفيضانات وكيفية عمله بشكل أفضل مع السدود الأخرى في الأوقات الحرجة، وجزء آخر درس خصائص حوض السد، والسرعة في خزان السد، والضغط، والتسرب وغيرها من الخصائص التي تؤثر على تشغيل السد. على الرغم من هذه الأبحاث وتنوع الموضوعات التي تمت مناقشتها، لا توجد أبحاث راسخة حول تشغيل المسيل المائي السفلي والمسيل المائي للطوارئ باستخدام برامج محاكاة ديناميكيات الموائع الحسابية.

تعتبر برامج المحاكاة تقنية أساسية لأن لها تأثيرًا مهمًا في تحديد الخصائص الهيدروليكية للمسيل ودراسة فعاليته في ظل ظروف التشغيل المختلفة. ولأن المسيل المائي عنصر مهم في جسم السد، فقد سلط البحث الضوء على ضرورة إجراء محاكاة باستخدام برامج ديناميكيات الموائع الحسابية المناسبة لهذا الجزء .وقد استعرض هذا البحث أيضًا الأبحاث السابقة حول البرمجيات وقدرتها على محاكاة السدود التي تم إنشاؤها مسبقًا أو قيد الإنشاء لتحليل خواصها الهيدروليكية.

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1. Introduction

The Makhool Dam is one of the dams on the Tigris River basin in Iraq, suggested located northwest of Baiji, after the meeting points of the Tigris River with the Lower Zab River as shown in Figure 1[1]. Hence, the construction of the dam project will help in managing the excess water in the river and it's tributaries. It is considered one of the largest proposed hydraulic works in accordance with the International Commission on Large Dams (ICOLD).

This project is significant for the development of the Iraq's economy and the improvement of its social conditions, especially in consideration of the water shortages in the country. [2] There are a group of academic studies, scientific research, and technical reports that dealt with the Makhool Dam project from multiple aspects [3], including:

Engineering and hydrological studies dealt with dam Layout storage capacity characteristics of the reservoir and water flow estimates. it too affected along the abstract and environmental challenges relevant to the structure and Method of the levee [11-26.

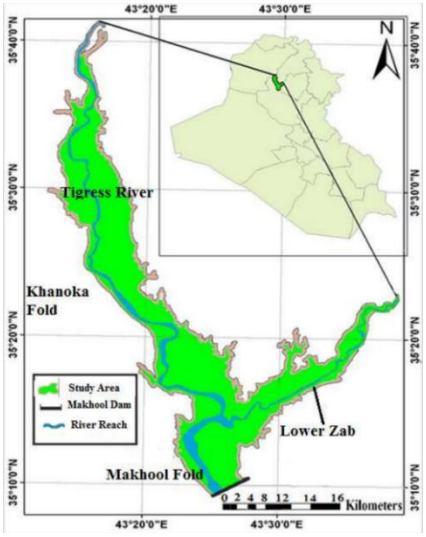

Figure (1): Makhool Dam region.

Despite these studies that dealt with the Makhool Dam, some aspects still lack sufficient research, such as enhancing studies using modern techniques such as advanced computer modeling, to improve the accuracy of assessments and forecasts, especially for the bottom and emergency spillway of the dam. For several years now numerical modeling has become an essential element in Lay outing and assessing dams to increase engineering structures' reliability and safety [4]. Makhool Dam, like other major dams, would greatly benefit from numerical modeling applications, especially about the spillway of the dam. Analyzing the hydraulic flow in a spillway using numerical modeling helps ensure that water can pass safely during periods of high floods, without causing erosion or structural destruction and analyzing the spillway properties [5]. The use of numerical modeling software such as HEC-RAS, ANSYS, FLOW-3D, PLAXIS, and GeoStudio can greatly enhance the accuracy and efficiency of designing and evaluating the spillway [6]. These programs employ enhancements of analytical methods that safeguard and maintain the structural soundness of water facilities by minute analysis of hydraulic flow dynamics, stresses and strains, and the parameters that affect the stability and sustainability of dams. [7],[8].

For instance, the FLOW-3D program that focuses of three-dimensional fluid dynamics and used to model water flow through Complex structures like dams and spillways can be used to study hydraulic consequences with great Precision [910]. The research review includes a group of researchers who applied programs to parts of the dam body and the ability of the programs to analyze their properties.

2. Material and Method

The review paper includes a comprehensive survey of the review papers and previous studies on the Makhool Dam that deal with the hydraulic performance of the dam and the factors affecting its operation. It also includes the historical development of research in the field of studying the dam and how to develop it and minimize operational risks from the design period of the dam in 1995 to the latest studies in 2024.

As in **The Tigris Center, in 1995,** conducted comprehensive hydrological research of the situation regarding the Tigris River and existing dams. The Al-Fatha Dam was discovered to be not economically feasible, and the Makhool Dam may not be able to protect the downstream areas from possible flooding. Nonetheless, the Makhool Dam being constructed at a higher elevation might be able to provide an alternative to the Al-Fatha Dam project. An important aspect is flooding possibility and the economic viability of the dams needs to be considered [11].

While **in Al-Furat Center, in 2002,** The researchers worked with the Ministry of Water Resources to use the physical hydraulic model for the Makhool Dam in 2002. Discharges, pressures, velocities, and water levels at certain points were measured by using a Reebok weir, digital current meter, and digital point gauge. Hence, the study was based on the hydraulic efficiency of the model and prototype structure through gravitational and inertial forces. To determine dam structures such as the bottom spillway, emergency spillway, stilling basin, power station, and fish pass the model scale of 1/100 was used. Then, it was observed that modification of the back channel and stabilization basin was useful in achieving certain flow requirements. In this study suggested to decrease the length of the spillway, increase the sidewalls in the stilling basin, and adjust the fish pass to avoid overtopping the structure. The model as shown in Figure 2.[12].

Al-Obaudi, R. F. A. (2002), focused in the study on assessing the hydraulic performance of large radial gates in closed conduits under high head conditions at the Makhool Dam and the Key findings of the study include firstly the flow beneath the gate was observed to be unrestricted for all runs, regardless of discharge variations, and downstream tailwater elevation did not affect the gate's hydraulic performance. secondly, the discharge coefficient equation (1) was found to be suitable for the Makhool Dam Bottom Outlet operation, with a specific formula provided .and the flow depths at the vena-contracta downstream of the

gate were dependent on the gate opening and could be calculated using equation (2)[13].

$$C_d = 1.93 * \left(\frac{G_o}{D}\right)^3 - 2.7169 * \left(\frac{G_o}{D}\right)^2 + 1.1407 * \left(\frac{G_o}{D}\right) + 0.5986 \quad (1)$$

$$\frac{H_2}{D} = 0.818 * \left(\frac{Go}{D}\right)^{1.2877} \quad (2)$$

Figure 2: The physical model of dam structures

Figure 3 shows the dam body with the radial gate in a physical model.

Figure 3: The radial gate in physical model

Al-Delewy, A. H. A., et. al (2005), focused in their research on the monthly operation of Makhool Dam w.r.t. the release and storage penalties by designing the discrete differential dynamic algorithm. As stated above, the development of water operation model is to meet the water demands, attain flood control and achieving hydroelectric power production. The main objective was to determine the best operational strategy for Makhool Dam that would enable it to realize its intended benefits such that the targets such as water demand, flood management, and power production are met. As a result, the study was designed to underline both the necessity and feasibility of optimal dam operation (although there are different amounts of natural water supply throughout the seasons) through Dynamic programming. The latter was introduced to ensure the possibility of solving this problem without any constraints on the rules of calculations. The specific operating rules of a Imitation Representation reflecting the wet and dry years were considered as part of the assessment of the system. the insurance of Improved Method was not fit to play the downriver demands during sure periods once the bekhma levee was not dynamic. The research presented the choice of factors such as irrigation needs and flood management as the main ones for applying weighting factors in the optimization method [14],[15].

Sissakian, V. K., et. Al (2006), studied evaluating the steep slope scarps along the western limits of the Makhool dam reservoir in Central Iraq. One of the study objectives was to determine the level of danger that these unstable slopes may render the dam less stable, in particular, it is unclear whether reservoir construction may modify the characteristics of previously exposed rocks and soils [16].

Khayyun, T. S. (2006), examined hypothetical dam failures of Mosul and Makhool dams using the FLDWAV computer program. Four scenarios were Checked investigating parameters like breach width and depth. Results showed critical flood areas and the importance of resistance on dam-break surges. The study developed dimensionless parameters for early warning systems [17].

Abbas, M. M. (2009), Studied two models designed to determine the hydraulic performance of the Makhool Dam stilling basin by experimental analysis, concentrating on the hydraulic jump characteristics and the basin design. The methodology was based on the comparison of the hydraulic jump lengths, jump locations, and the effect of the chute block dimensions on the performance of the two models analyzed. The study analyzed the hydraulic behavior of the water at various discharges and the basin design efficiency. The research showed that the second model was better than the first model in terms of hydraulic jump characteristics, with lower Froude numbers and better TWY1 values. Moreover, the researchers mentioned that the distance of the stilling basin could be shortened while keeping high level of performance unchanged. Recommendations were forwarded for further research and this included determining the detailed fluctuations in pressure for a more comprehensive analysis [18,19].

Abbas, M. M. (2013), conducted a pressure distribution experimental study on the surface of the Makhool Dam spillway. Coupled to plot pressure distribution on the spillways on varying discharges and channel locations was as one of the objectives of this study. The work was a series of tests on the design of the model spillway, the flow conditions, and the stress history of the actual spillway were simulated using a piezometer attached at different locations along the spillway surface. The model was discharged four times to gather data on the pressure distribution on the spillway surface by using piezometers to measure the pressure at different points along the spillway surface. Two regions of negative pressure were identified: I leave one at the ogee curve while the other is put just after, the sloping straight line after it ends. To avoid cavitation problems, the proposed the reduction of the slope of the ogee surface or the modification of the ogee formula [20].

Al-Shahry and Saleh, (2017), conducted a study on flood routing in the Tigris River at Baiji Station and Makhool Dam Reservoir. The study utilized mathematical Representations to predict levels in the reservoir and Baiji Station based on outflow discharge. It demonstrated that flooding in Baiji was unlikely and the levels in the reservoir did not reach a critical

situation. In this case, the importance is in identifying the complexity and the functional aspect of the flood routing of the system of the Makhool Dam to identify potential flood risks and the water level in the reservoir [21].

Almufti, T. M., & Al-Naemi, A. I. S. (2018), Conducted a research study whose purpose is to limit the extensions of the Makhool structure in the center of Iraq by using remote sensing techniques like satellite systems and LANDSAT7 ETM. This opening phase represents the attempt to resolve the differences in the results of previous studies on the shape and dimensions of the structures which leads the participants to work as if they were going to build a real structure. Based on the satellite data, earlier studies, and the well drilling undertaken by the authors an attempt is made to determine the size of the hydrocarbon reservoirs in this area. These geomorphic units are recognized by the coloration, the shades, and the textural characteristics of the emerging rocks, and where the evaluation is even more targeted it is done based on the drainage pattern. in the Research Discover, the Makhool has been confirmed to be twice as long as the previously reported 37 km. It also shows stages of profound uplift that created Tigris River folds thus altering the structural configuration. While the southeastern and northwestern regions of the Makhool structure have limited hydrocarbon potential, the central part is the area with higher hydrocarbon reserves in comparison with other regions [22].

Engineering Consulting Bureau, University of Anbar, (2020), constructed a technical report for the Makhool Dam project. The study stressed the need for the dam as a result of the large variations in the inflow which was a result of the reduction in the rainfall. The dam was underscored as a key means of water resources managing and curbing sediment (Mosul Barrage) to secure Baghdad against floods. Furthermore, the dam can be used to meet demands when there is a drought and has maximum release measures. The essence is the analysis of the climate change effects on water resources and the Makhool Dam which is the key water management facility and flood protection[1].

Al-Juboory, (2022), investigated the impact of the Makhool Dam and Samarra Barrage on the reduction of flooding in Baghdad, easing the situation of the Samarra Barrage and electricity production. The research revealed that the Makhool Dam is way smaller than other dams and would not be able to protect Baghdad City from flooding. It was highlighted that the AlTharthar inlet was insufficient for high discharges and it was proposed that a canal should be built to directly deliver water to the AlTharthar Lake. This significance is to be aware of the failure of the Makhool dam in flood mitigation and the suggested remedies for that [23].

Altawash, M. M. et. al, (2022), studied the velocity patterns and water depths inside the Makhool Dam reservoir at the highest operational water elevation of 150.25 m.a.s.l. The velocity patterns and water depths in the reservoir were analyzed with the help of HEC-RAS Two Dimension Software and a mathematical model was prepared. To understand velocity distributions, the outlets discharges were varied, and the effects of opening and closing of the spillway gates were modeled [24].

Al-Juboory, A. K. H. K. (2022), examined the efficacy of a storage system in the Makhool reservoir and Samarra barrage which consist of two reservoirs to defend Baghdad City from floods and alleviate the Samarra barrage pressure. The research was intended to appraise the capability of the system to generate hydroelectricity and deliver water for dry seasons, on the Tigris River, Iraq [25].

Hameed, H. K, et. al (2023), conducted a hydrostatic analysis of the water seepage from the Makhool dam in northern Iraq using the finite element method with the help of modern software. The research dealt with the identification of the areas where the foundation of the dam was weak, mainly on the right and left sides, to evaluate the seepage levels and suggest the required modifications by utilizing the finite element method through the SEEP/W software for seepage analysis[26]. as shown in figure 4.[27].

Irzooki, R. H. et. al (2023), studied the stability of the slopes of Makhool dam under maximum seismic acceleration that occurred in the dam area, which was 0. 29g with an inclination angle of 7. 3ML as a result of an earthquake in 2017. The study utilized Geo-slope programs and the finite element method [28],[29]to assess dam slope stability under earthquake conditions for three scenarios: in cases of completion of construction tasks, accomplishing the maximum reservoir water level, and during rapidly filling processes of the reservoir. Regarding the seismic safety of the dam slopes, the analyzed factors for the slopes were found stable and met the acceptable safety levels of the Makhool Dam project, except the coincidence of an earthquake with rapid reservoir emptying might cause critical stability or collapse in some parts of the upper slope [30].

M. R. A. Al-Zaidy (2023), combined all the aspects of the absolute significance of the Makhool Dam project by his literary studies.

In this research, the researcher tried to address the ambiguity that accompanied the construction of the dam project over the years. the geologic Structure of the levee place was checked by using modern and sophisticated techniques [31], and a survey of real events, and a review of ministry decisions on the levee.

In conclusion, the research noted that despite the damage to neighboring areas, the government will compensate for this while trying to minimize the damage through some modifications [32].

Rasheed, N. J, et. al. (2024), focused on The Influence of Climate Change on Sedimentation within Makhool Dam Reservoir. Using HEC-RAS software the sediment and flow dynamics of the Tigris River were simulated under different operating conditions. The results indicated that the sediment mass is expected to increase at the confluence of the Greater Zab with the Tigris River. The study indicated that the Layout life of the Makhool reservoir could be very importantly extended under different emission scenarios highlighting the reservoir's ability to trap sediment [33].

The studies reviewed above cover a wide range of topics related to the hydrological characteristics of the dam and flood routing. Research has addressed the impact of the dam on flood mitigation in Baghdad with the characteristics of the dam's stilling basins using physical models as well as focusing on the study of pressure and velocity distribution in the dam using simulation software.

Furthermore, the studies examined the effectiveness of storage systems for flood defense and hydropower generation, as well as the dam's slope stabilization and sediment control measures. Existing studies on the dam have referred to a comprehensive analysis of all its parts, but there is no detailed study of the spillway using advanced simulation software to study its characteristics. This is a deficiency in current research. Therefore, studies using computational fluid dynamics (CFD) simulation programs are recommended to fill this gap and improve our understanding of the characteristics of the spillway more accurately.

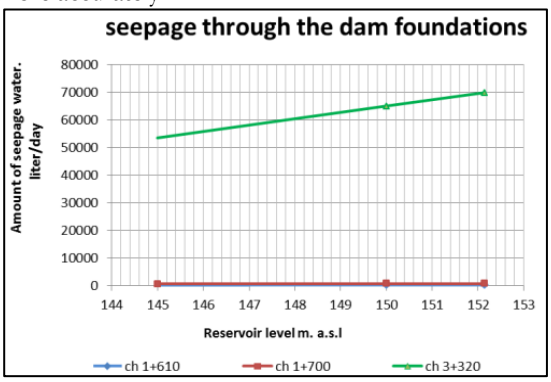

Figure (4): Amount of seepage through Makhool dam at three different stations.

3. Previous studies using simulation software

Computational Fluid Dynamics tools are software applications used to simulate fluid flow, The CFD Module is an optional package modeling with customized physics interfaces and functionality optimized for the analysis of all types of fluid flow[34]. It is developed for a wide variety of users including researchers, developers, teachers, and students. It is not just a tool for CFD experts; it can be used by all engineers and scientists who work with systems in which momentum transport through fluid flow is an important part of a process or application [34]. Modeling and simulating fluid flow by use of CFD modeling is a cost-effective way for engineers and scientists to understand, develop, optimize, and control designs and processes [35]. As a basic, the CFD model in an open channel depends on the continuity and Navier Stocks (momentum) equations to solve complicated flow problems over the spillway [36]. there are many CFD commercial software designed to represent and solve governing equations of fluid flow such as(Flow Modeling Software) FMS-1D, (Integrated Simulation of Solute - Fluid Interaction) ISIS-CFD for 1Dimensional Models, HYDRO,(Navier-Stokes Solver in C for 2D and K-epsilon) NSC2KE, (Navier-Stokes 2 Dimensional) NaSt2D for 2Dimensional Models and (Simulation of Turbulent flow in Arbitrary Regions - Computational Dynamics) STAR-CD, FLOW 3D, CFX, (Sediment Simulation in Intakes with Multiblock option) SSIIM, Fluent for 3Dimensional Model [37],[38].

Most of this software contains models to represent complex flow over spillways which help to reduce the time needed to write the code. These platforms took more than 40 years of experimentation and development by companies and organizations to reach these remarkable results in spillway modeling [39]. The paper includes a review of global and local research to evaluate the hydraulic performance of dams, especially the spillway, by using CFD programs.

Lotfi, R., et. al (2012), studied the FLOW3D numerical model to evaluate the flow over a rectangular broad-crested weir and stilling basin. FLOW3D predicted flow Layouts that aligned with the general flow profile in the hydraulic structure demonstrating its capability to predict a hydraulic jump. Two or different modifications in the end sill layout were suggested and investigated in order to increase the hydraulic energy dissipation and also the quality of the hydraulic jump.

The numerical Imitation indicated that these modifications could very importantly Improve the energy-moistening Method by decreasing the hydraulic jump length in the stilling basin while increasing the inlet chute length [40].

Nama, A. H. (2015) which were directed at determining the spatial distribution of bed and bank shear stress in the meanders of the Tigris River within Baghdad City: Al- Al-Kadimiyah, Al- Atafiyah and Al –Jadiriyah bends.

The simulation was conducted using a steady flow hydraulic model with the HEC-RAS software one of the CFD programs to analyze flow characteristics across ten slices in the river for various discharge scenarios (400, 800,1300) m^3/s.

The methodology involved using the reach-averaged boundary shear stress equation to estimate shear stress and the Federal Highway Administration guidance for high shear stress locations, with data processing done using Arc-GIS software. Results showed that the meandering effect increased the maximum shear stress in the bends by approximately (16, 22, and 31%) for different discharge levels[41].

Mohammed, M. F., et. al (2017), focused on enhancing the thermal Effectiveness of flat plate solar water collectors using modified Layouts like twist strips and helical springs inside riser pipes. The Imitation was conducted in a three-dimensional laminar regime using FLUENT software Edition 14.5. It complicated answering the government equations (continuity impulse and energy) to analyze the effect of run-along temperature dispersion inch the collectors with and without the inserted devices results showed that collectors with these Improvements had higher warmth change Productivity compared to those without whatever modifications.[42]

Al-Abbas, A. H. (2017), focused on conducting 3-D numerical Imitations of thermal collectors in solar heating systems comparing conventional systems with multipurpose solar water and air heaters. The

Imitation was conducted using the commercial computational fluid dynamics (CFD) program AVL Fire ver.2009.2.

The RNG k - ε turbulence Representation was employed for the CFD study which one of the turbulence models is solving continuity momentum and energy equations in a finite-volume framework.

The study involved the Representation of the geometry of absorber plates and riser tubes for both solar water and air heaters comparing simulated results with experimental Information for validation[43].

Asghar, M. Haris (2020) explored how he conducted his study on flow characteristic of Domeli dam spillway employed with CFD modeling. According to the data, it was noted that the aspect of the computational fluid dynamics model of the efficiency of the estimation of the flow characteristics of the spillway showed the certainty of the software for the flow depths with a difference of around one percent between the simulations values and the observed one [37].

Rajaa, A. I., et. al., (2020), focused on comparing turbulence Representations to simulate flow Layouts over an ogee spillway at the Mandali dam in Iraq (as a case study) [44].

The Imitation was conducted using the Flow-3d software with the Volume-of-Fluid (VOF) Procedure to capture the free surface for each turbulence Representation. The methodology involved using a uniform mesh with a 20 cm cell size in all directions of the control volume to Improve the stability and Precision of results.

Results of the simulation in Figure 5 showed that the Large Eddy Imitation (LES) Representation outperformed the turbulence closure Representations in replicating laboratory results [45].

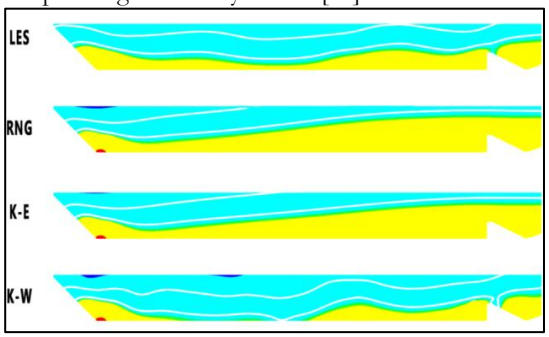

Figure (5): Simulate flow at the Mandali dam

Gandomi, M. Ů et. al., (2022) focused their research on the simulation of an ogee spillway at Shahid Abbaspour Dam using FLOW3D software as shown in Figure 6. Among the factors taken into account in numerical model, the simulation of turbulence and flow characteristics were important. Other related researches include analyses on the trapezoidal weirs, the water surface profiles in the duckbill weirs[46], and the flow hydraulics in numerous kinds of weirs.. The simulation results showed that increasing the dam's weir height from 510 to 513.5 meters, along with fully opening the gates, did not create negative pressure on the weir surface and kept the cavitation index within an acceptable range. The study utilized the Flow3D software to model the weir and validated the results against physical model data, showing good agreement. The research investigated flow conditions for discharges of 3000 m3/s and 15000 m3/s, focusing on the cavitation index and negative pressure on the weir in new conditions [47].

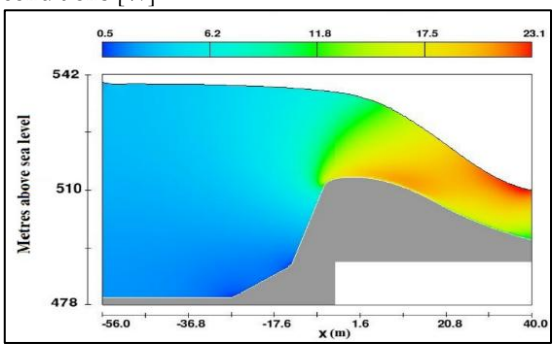

Figure (6): Velocities in the 3D model of Shahid Abbaspour Dam

Abdulrahman, K. Z., et. al. (2024) used in their study flow 3d software to create a 3D numerical model to analyze the flow characteristics of the Majd Al-Sabah spillway at Dokan Dam in Iraq. The effectiveness of the developed model was confirmed with physical experimentation [48] and the error of the flow estimates was determined and was found to be 5% or less. There were fluctuations in the discharge at low levels while at high water levels, the discharge was permanently washed off due to the continuity of the process. Regarding the pressure distribution, variations within the vertical column were emphasized and the highest pressure was recorded at the bottom of the column. Regarding velocity, the maximum and minimum velocities were recorded in sectors 3 and 4 for water levels 516 and 512 meters, respectively. Further the Froude number analyses revealed that the bottom tunnel flow becomes supercritical for zones of high water levels because of higher velocities of the flow [49].

Azzubaidi, R. Z., et. al. (2024) analyzed the hydrodynamics of Al Adhiam Dam and works out the behaviors of the stabilization basin with the help of number simulation models. FLUENT was used to simulate the flow in the spillway of the Al Adhiam Dam. The computation of the free surface was done according to the fluid volume method. Concerning the turbulence, the SST kω turbulence model was selected particularly for this model. The study showed that the spillway can carry the design discharge and flood wave and that negative pressure occurs at some points in the stabilization basin due to the high velocity [50]

Dehghan, M. (2024). Performed numerical simulation of downstream bed scour with the Flow-3D model to understand the effect of dam design on scour. The model was calibrated using a laboratory sediment transport study [51]. Subsequently, 18 different cases of skewed and triangular piano dams were studied under varying discharge and abutment conditions. It was observed that the flow rate in the piano key dam was 25%-45% lower compared to the skewed dam. Maximum drift depth decreased when the dam depth percent was increased by 29% in the trapezoidal dam and 26.6% in the triangular dam. Also, a decrease in maximum drift depth was observed in the trapezoidal and triangular dam when reducing

discharge and aquifer depth. Increasing the floodplain depth causes a loss of energy for the jets falling from the dam while reducing the bed capacity leads to an increase in drift.[52].

4. Conclusion:

This review paper aimed to assess the hydraulic characteristics of the Makhool Dam in Iraq, synthesizing existing research and pinpointing areas requiring further investigation. Research on the Makhool Dam has advanced considerably, employing both physical and numerical models to analyze various dam aspects, from flood management and hydropower generation to seepage and structural stability under seismic stress. However, a significant gap remains regarding comprehensive analysis of the spillway's hydraulic properties, particularly the bottom and emergency spillways. Existing studies have largely overlooked the application of Computational Fluid Dynamics (CFD) for these components, which is essential for accurate modeling under varied operational conditions. To support scientific progress in this field, future research should prioritize CFD simulation for spillway analysis to enhance the reliability and safety of dam operations. This includes the use of advanced software such as FLOW-3D and HEC-RAS to simulate complex fluid interactions and assess spillway performance. Such efforts could also inform best practices for other hydraulic projects, extending their findings to similar infrastructures. The continuation of research in spillway hydraulics is crucial, particularly regarding resilience to climate-induced hydrological changes. I recommend supporting initiatives and leaders focused on CFD model implementation, as this approach allows for high-fidelity assessments and risk mitigation. Conversely, reliance solely on traditional physical models without CFD integration is insufficient for the predictive needs of modern hydraulic engineering and should be reconsidered. Simulation software.

5. More Recommendations

To ensure better operation of the spillway, it was proposed to conduct a numerical model simulation that includes the development of a hydraulic model and analysis of them at minimum cost and time.

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