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Research Article:

A comprehensive Analysis of Dewana Dam Spillway Failure: Causes, and Consequences

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Abstract

In February 2024, the Dewana Dam spillway in the Kurdistan Region of Iraq experienced a critical structural failure during a moderate flood with an estimated peak discharge of 200 m³/s. This study presents a forensic analysis of the incident, examining hydraulic, structural, and geotechnical factors behind the failure. Damage was concentrated in the lower spillway chute, where uplifted and displaced concrete panels exposed a friable claystone–sandstone foundation. Subsequent erosion formed large scour cavities and further destabilized the structure. The failure was chiefly linked to construction deficiencies, including poor waterstop installation, pre-existing cracks, and ineffective seepage control, which together enabled excessive uplift pressures. The untreated foundation—left exposed during a prolonged construction pause—was not properly rehabilitated before work resumed, heightening its vulnerability to erosion. The failure mechanism mirrors well-documented spillway chute instabilities associated with poor subgrade conditions, insufficient slab restraint, and weak construction quality control. This incident underscores the importance of integrated detailing, robust foundation treatment, and continuous oversight in spillway design and construction.

1. Introduction

Spillways serve as critical safety components of dams, designed to safely convey excess water downstream and prevent overtopping (Salunkhe, 2020). However, the integrity of a spillway depends on rigorous design, quality construction, and regular maintenance. Any shortcomings in these areas can result in severe structural failures with far-reaching consequences (Khatsuria, 2005). The Dewana Dam spillway, a relatively new hydraulic structure commissioned in 2022, provides a compelling case study of how latent vulnerabilities can manifest under normal hydraulic conditions. During its initial year of operation in 2022, the Dewana spillway did not experience any flow. In 2023, it successfully passed a peak flood of approximately 160 m³/s without visible damage, offering initial confidence in its performance. However, this perception was abruptly challenged in February 2024, when a subsequent flood event with a slightly higher peak discharge of around 200 m³/s caused significant structural damage to the chute spillway. Most notably, the chute slab near the stilling basin—located along the steepest section of the chute—experienced catastrophic failure. The slab broke, uplifted, and was displaced downstream, exposing the underlying low-quality foundation rock to direct high-velocity flow. This exposure initiated aggressive erosion processes, resulting in deep scour holes and further degradation of the structure. A key mechanism in such failures is flow-induced uplift pressure beneath spillway chute slabs, particularly in cases where slab joints are unvented or have poor drainage (ICOLD, 2015) (USBR, 2022). (Wahl et al., 2019) demonstrated that uplift pressures below chute slabs at unvented, open, offset joints can reach damaging levels during high-flow events, especially if foundation drainage is inadequate. Similarly, (Wahl

& Heiner, 2024) provided predictive methods for uplift pressures and joint flows along spillway chutes, showing that even small gaps or discontinuities can allow pressure build-up that compromises slab stability. The Dewana dam spillway event bears notable similarities to the 2017 Oroville Dam spillway failure in California, where undetected foundation weaknesses, combined with poor construction practices and inadequate maintenance, led to progressive erosion and large-scale damage (Independent Forensic Team Final Report, 2018). Both cases highlight the critical importance of robust geotechnical investigations, attention to foundation conditions, and continuous inspection regimes. As emphasized by (Arifani & Prakoso, 2019), inadequate soil investigation during the design phase can lead to miscalculations in slope stability, ultimately resulting in operational failures. Similarly, neglecting preventive maintenance allows minor issues—such as concrete deterioration or joint separation—to escalate into major structural threats under hydraulic loading. The Dewana Dam spillway failure underscores the need for a comprehensive forensic assessment to understand the contributing factors and failure mechanisms involved. This study aims to systematically analyze the causes and consequences of the failure and extract actionable lessons to guide the design, construction, and maintenance of future spillway systems.

2. Materials and Methods

This study employed a multidisciplinary forensic engineering approach to investigate the failure of the Dewana Dam spillway. The methodology followed practices commonly adopted in post-failure investigations of hydraulic structures, integrating structural inspection, geotechnical evaluation, hydraulic analysis, and comparison with relevant historical failures.

2.1 Study Area

The Dewana Dam is situated in the Darbandikhan District, within the Kurdistan Region of Iraq, as illustrated in Figure 1. Strategically positioned in a mountainous terrain, the dam was constructed to address both water management and regional development needs. With a total storage capacity of approximately 21 million cubic meters (Technical Dam Design Report, 2014), it serves as a vital infrastructure asset supporting multiple sectors including agriculture, fisheries, and tourism. The dam is equipped with an ungated overflow spillway, designed to automatically convey excess water during flood events without the need for mechanical operation. Table 1 provides a summary of the dam and spillway's main characteristics from the design documents of the Dewana dam, which form the basis for the failure analysis presented in this study. Figure 2 shows the spillway profile.

2.2 Site Inspection and Damage

Documentation A detailed field investigation was carried out immediately following the February 2024 flood event. Visual inspection and photographic documentation were performed to characterize the extent and nature of structural damage. Specific attention was given to:

- Displacement and cracking patterns in the chute slabs.
- Uplifted concrete panels and joint separations.
- Exposed foundation rock quality and erosion features.
- Waterstop installation condition.
- Upstream key of the panels and their effectiveness. Figure 3 and Figure 4 are two photos for pre and post failure conditions; respectively.

2.3 Hydraulic Back-Analysis

A hydraulic back-analysis was conducted to estimate flow conditions and corresponding pressures acting on the chute floor during the flood event. Uplift pressure estimation at slab joints was performed using the methodologies described by (Frizell et al., 2013), which account for flow-induced pressure transmission at unvented open joints and slab discontinuities. Assumptions regarding joint geometry, and foundation permeability were informed by design drawings and site observations. The flow-induced pressures were compared to the expected slab weight to assess the plausibility of uplift-driven failure.

2.4 Ansys Fluent Software

In the current study ANSYS-CFX code has been used for flow simulation in the side channel spillway (Couto, 2012). The code is based on finite volume method, which discretizes Naiver stokes equations at each computational cell. In turbulent flow, velocity at each point consists of two components, mean $(\overline{\boldsymbol{U}})$ and fluctuating velocities $(\boldsymbol{u'})$. The mass and momentum equations (Versteeg & Malalasekera, 2007) in the time average form for incompressible flow can be written as:

$$\frac{\partial}{\partial x_i}(\rho \bar{U}_i) = 0 \ldots\ldots$$

$$\frac{\partial}{\partial x_i}\rho \bar{U}_i \bar{U}_j = -\rho g_i - \frac{\partial \bar{P}}{\partial x_i} + \frac{\partial}{\partial x_j}[\mu\left(\frac{\partial \bar{U}_i}{\partial x_j} + \frac{\partial \bar{U}_j}{\partial x_i}\right) - \rho \overline{u_i' u_j'}] \ldots\ldots$$

The Naiver - Stokes equations with time average velocity called Reynolds averaged Naiver – Stokes (RANS) equations. This method eliminates turbulent fluctuations by the averaging process. The averaging of nonlinear terms in the Naiver Stokes equations causes additional unknowns called Reynolds stress. Most of commercial CFD codes use time average equations such as RANS equations for modelling turbulent flow. The term $(-\rho u_i' u_j{}')$ is referred to the Reynolds stresses, in three dimensional (RANS) equations there are six unknown terms, they behave like stresses. The turbulence modelling is a computational procedure that can close the governing equations by modelling Reynolds stresses (Hân, 2013). Numerous turbulence models are available based on RANS equations. ANSYS-CFX contains numerous turbulence models which can be divided into two groups namely; eddy viscosity and Reynolds stress models.

2.5 Geotechnical Assessment of Foundation Conditions

A geotechnical assessment was conducted to evaluate the foundation conditions beneath the damaged spillway slabs. Visual inspection of the exposed subgrade revealed significant erosion and material loss, particularly beneath the displaced slab sections. Erosional depths reached approximately 1.8 meters, indicating that the underlying rock was highly friable and of insufficient strength to withstand high-velocity flows and uplift pressures. To contextualize these findings, historical geotechnical investigation reports, borehole logs, and construction quality control records were reviewed. The data revealed a notable discrepancy between the originally assumed foundation conditions during design and the actual in-situ state at the time of failure. Further investigation revealed a key construction-phase deficiency: the spillway foundation excavation had been completed several years prior to slab placement but was left exposed to environmental weathering due to project funding delays. The exposed foundation—primarily composed of claystone and interbedded sandstone—underwent significant degradation over a four-year hiatus before construction resumed as shown in Figure 5 that has been taken from a reliable reference (Omed Yousif, 2024). Critically, the weathered and weakened surface layers were not adequately removed or reconditioned prior to concrete placement, resulting in a compromised bearing stratum with reduced erosion resistance.

3 Review of the Design and Operational Records

To evaluate the adequacy of the original design and its assumptions, the following materials were reviewed:

- Design reports, including spillway hydraulic and structural calculations.
- Drawings detailing slab joint spacing, thickness, reinforcement, and anchorage.
- Construction and quality control documentation, including concrete strength tests and foundation preparation records.
- Operation and maintenance logs from 2022 to 2024, including records of inspections, any reported issues, and flood hydrographs.

This review helped assess whether the failure could be attributed to design underestimation, construction deficiencies, or inadequate maintenance—as often found in similar failures (Independent Forensic Team, 2018).

4 Results and Discussion

Identifying the primary cause of the initial failure in the Dewana Dam spillway presents a complex engineering challenge, particularly given the severity of structural damage observed during the flood event. The lower chute section was subjected to high-velocity flows that exerted significant erosive forces, ultimately resulting in the loss of concrete slabs and exposure of the underlying foundation. A detailed evaluation of the failure mechanism necessitated the examination of several failure modes commonly associated with concrete spillway chute distress, in order to reach a well-supported conclusion regarding the most probable cause of failure. The analysis focused on the following potential mechanisms:

- **Cavitation:** Flow high velocity, discontinuities and surface irregularities may have generated localized low-pressure gradients, leading to cavitation erosion.
- **Joint, cracks and Waterstop Failure:** Improper installation and deterioration of waterstops enabled seepage through joints, increasing internal pressures and weakening structural continuity.
- **Poor-Quality Foundation:** The foundation, composed of friable claystone and sandstone, had not been adequately treated and was highly vulnerable to erosion.
- **Uplift Pressure:** The absence of anchorage systems and inadequate drainage likely allowed the accumulation of uplift pressure beneath the slabs, contributing to their displacement.

Cavitation

According to the numerical simulation results obtained using ANSYS Fluent, the maximum flow velocity at the downstream end of the spillway chute reached approximately 23 m/s, as illustrated in Figure 6. To assess the potential for cavitation-related damage, a detailed site inspection was conducted in conjunction with hydraulic analysis. Observations did not reveal typical signs of cavitation-induced distress such as pitting or surface degradation. Based on the simulated velocity

(23 m/s) and its corresponding flow depth of 0.1 m, the computed cavitation number was approximately 0.375 (see Equation 1). As this value exceeds the critical threshold of 0.25 suggested by (Falvey, 1990) (see Table 2), the flow conditions were not considered conducive to cavitation damage. Therefore, cavitation was ruled out as a significant contributor to the spillway chute failure in this case.

$$\sigma = \frac{P - Pv}{{}^{1}/_{2}\rho V^{2}} \text{.....................................(eq.1)}$$

Joints, Cracks and Waterstops

A key factor contributing to the initial distress observed on the chute floor was the presence of cracks, along with inadequate joint detailing and poor performance of waterstops. Evidence of cracking was observed shortly after the completion of construction, as shown in Figure 7, indicating potential issues related to early-age shrinkage, poor finishing, or insufficient curing. Figure 8 illustrates a substantial 10 cm vertical offset between adjacent panels, where no cushion was provided to control differential movement. Additionally, Figure 9 highlights improper waterstop installation, which allowed seepage along the joint line, increasing the risk of uplift pressure beneath the slabs. The combination of these deficiencies—cracking, joint misalignment, lack of cushioning, and ineffective seepage control—significantly undermined the structural integrity of the spillway chute and contributed to its eventual failure. In well-designed chute structures, a cushion is typically incorporated at the downstream end of a chute panel—specifically at the cutoff wall located at the upstream edge of the adjacent downstream panel—to provide structural support for the upstream panel edge. This detail plays a critical role in preventing differential movement between adjoining panels by distributing applied loads and maintained consistent contact under both static and dynamic hydraulic conditions. In the case of the Dewana Dam spillway, the absence of this cushion detail allowed adjacent panels to move independently, leading to vertical misalignments and the development of offsets within the flow path, which increased the susceptibility of the structure to hydraulic and structural failure. Moreover, the waterstops, which are critical for preventing seepage through joints, were either poorly installed or failed to maintain an adequate bond with the adjacent concrete panels. This created preferential seepage paths beneath the chute panels, promoting the development of uplift pressures and subsequent slab instability.

Poor Quality Foundation

Another cause for the failure of the Dewana Dam spillway was primarily due to its construction on poor-quality bedrock. This substandard foundation material was highly susceptible to erosion. Over time, water infiltrating through cracks and inadequately sealed joints began to undermine the integrity of the subgrade. As the erosion progressed, it caused parts of the chute slab to crack and shift. The resulting gaps allowed even more water to enter and accelerate erosion within the foundation as shown in Figures 10 and 11. This process led to the displacement of slab sections, exposing the already weak bedrock to further degradation. Ultimately, the erosion reached a critical level, forming deep scours and severely compromising the structural integrity of the spillway. Another factor that may have contributed to the failure is the orientation of the bedding planes in the jointed rock foundation. The bedding planes were observed to be approximately parallel to the spillway chute slope, which could have facilitated the downslope movement of the concrete panels. This condition becomes particularly critical under the influence of stagnation pressure forces, which act parallel to the panel surface at locations where offsets or misalignments exist. Combined with the inherently weak shear strength of the bedrock, this geological configuration likely reduced the resistance to sliding and exacerbated panel instability during high-velocity flow events. The case might not be worsened like this if the bedding plane angle were perpendicular to the chute angle as shown in Figure 5.

Uplift Pressure

Prolonged water percolation beneath the chute panels led to progressive erosion of the underlying low-strength foundation material. The absence of a cushion at the cutoff key, which is typically used to prevent differential settlement, likely contributed to localized displacement between adjacent panels. This displacement may have created geometric offsets within the flow path. At such offsets, a stagnation zone forms where the high-velocity flow directly impinges on the upstream face of the discontinuity. In this region, the velocity head of the approaching flow is transformed into pressure head, generating stagnation pressure (Chow, 1959). This concentrated pressure can significantly increase uplift forces acting under the chute slabs, potentially leading to structural failure if not properly mitigated. When a discontinuity or opening exists within the slab joint, this stagnation pressure may be partially or fully transmitted through the joint, inducing uplift forces beneath the concrete slab (peterka, 1978). For high-velocity flow (flow over steep chutes), stagnation pressure can result in very high uplift pressures due to the conversion of the velocity head to a static head which can lead to slab uplifting (jacking) and removal of sections of the concrete lining (Frizell, 2007).To estimate the flow velocity immediately upstream of the offset, Equation (2), as proposed by (Rouse, 1946), was utilized

$$\frac{v_y - V}{V\sqrt{f}} = 2\log_{10}\frac{y}{y_0} + 0.88 \quad \text{(eq.2)}$$

Where v_y= velocity at distance y above the boundary; f = Darcy Weisbach friction factor; y = distance from the boundary; y_0 = total flow depth; and V = mean flow velocity.

Taking an offset height of 5 cm as a representative example, the flow velocity was calculated at the midpoint of the offset—2.5 cm above the boundary layer. At this location, the velocity was found to be approximately 23.45 m/s. Once the mid-height velocity v_y was determined, the corresponding stagnation pressure was found equal (274.95 KN/m^2) using Equation (3).

$$\frac{Ps}{\gamma} = \frac{v_y^2}{2g} \quad \text{(eq.3)}$$

Where Ps = stagnation pressure; γ = unit weight of water; v_y = approach velocity of the stagnated flow; g = acceleration due to gravity.

The uplift pressure head can be expressed as a percentage of the velocity head within the boundary layer at the mid-height of the offset, To calculate the total uplift force acting under the spillway slab, the computed stagnation pressure (Ps) is multiplied by both the panel area and the percentage factor, which accounts for the influence of joint geometry. For instance, with a stagnation pressure of 274.95 kN/m^2, a panel area of 10 × 10 m², and a percentage factor of 80% corresponding to a gap width-to-offset ratio of 0.06 (i.e., 3 mm / 50 mm), the total uplift force is calculated as:

$$\begin{aligned} Total\ uplift\ pressure\ force \\ &= (274.95 \times 10 \times 10) \times 0.8 \\ &= 21{,}996\ KN \end{aligned}$$

Table 3 presents a summary of uplift pressure forces calculated for various offset heights and corresponding stagnation pressures. The results presented in Table 3 indicate a clear relationship between the offset height and the corresponding stagnation pressure and total uplift force acting under the spillway slab. As the offset height increases, the velocity (v_y) also increases, which directly contributes to a higher stagnation pressure. This trend is consistent with hydraulic theory, where larger offsets generate more intense flow impingement and pressure buildup at the base of the slab. For the maximum offset of 10 cm, the computed v_y reaches 24.43 m/sec, resulting in a stagnation pressure of 298.41 KN/m^2 and a corresponding uplift force of 23,872 KN In contrast, the smallest offset of 2.5 cm yields a lower v_y of 22.47 m/sec, stagnation pressure of 252.45 KN/m^2, and a reduced uplift force of 20,196 KN. This clearly demonstrates that even small variations in offset height can significantly influence the hydraulic loading on the slab. Importantly, when comparing these uplift forces to the self-weight of the slab (estimated at 941.76 KN), it becomes evident that the uplift force greatly exceeds the gravitational resistance in all cases—by a factor of more than 20. This indicates a highly unstable condition, where the slab is vulnerable to displacement or complete failure (see Figure 4) unless additional resisting mechanisms (e.g., anchors or dowels) are provided.

5 Conclusion

The failure of the Dewana Dam spillway during the February 2024 flood event provides a compelling case study of how hydraulic, structural, and geotechnical deficiencies can interact to compromise the integrity of critical infrastructure. The investigation revealed that the primary causes of failure were: (1) improper installation of joint waterstops, allowing uncontrolled seepage and uplift pressures beneath the slabs; (2) pre-existing cracks in the chute panels, which weakened the structural continuity; and (3) a weathered, untreated foundation composed of low-strength claystone and sandstone, left exposed during a prolonged construction delay and not adequately reconditioned prior to concrete placement. These deficiencies led to the uplift and displacement of chute slabs, exposure of erodible foundation material, and progressive scour, ultimately resulting in substantial damage to the spillway's downstream section. The mechanism of failure is consistent with known failure modes in spillway engineering, emphasizing the combined role of inadequate detailing at slab joints, cracks, poor subgrade conditions and uplift pressure.This case underscores several critical lessons for hydraulic infrastructure design and construction:

- Joint systems must be fully embedded and properly detailed to prevent leakage and pressure buildup.
- Concrete slab integrity must be ensured through appropriate reinforcement, curing, and crack control measures.
- Geotechnical preparation must not be compromised by construction delays; weathered

foundations must be re-excavated or treated to restore strength and erosion resistance.

- Quality control and inspection during all construction phases are essential for long-term structural performance.

The Dewana Dam spillway failure adds to the growing global body of evidence stressing the need for integrated hydraulic and geotechnical design approaches, especially for spillways expected to operate under extreme flow conditions. The findings offer valuable guidance for improving the design resilience, operational safety, and maintenance planning of future dam spillway projects.

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تحليل شامل لفشل مفيض سد ديوانه: الأسباب والعواقب

المستخلص

في فبراير ٢٠٢٤، شهد مفيض سد ديوانة في إقليم كردستان العراق فشلاً إنشائياً خطيراً أثناء فيضان معتدل بلغ تصريفه الأقصى نحو ٢٠٠ م^3/ث. تقدم هذه الدراسة تحليلاً جنائياً للحادثة، يدرس العوامل الهيدروليكية والإنشائية والجيوتكنيكية المسببة للفشل. تركز الضرر في الجزء السفلي من قناة المفيض حيث رُفعت الألواح الخرسانية وانزاحت، ما كشف الأساس الهش المكوَّن من صخور طينية ورملية ضعيفة. أدت التعرية اللاحقة إلى تكوّن حفر انجراف كبيرة وزادت من عدم استقرار الهيكل. ويُعزى الفشل بالأساس إلى قصور في التنفيذ، منها ضعف تركيب مانعات تسرب الوصلات، ووجود تشققات سابقة، وعدم فعالية السيطرة على التسرب، مما سمح بارتفاع الضغوط أسفل الألواح. كما أن الأساس، الذي تُرك مكشوفاً أثناء توقف طويل في الإنشاء، لم يُعالج بالشكل الكافي قبل استئناف العمل، ما زاد من قابليته للتعرية. آلية الفشل هذه تتوافق مع أنماط معروفة لعدم استقرار قنوات المفيض في الأدبيات، خصوصاً تلك المرتبطة بضعف طبقات التأسيس، وعدم كفاية تثبيت الألواح، وضعف ضبط الجودة أثناء التنفيذ. وتبرز حادثة سد ديوانة أهمية الدمج المتكامل للتفاصيل الإنشائية، والمعالجة المتينة للأساسات، والرقابة المستمرة في تصميم وتنفيذ أنظمة المفيضات

الكلمات المفتاحية:

فشل المفيض، سد ديوانة، ضغط الركود، تصميم المفيض، قناة المفيض، رفع ألواح القناة، ضغط الرفع، تعرية الأساس، تفاصيل الوصلات.

Table 1:Spillway Properties

Item	**Value**
Spillway slab thickness	0.40 m
Spillway width at the upstream	80 m
Spillway width at the downstream	60 m
Length of the Panels	12.0 m
Width of the panels	10.0 m
Spillway Slope	1:2
Chute length	102 m
Design Discharge	1120 m^3/sec

Table 2: Cavitation Indices to be Considered in Design

Design consideration	Cavitation index
No need for protection against cavitation	> 1.8
Modified by the removal of irregularities	0.25-1.8
Design modification	0.17-0.25
Protected by aeration galleries with built steps	0.12-0.17
No protection is possible, and needs a redesign	<0.12

Table 3: Effect of offset height on calculated stagnation pressure and resulting total uplift force on the spillway slab

Offset	v_y	Ps kN/m^2	Total uplift pressure force (KN)	Panel weight KN
10 cm	24.43	298.41	23,872	941.76
7.5 cm	24.025	288.6	23,088	941.76
5 cm	23.45	274.95	21,996	941.76
2.5 cm	22.47	252.45	20,196	941.76

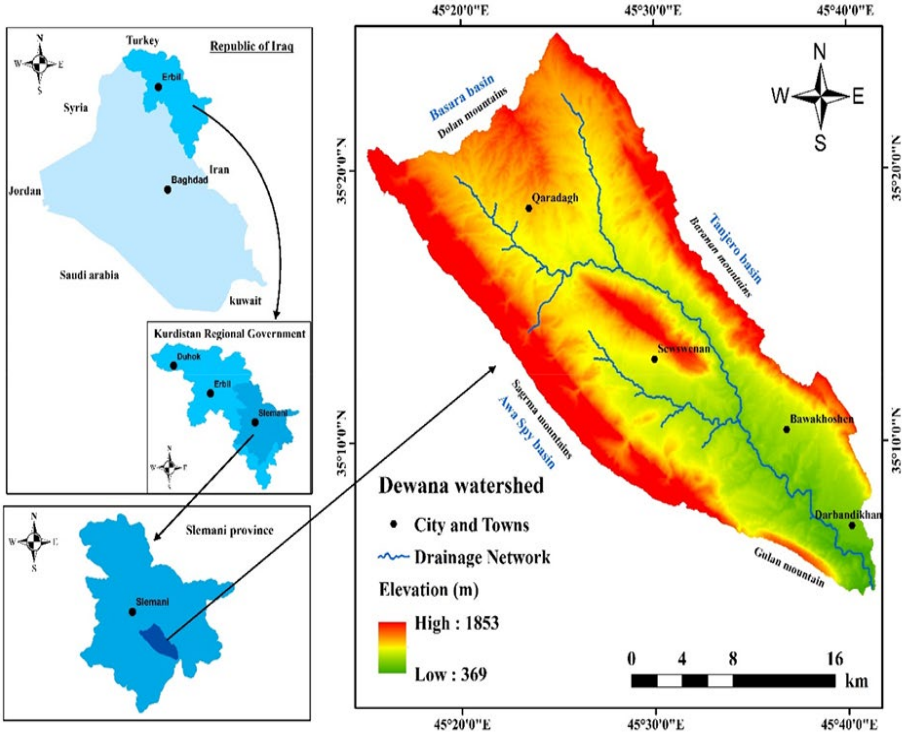

Figure 1:Location map of the Dewana dam created by ArcMap GIS (Ahmad et al., 2024)

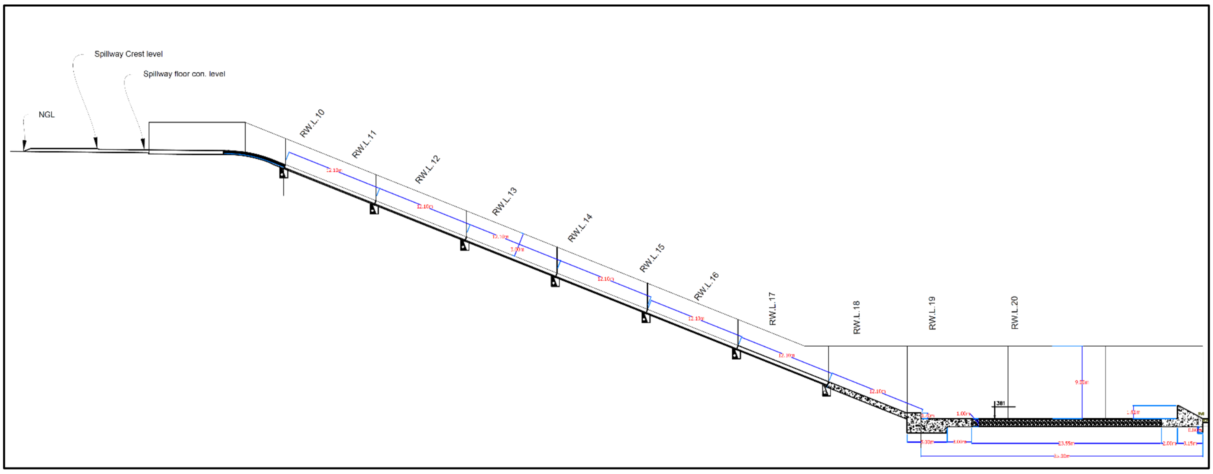

Figure 2:Profile of the Dewana Dam Spillway

Figure 3:Bad Joint Arrangement Just After Construction.

Figure 4:Photo Showing Some Displaced Panels.

Figure 5:Exposed foundation showing thin jointed beddings downstream.

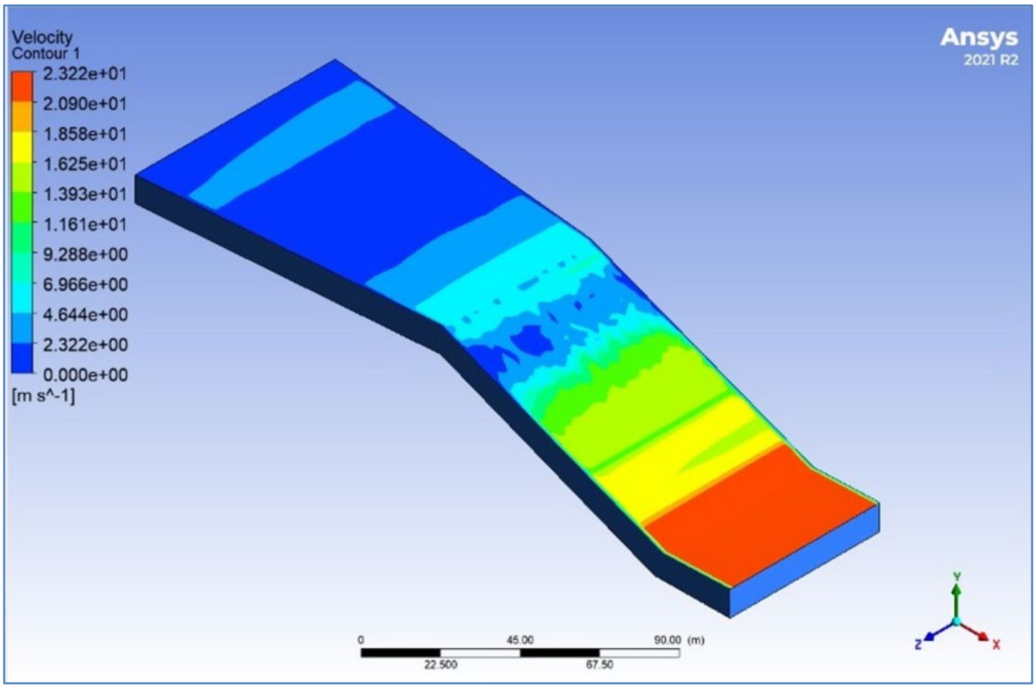

Figure 6:The Results of the ANSYS Software

Figure 7: Cracks and bad joint finishing

Figure 8: Offset of the panel.

Figure 9:Improper waterstops installation.

Figure 10: Weathered rock beneath the chute slab of the Dewan Dam spillway.

Figure 11:Poor quality rock beneath the chute slab of the Dewan Dam spillway.