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MODELING THE IMPACT OF MOSUL DAM FAILURE ON DOWNSTREAM FLOODING ALONG THE TIGRIS RIVER

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Abstract

Dams are a strategic structure for any country where they provide the water for agriculture, power generation, and economic improvement. However, the large volume of water that is retained behind the dam could cause a significant flood risk if the rapid release of the water occurs due to dam failure. Therefore, it is essential to study the dam break for any existing dams to predict the flood maps. This research is carried out to simulate and analyse the seepage, stability, and flood wave resulting from the dam break at Mosul Dam in Iraq using SLOPE/W, SEEP/W, and the HEC-RAS software. The phreatic line and the pore water pressure were modelled for varied levels (300-338 m) above sea level. The Digital Elevation Model (DEM) with a resolution of 30 m has been used. The results revealed that a seepage problem may occur on the downstream face of the dam, potentially leading to seepage failure when the water reservoir reaches flood level. Additionally, the results indicated that the maximum flood discharge that resulted from the Mosul dam failure was about 200000 m^3/s. The flood wave could arrive in Mosul city after 11 hours with a water level about 230 m above sea level and arrive in Baghdad city after 78 hours with a water level 38.4 m above sea level.

Keywords: 2D HEC-RAS Model, Dam break, Dem, Geoslpoe, Mosul dam.

1. Introduction

Dam failures are a serious issue around the world because they can cause heavy loss of life, major damage to property, and severe environmental impacts. In sudden failure events, a large volume of water is released from the reservoir in only a short time [1, 2]. One frequent cause of such failures is internal erosion, also known as "piping," where water passes quickly through the dam body and removes soil particles along its path. This usually happens in materials with high porosity or poor compaction, which makes embankment dams more susceptible to piping problems. Geotechnical structures can also collapse when the water pressure inside the soil becomes high enough to wash out the soil particles [3-5]. Different studies have used several terms and modelling techniques to describe and simulate erosion caused by seepage.

The process of dam failures has been investigated by several researchers using a number of advanced numerical modelling techniques. To investigate the downstream propagation of waves of flooding following a dam failure, especially in heavily populated areas, Haltas et al. [6] employed two numerical techniques to simulate the behaviour of water produced by the failure of the Örkemez Dam applying the HEC-RAS and FLO-2D software. The propagation of flooding outside of the narrow valleys in the Turkish regions of Istanbul and Eskişehir was simulated by FLO-2D, while the propagation of waves into those valleys was simulated by the HEC-RAS model. Due to the analysis's conclusions, flood waves approaching residential areas can reach heights of up to five meters and have a maximum velocity of approximately three meters per second. Eskişehir's flooded area approximated roughly 127 square km. Similar to this, Amini et al. [7] evaluated the maximum probable flow of Vahdat Dam in Iran's Kurdistan Province under two separate failure conditions: piping damage and bypassing. For both scenarios, simulations were conducted applying HEC-RAS, and the leakage area was estimated applying empirical equations. The results they obtained explained that the flooding wave travelled downstream and gave predictions of the maximum flow. The results confirmed the reliability of HEC-RAS in accurately modelling dam failure events for different breach types.

Mishal and Khayyun [8] used GEOSLPOE software to analyse the Al-Adhim earth dam, which is located across the Al-Adhaim River in Iraq. Their objective was to create an empirical equation for calculating the safety factor of earth dams made of the same materials and geometries with different soils condition. They determined that the incorporating of additional variables into the widely used limit equilibrium methods could provide new approaches for calculating the safety factor against sliding. They demonstrated that, in general, the empirical equation can encompass all derived empirical equations when the determining factor of safety remains low. Kumar et al. [9] employed the 2D HEC-RAS v.5.0.7 simulation software along with data from the Global Flood Monitoring System (GFMS) to create a framework for evaluating flood intensity and identifying high-risk flood zones in Prayagraj, India, near the confluence of the Ganga and Yamuna Rivers.

Albu et al. [10] studied and analysed potential theoretical breach scenarios for the Sulit Dam, located on the Sitna River in Botoş, Romania, and assessed the related risks. They employed 2D HEC-RAS software to simulate breaches of different scales within a complex floodplain. The study mainly examined several hydromorphometric factors such as flood travel speed, duration, wave height, and flow velocity. The results showed that the two-dimensional model worked well for estimating the possible damage to buildings and different land-use areas exposed to flooding. Ongdas et al. [11] conducted a pilot study on the Yesil River to identify flood inundation areas using a hydrodynamic model in 2D HEC-RAS. Various flood scenarios were simulated with cell sizes of 25, 50, and 75 m. The results indicated that the model performance remained consistent across the different cell sizes. The generated risk maps highlighted areas with higher exposure to flooding. Mohammed et al. [12] utilized HEC-RAS software, based on the Saint-Venant equations, to model the potential failure of the Haditha Dam on the Euphrates River. The simulation revealed that the value of the maximum discharge was equal to 202,547 m^3/s at the dam and a minimum discharge of 111,340 m^3/s further downstream. The study revealed that the elevation of the flood wave progressively increases until reaching its peak, after which it gradually declines, with this process taking longer at locations farther from the dam. Hosseinzadeh-Tabrizi et al. [13] simulated piping and overtopping failure scenarios at the Sattarkhan Dam in northwestern Iran to forecast the potential flood impacts on downstream urban areas. Paşa et al. [14] assessed the failure scenarios for two adjacent dams (a concrete buttress dam and an earth-fill dam) near a major highway and populated areas using 2D HEC-RAS, identifying high-risk zones and worst-case impacts on structures.

Al-Ansari et al. [15] Reported that seepage problems at the Mosul Dam have been evident since its commissioning in 1986, putting the structure at an extremely high risk of failure. A potential failure could endanger over six million people and inundate an area of approximately 7202 km^2. The study emphasized that the ongoing grouting operations are insufficient to fully mitigate the risk. Al-Ansari et al. [16] highlighted that the dam's foundation rests on soluble gypsum beds, a critical flaw that was underestimated during the design phase. Experts recommended to maintaining the reservoir water level at or below 319 m above sea level to minimize the dam failure risks. Observations showed that the grouting operations failed to reach deeper gypsum layers, allowing cavity formation and seepage pathways to persist and expand beneath the designed grouting limit.

Mosul Dam on the Tigris River faces serious safety concerns due to its gypsum and limestone foundation, making it vulnerable to seepage and potential failure. Existing research rarely addresses the unique risks of this dam, and integrated modelling using advanced tools remains limited. Key challenges include geological uncertainties, complex flood wave modelling over long distances, limitations in stability analysis methods, and a lack of historical data for validation. This study aims to simulate seepage behaviour using GEOSLOPE, assess dam stability under various scenarios, model flood wave propagation with HEC-RAS to predict downstream impacts, and conduct a risk assessment to support emergency planning and protect populations along the Tigris River.

This study focuses on the Mosul Dam as a case study, employing the Finite Element Method (FEM) in conjunction with HEC-RAS and GEOSTUDIO software to evaluate dam stability and the downstream impacts of potential flood waves. The SEEP/W module of GEOSTUDIO was used to analyse seepage behaviour through the dam's earthen sections, while the SLOPE/W module assessed the factor of safety for slope stability under various analysis methods, elevations, and soil conditions. Given the potentially catastrophic consequences of a failure of the Mosul Dam, the study emphasizes the importance of ensuring dam safety, as it is a key component of national protection, human lives, and critical infrastructure. Figure 1 explains the methodology that adopted in this study.

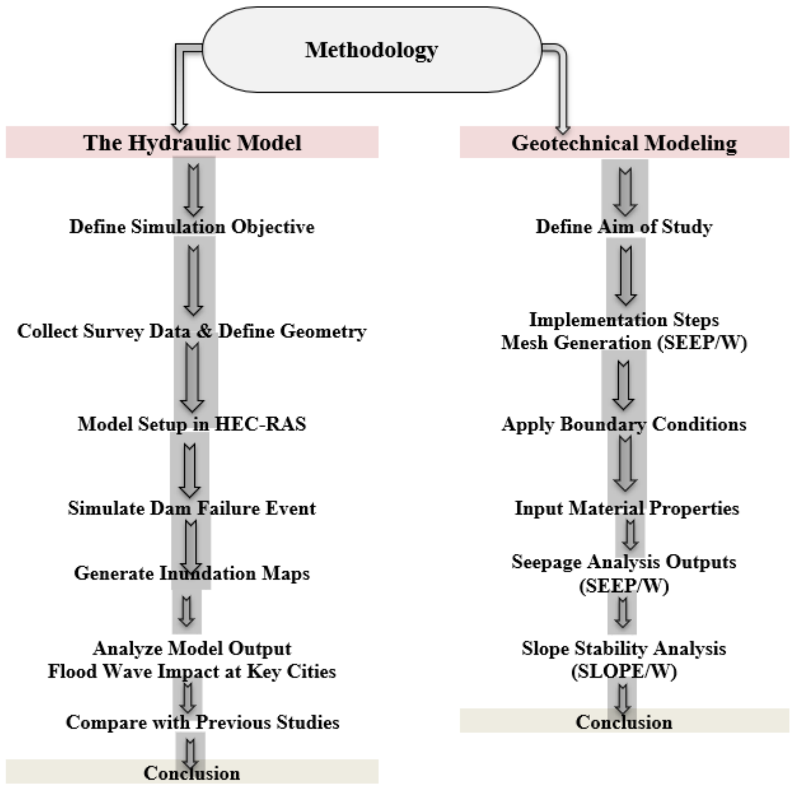


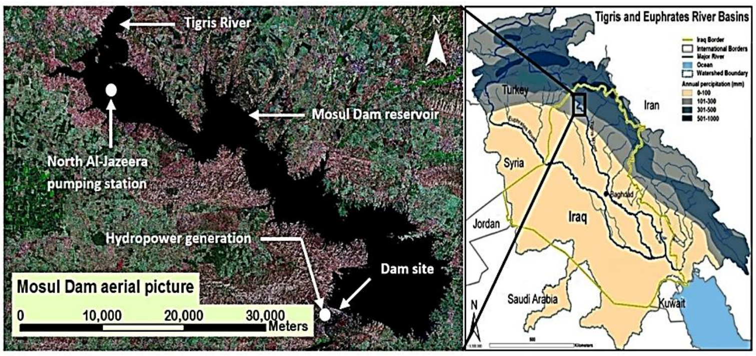
Fig. 1. Flowchart of methodology.

2. The Geotechnical materials and methodology

2.1. Study site

This study discusses the simulation of seepage at the Mosul Dam, Iraq's largest dam and one of the largest in the Middle East. It is located in northern part of Iraq on the Tigris River about 80 km from the Syria and Turkey borders, and 50 km northwest of Mosul city, specifically at the following geographical coordinates: Latitude: approximately 36.6294° North and Longitude: approximately 42.8210° East. The dam is built on the Fatha Formation, characterized by alternating layers of gypsum, marl, and limestone (Fig. 2). The dam's abutments are placed in the Miocene period of the Fatha formation, which contains claystone, marl, gypsum, and limestone. The upper part of this formation has a higher claystone ratio, while in the upper sections, the gypsum and limestone layers are more karstified and thinner.

The Mosul Dam serves multiple purposes, including water storage, flood control, irrigation, and electricity production. It stands 113 m tall, stretches 3.4 km in length, and has a storage capacity of 11.11 billion m3. Despite its size and importance, the dam has faced issues during its construction due to the gypsum and limestone layers in the foundation, which have impacted its operations. Seepage analysis is critical for understanding potential water loss, and pore pressure distribution, and identifying risks like piping that could compromise the dam's stability. Following damage from the ISIS occupation in 2014, the dam underwent repairs and grouting, ensuring its safety. The dam now operates at a level of 319 m above sea level and can reach 325 m without significant problems [17]. Figure 3 shows a typical cross-section of the Mosul Dam.



(a) **(b)**

Fig. 2. Mosul dam location map (A) Mosul dam aerial picture, (B)Location of Mosul dam at Tigris river).

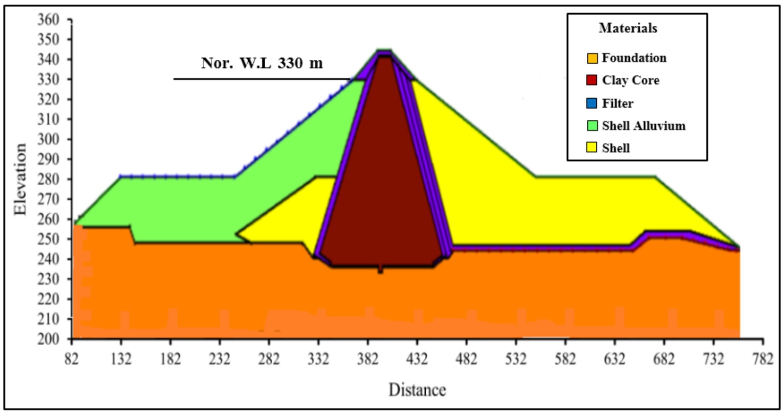


Fig. 3. Engineering typical cross-section of Mosul Dam (Elevation in meters, Distance in meters).

2.2. Geometry and material of Mosul dam

The material properties for the Mosul Dam section, which consists of five zones, were used to simulate hydraulic behaviour within the SEEP/W model. These properties, such as modulus of elasticity, permeability, Poisson's ratio, unit weight, cohesion, and angle of internal friction, were applied to the designated zones as listed in Table 1. The data were obtained from the official design report of Mosul Dam provided by the State Commission for Dams and Reservoirs, Iraq. these values are presumed to originate from geotechnical investigations conducted during the dam's design phase [18].

Table 1. Material properties of Mosul earth dam, state commission for Dams and reservoir, Iraq.

Material zone	Modulus of Elasticity MN/m^2	Permeability m/s	Poisson's Ratio	Unit Weight KN/m^3	Cohesion KN/m^2	Angle of Internal Friction degree
Shell Alluvium	35.215	7.1×10-4	0.25	26.85	0	41
Shell Conglomerate	35.215	4.5×10-4	0.25	25.35	0	42
Core	35.215	1.8×10-8	0.35	20.86	53.5	27
Filter Material	35.215	9.7×10-5	0.25	22.67	0	38
Foundation	54.936	1×10-8	0.35	19.35	0.0014	30

2.3. Geotechnical modelling

2.3.1. SEEP/W and SLOPE/W

The Geo-Slop model includes SEEP/W code product which is applied for analysing the seepage of the groundwater and studying the problems of leakage which leads to excess pore pressure through porous materials like rocks and soil. It's a comparison tool that helps with analyses ranging from steady simple, saturated state cases to unsteady sophisticated, saturated, or unsaturated de-pended timed program. The other code of Geo-Slop is SLOPE/W. This code is employed to assess the safety factor for slope failure under various soil types and conditions using different methods, and varied elevations. This code (SEEP/W) can be used also for analysing and designing Geotechnical and hydrogeological civil engineering products [19, 20]. The steps for implementing the seepage analysis are described as follows:

2.3.2. Mesh generation for Seep/ W and Slop/W software

The mesh generation process was implemented by using the SEEP/W software. The properties of the material of the dam section with the exact dimension can be provided to the software, and the testing of the dam cross-section was prepared accordingly. The finite element method is applied in many forms such as trapezoidal, triangular, rectangular, and square shapes of element in various sizes. After inputting all data for mesh generation, the software of Seep/W checked the given data and appeared to report messages that referred to that the power was enough and there were no errors in its development [21]. Figure 4 shows the mesh generation for the section of Mosul Dam.

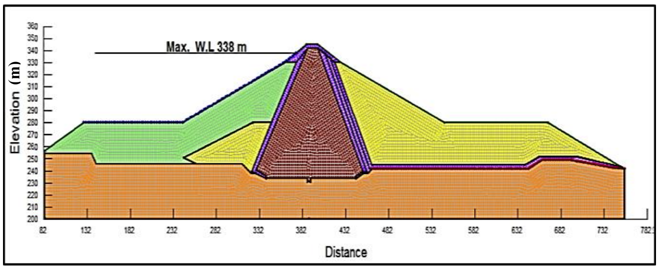


Fig. 4. Mesh generation process for the structural and geotechnical section of Mosul dam (Elevation in meters, distance in meters).

2.3.3. Boundary conditions implementation

The cases of runs were prepared for these cases: Max. Water level elevation (338 m.a.s.l.) (Fig. 3), Ordinary water level elevation (319 m.a.s.l.), and Min. water level elevation (300 m.a.s.l.). The boundary conditions are applied as follows: the cases above considered the top boundary is off and the boundary downstream is represented to be the Dirichlet boundary according to the Ministry of Water Resource in Iraq [22, 23], and close to zero transition conditions, for example, Neuman limit conditions for all the above-mentioned conditions are considered in setting down, up, and base points.

2.4. Hydraulic modelling

2.4.1. Surveying data and model geometry

HEC-RAS is a crucial software tool for simulating dam failure analysis. The Mosul Dam failure was modelled using the HEC-RAS 2D system, enabling the prediction of flood wave characteristics, including water depth and arrival time, for major cities within the study area. The government can prepare an emergency plan to tackle the flood situation before any disaster happens and transport the people to another location before the reaching of the flood wave. An inundation map can be used further for designing early warning systems so that losses can be reduced. The model geometry was conducted depending on the Digital Elevation Model (DEM) which covered the study area from Mosul Dam to the south of Baghdad City (USGS) [24-27]. The study area was represented by a 2D geometry model which is divided into about (1.6) million cells as shown in Fig. 5.

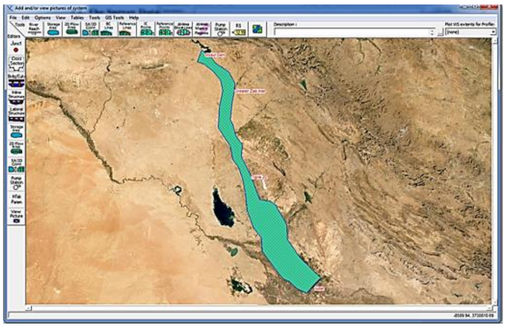


Fig. 5. The 2D geometry of the model from Mosul dam to the downstream of Baghdad city.

2.4.2. Modeling process and boundary conditions

The assumption for the dam break in this study is considered depending on body dam failure (piping failure) in a lake level of 319 m.a.s.l. The definition of the boundary condition was critical for the correct simulation of the dam break event. The existing studies were analysed and taken into consideration while defining the inflow hydrograph to the model, and the maximum discharge that resulted from this failure is about (200000) m3/s as shown in Fig. 6 which stated the strategy study for lands and water resources in Iraq, 2014. The roughness coefficient for the study area had been considered as 0.05 and this value has been selected according to them. As the river cross section which is used in the study is the same cross section of the strategy study of the Iraqi Ministry of Water Resources, where the

Manning roughness of the model in the above study is 0.03, this value was used our study for the river, an 0.05 for the flood plain and the surrounding area and the cities as the HEC RAS Manual recommended. These values are quite close to those adopted by existing studies since such extreme conditions' parameters cannot be validated in a real situation [28].

At any point, the assumptions made about the dam breach dynamic, and the precision of the available topographic information have an impact on model results much higher than the variation (in a common range) of the roughness coefficient. On the other hand, the upper Zab, which is one of the rivers that feeds feeding Tigris River, is connected with the geometry system with a maximum discharge of 13100 m3/s to simulate the worst case that may happen. Immediately after the simulation starts, a dam break has been represented by a water flood downstream of Mosul Dam. At the first step, downstream of Mosul Dam, river nodes were dry. In this way, a real flow hydrograph downstream of the dam has been developed. Dam break increases and consequently flood available area increase for water from upstream to downstream. The dam collapse phase follows and the progressive enlarging and lateral erosion phase; these have been simulated by the progressive high flood wave starting from the dam centre to the sides.

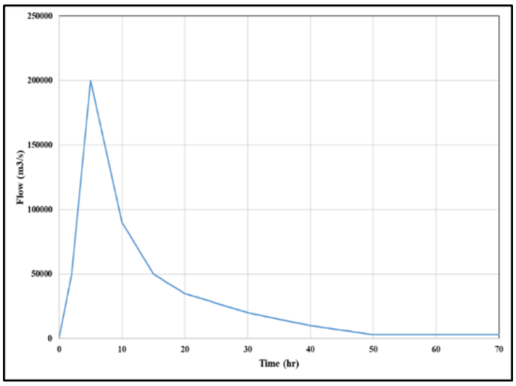


Fig. 6. Hydrograph out of Mosul dam during the breach – Starting level 319 m.a.s.l.

3. Results and the Discussion

3.1. Geotechnical modelling

3.1.1. Phreatic line, equipotential lines, flow net and, activity and vectors of the velocity

The code of SEEP/W is used for analysing the seepage in the Mosul dam embankment and its establishment for different levels of the lake situations to get a lot of information. For this purpose, the resulting flow net has been specified for the study area and different levels. The flow net consists of equipotential lines, streamlines, and vectors of velocity which indicate the seepage, and the phreatic line shows the behaviour of the seepage in the Mosul dam. These properties suggest that the flow lines and equipotential lines at 300 and 338 meters above sea level match well, which supports the idea of leakage [29].

3.1.2. Seepage, pore pressure, flux, and exit gradient

Figure 7 shows the phreatic line and pore water pressure contours at reservoir elevations of 300 and 338 m.a.s.l. The phreatic line starts at points at the water line at the upstream side of the dam and continues at approximately a straight line until it reaches the core of the dam. Within the core, the phreatic line starts gradually drawing down until it becomes tangent to the filter downstream of the dam. However, the phreatic line drops within the blanket drain to zero pressure. The phreatic line at the shell is approximately straight and starts to gradually draw down within the core due to low hydraulic conductivity. At two elevations, the phreatic line is decreased whenever the reservoir level elevation is decreased. The recorded seepage at the designated section was 1.507×10^{-6} m³/s/m of dam length at the highest water level (W.L.) and 5.603×10^{-7} m³/s/m of dam length at the lowest water level. The phreatic line intersected the filter layers without reaching the back face of the dam, indicating the dam's safety against piping. The pore water pressure contours within the regions under the phreatic line are positive and above it is negative at the phreatic line zero pressure, atmospheric pressure. The pore water pressure under the phreatic line starts to increase from reservoir elevations 300 and 338 m.a.s.l to the bottom of the dam within ranges from 200 kPa to 800 kPa at elevation 300 a.m. s.l, at elevation 338m.a.s.l, the pore water pressure ranges from 200 kPa to 1200 kPa.

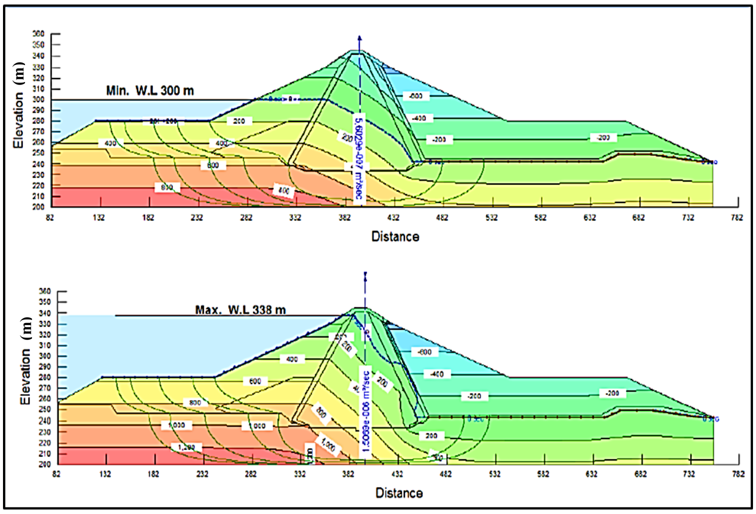


Fig. 7. Seepage analysis based on SEEP/W model results at Mosul dam (elevation in meters, distance in meters).

3.1.3. Slope stability analysis

The stability assessment of the dam's front slope was conducted using the slope/w model, incorporating pore water pressure values derived from seep/w analysis. As depicted in Fig. 8, stress distribution within the dam ranged from 2600 kPa at the base to 200 kPa near the crest. The computed safety factor for the front slope was 1.356 at the maximum water level and 1.324 at the minimum water level, as presented in Fig. 5. These values were compared against the recommended safety factors outlined in the USACE 2003 design guidelines. Since the obtained safety factors surpass the permissible limits, the dam is deemed stable against slope failure [30].

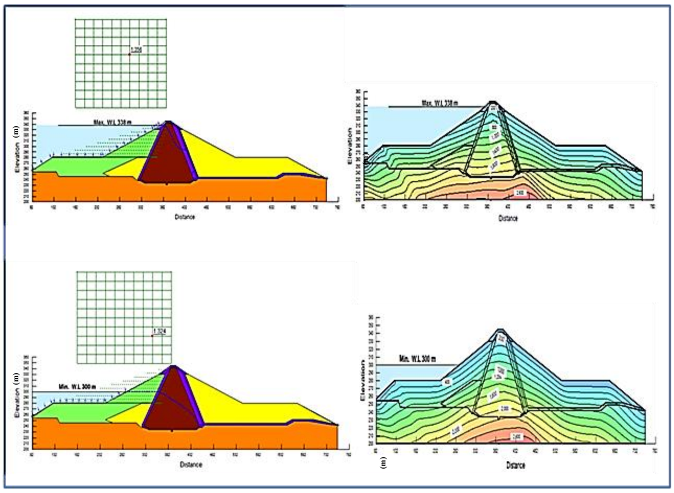


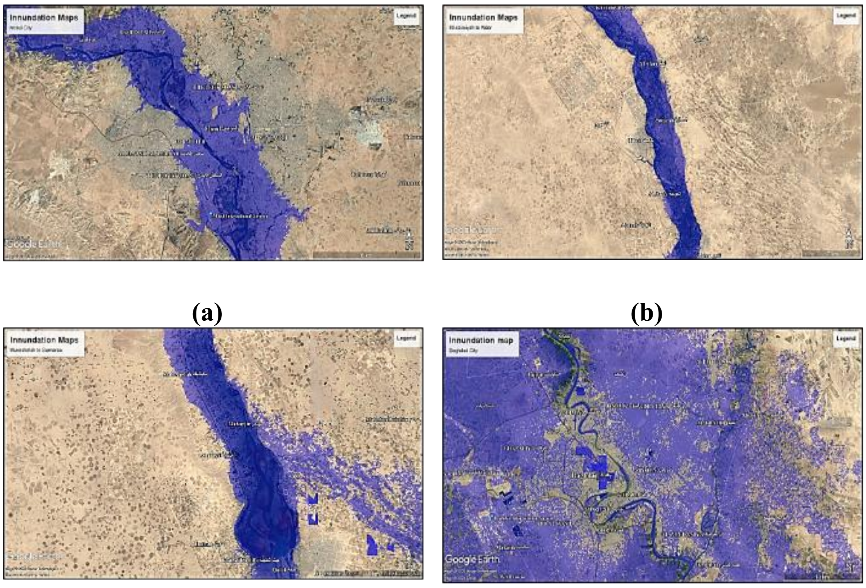
Fig. 8. Stress distribution and slope stability analysis (factor of safety for the dam's front face was assessed under max. and min. W.L., along with an evaluation of internal stress values).

3.2. Hydraulic modelling

Dam break flood maps are an essential tool in preparing emergency plans, environmental studies, and flood insurance. By analysing flow parameters, it was found that dam failure causes significant damage to downstream areas, with dam breach flood maps showing these areas to be most vulnerable to flooding. Emergency plans play an important role in helping authorities respond quickly during disasters by informing residents of potential risks and taking appropriate preventive measures. In this study, the flood map was prepared using the Ras Mapper tool within the HEC-RAS model. A detailed flood map is generated after the dam breach simulation is complete. The tool also allows for an animation of the flood wave path and its propagation across downstream areas. After running the model in HEC-RAS, the results were exported to Ras Mapper, which is one of the most important graphical output tools in the program, as it provides an accurate and clear visual representation of flood maps resulting from different landslide scenarios [31-33].To generate inundation maps, it is very important to simulate the results of water depth along the study reach as shown in Fig. 9(a)-(d), this figure shows the inundation maps in the main cities along the study reach. Table 2 below shows the computed arrival time and the Maximum water level for the flood wave resulting from the Dam break in the Model.

The results showed that most of Mosul City is inundated with the flood wave, and this wave may reach the city after 11 hours with a maximum water level of 230 m.a.s.l., the flood wave will continue downstream reaching Qyarrah city and reach it after 19 hours with a maximum water level 182.33 m.a.s.l., and the wave will enter the Baiji city in maximum water level of 120.13 m.a.s.l. after 34 hours. The results of the model noticed that the city of Tikrit will be in danger of inundation after 42 hours and the water level in this city will be at a maximum of 91.4 m.a.s.l., the wave will pass its way along the Tigris River and arrive to Samara after 47 hours from the starting of the failure and the highest water level in Samarra will be 74.15 m.a.s.l., the path of the flood wave will continue in its line and pass through

Balad City after 60 hours with the water level of 51.2 m.a.s.l. At the maximum. The city of Baghdad, which is the capital of Iraq, will be in danger of flood due to the Mosul Dam failure, there are more than 8 million who live in Baghdad and they will be exposed to the risk of the flood wave after 78 hours from the breach and the water wave will arrive with the maximum level at 38.4 m.a.s.l., that will make all the city under the danger of inundation. Figure 10 shows the maximum wave with arrival time along the study reach.



(a) (b) (c) (d)

Fig. 9. Flood inundation resulting from a simulated Mosul Dam break. The shaded blue areas represent varying flood depths, with darker shades indicating deeper inundation. The extent of flooding is illustrated in: ((a) Mosul city,(b) Tikrit city,(c) the northern part of Samarra city, and(d) Baghdad city.)

The results of this study were compared with those of a previous dam break analysis of Mosul Dam conducted by Al-Taiee and Rasheed [34], who used the Simplified Dam Break (SMPDBK) model. The results of the previous study showed that the flood wave resulting from the collapse of the Mosul Dam could reach the city of Mosul approximately 9 hours after the collapse. As to the recent assessment, which utilised a two-dimensional HEC-RAS model, the wave could be in the city in approximately eight hours. The topographic features of the area will have a significant effect on how far the flood expands. More accurate and realistic findings were obtained in part by using an updated digital elevation model (DEM). In order to provide an increased understanding of the flood effect down the Tigris River, this study is the first to attempt simulating a Mosul Dam failure scenario for a large distance, that is over 350 kilometres downstream.

Due of the high amount of people in the downstream areas and the Mosul Dam's enormous storage capacity of about 11 billion cubic meters, the likelihood of its collapse is seen as one of the most alarming scenarios. It becomes apparent although the St. Francis Dam fall in 1928 and the South Fork Dam collapse in 1889 caused a great deal of damage, their effects were smaller in terms of scope and water volume than what would result from the collapse of the Mosul Dam. It is an urgent need for comprehensive risk assessments and improved emergency preparedness strategies because a dam collapse might endanger the lives of millions of people and flood large cities in a matter of hours [35, 36]. Through the use of shallow water equations in the HEC-RAS 2D model, this study is strongly linked to fundamental physical concepts that are incorporated into the hydraulic modelling process, making the simulation both practically useful for flood risk assessment and physically accurate.

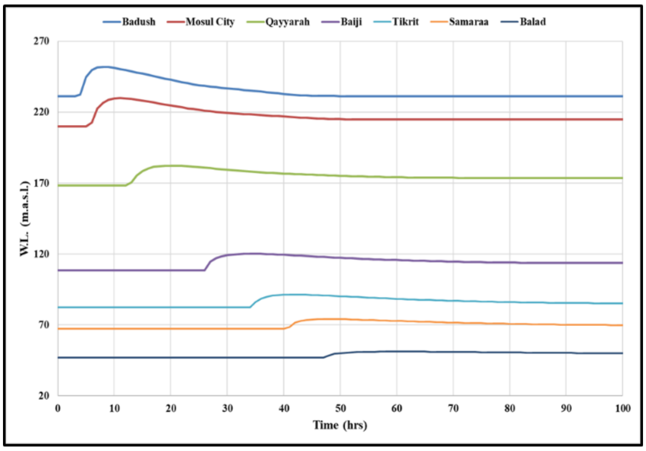


Fig. 10. The maximum wave with arrival time along the study reach.

Table 2. The results of the arrival time with a max. elev. of the Mosul Dam failure at 319 m.a.s.l.

Location	Arrival Time after a dam failure (h,m)	Max. W.L. (m.a.s.l)
Badush	8	252
Mosul City	11	230
Qyarrah	19	182.33
Baiji	34	120.13
Tikrit	42	91.4
Samaraa	47	74.15
Balad	60	51.2
Baghdad	78	38.4

4. Conclusions

In this study, the GEOSLOPE and HEC RAS models to analyse the stability, the seepage of the Mosul Dam, and the flood wave resulting from the dam break along the Tigris River give indications as shown below:

- It is recommended to keep the water level of Dame not exceeding 330 m.a.sl. to avoid any seepage that may happen in the body of the Dam. The phreatic line starts at points at the water line at the upstream side of the dam and continues at approximately a straight line until it reaches the core of the dam.

- The assessment of slope stability confirms that the dam is secure against slope failure. This conclusion is drawn by comparing the calculated safety factor with the acceptable values outlined in the USACE 2003 design guidelines, where the obtained factor surpasses the recommended threshold.
- The maximum height of the flood wave due to the dam break will arrive in the center of Mosul city in about 11 hours. This wave will reach a height of more than 15 m.
- The flood wave will continue flowing along the path of the Tigris River in the direction of Baghdad City, and it will arrive in Baghdad in 78 hours with a maximum height of 38.4 m.a.s.l., all the cities along this path will be exposed to the danger of flood and need an emergency plan to execute at that time.
- The findings of this study closely align with those of previous research. The arrival time and the flood wave depth are estimated in this study and provide detailed maps of the potentially affected cities.
- The study stresses the need to keep emergency action plans up to date and to include flood risk considerations in urban development strategies. It also notes the importance it is to set up early warning and real-time monitoring systems in order to enable immediate evacuation and efficient disaster management.
- It is suggested to look into and simulate the flood wave that would arise from a possible Mosul Dam overtopping failure while incorporating the potential impact of climate change.

Additionally, In this study, several complex simulations were employed to assess the seepage, stability, and flood wave propagation of the Mosul Dam in the case of a dam break scenario. However, as with all modelling efforts, several limitations should be acknowledged to ensure the robustness and reliability of the findings. Additionally, the validation of the models used is critical for establishing the accuracy and real-world applicability of the results.

- Data Availability and Accuracy: The accuracy of the models depends heavily on the quality and resolution of the input data. In this case, the DEM (Digital Elevation Model) and material property data for the dam's construction might have limitations due to variations in measurement accuracy or temporal changes in the dam’s condition.
- Geotechnical Hypotheses: The leakage study is based on speculation on the features of both soil and rock beneath the foundation of the dam and in the region. Variation within the projected and actual actions of these elements might come from variance in their actions, like unplanned variations in porosity or stiffness. Considering being resilient, the SEEP/W model needs an inference that the components it analyses are optimal, which could cancel out particular regions in hydrological or geology.
- Simplified Hydraulic Model: whereas HEC-RAS is an effective approach to describing riverine flood waves, its inherent modifications such for considering identical characteristics of flow or leaving out additional flow impact can reduce the level of precision it is. Such simplified descriptions could not accurately convey the intricate nature for the dynamic procedures involved in a dam collapse event, which include waves or sediments movement.
- Hypothesis in Slope Stability Analysis: The Spencer Method's slope stability analysis takes the assumption of a simple failure mechanism circular slip

surfaces are standard of more intricate failure modes, such translating or wedge failure mechanisms. In situations when the materials of the dam behave non-linearly or when there are substantial structural flaws that are not taken into consideration in the model, a factor of safety could fail to accurately reflect the danger of failure in every scenario.

Abbreviations

DEM	Digital Elevation Model
FEM	Finite Element Method
GFMS	Global Flood Monitoring System
HEC-RAS	Hydrologic Engineering Center – River Analysis System
USACE	United States Army Corps of Engineers
USGS	United States Geological Survey

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