UNIVERSITI PUTRA MALAYSIA

***SIMULATION OF MOSUL DAM BREAKS USING BASEMENT MODEL***

**TALAL AHMED BASHEER**

**FK 2018 28**

**SIMULATION OF MOSUL DAM BREAKS USING BASEMENT MODEL**

**By**

**TALAL AHMED BASHEER**

**Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy**

**March 2018**

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# DEDICATION

To

All beloved members of my family

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Abstract of the thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Doctor of Philosophy

**SIMULATION OF MOSUL DAM BREAKS USING BASEMENT MODEL**

By

**TALAL AHMED BASHEERAL**

**March 2018**

**Chairman : Aimrun Wayayok, PhD**
**Faculty : Engineering**

Dams have been constructed for many purposes such as water supply, flood control, irrigation, and hydropower generation. They provide numerous benefits to civilization; however, floods resulting from a dam break could lead to tremendous loss of lives and properties. Mosul Dam, the largest dam in Iraq, is located in the north-western part of the country. The problem of Mosul Dam is the continuous corrosion in the dam foundations that contain gypsum and anhydrite formations, which dissolve under the effect of storing water in the reservoir. According to the US Army Corps of Engineers 2006 report “in terms of internal erosion potential of the foundation, Mosul Dam is the most dangerous dam in the world”. The main objectives of this research were to predict the flood occurrence after the probable Mosul Dam break and develop maps of the downstream flooded areas to identify the zones under potential risk in Mosul city. Dam break studies depend on three primary tasks mainly; predicting the breach parameters, estimating the breach flood hydrograph and routing this hydrograph downstream of the dam site. In this study, five breach prediction approaches were implemented to predict the breach geometry and the required time for breach formation. In addition to that, overtopping and piping failure modes were considered. For each approach, eight reservoir water levels, ranging from minimum operation level to maximum storage level with 5 m intervals, were studied. Sensitivity analysis was carried out to evaluate the effect of breach parameters on the resulting flood hydrographs. The topography of the study area was demonstrated using a 30 m × 30 m Digital Elevation Model (DEM). In this study, the downstream flood propagation of the Mosul Dam break was simulated using the two-dimensional BASEMENT version 2.5.3 numerical model. The numerical model was utilized to the Tigris River between Mosul Dam and south of Mosul city along 87.8 km. The breach flood hydrographs for each scenario were analyzed and discussed. The results show that the overtopping failure mode tends to give higher peak discharge values than the piping failure mode by 1.8 to 19.6% in case of 330 and 300 m reservoir water levels,



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respectively. In addition, results indicate that the most suitable method for estimating breach parameters for large dams was the Froehlich (2008) approach.

Furthermore, for large dams, such as Mosul dam, the sensitivity analysis shows that the breach side slope does not affect the peak discharge time and has a minor influence on peak outflow values. Meanwhile, the required time for the breach to develop was highly sensitive to both peak discharge and peak discharge time. For instance, increasing breach formation time by 50% led to decreasing peak discharge by 19.19% and shifted the peak discharge time from 6 hours to 9.5 hours. Based on the simulation results, indicative inundation maps for multiple scenarios have been presented in this study. The time lag between the start of the failure of Mosul dam and arrival of the peak flow to Mosul city for all cases were stated. In addition to that, the flood peak discharge, peak water level, and lag time of peak discharge along the Tigris River reach for various values of reservoir water level were specified and analyzed. A new empirical model relates the maximum wave depth along the main stream with the initial condition of the reservoir and the breach dimension has been developed. This new empirical model is highly significant in estimating the maximum flood depth as compared to the simulation results using BASEMENT model.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**SIMULASI PEMECAHAN EMPANGAN MOSUL MENGGUNAKAN MODEL BASEMENT**

Oleh

**TALAL AHMED BASHEER**

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Empangan telah dibina untuk pelbagai tujuan seperti bekalan air, kawalan banjir, pengairan dan penjanaan kuasa hidro. Ia memberi banyak faedah kepada ketamadunan; walau bagaimanapun, banjir akibat pecahan empangan boleh mengakibatkan kehilangan nyawa dan harta benda yang besar. Empangan Mosul adalah empangan terbesar di Iraq, terletak di bahagian barat laut negara ini. Masalah Empangan Mosul adalah kakisan berterusan di asas empangan yang mengandungi gipsum dan anhidrit, yang melarut di bawah kesan penyimpanan air di dalam takungan tersebut. Menurut laporan 2006 Army Corps of Engineers AS "dari segi potensi hakisan asas dalaman yayasan, Empangan Mosul adalah empangan yang paling merbahaya di dunia". Objektif-objektif utama kajian ini adalah untuk meramal kejadian banjir selepas kemungkinan berlaku pecahan Empangan Mosul dan membangunkan peta banjir kawasan hilir untuk mengenal pasti zon di bawah potensi berrisiko di bandar Mosul. Kajian pecahan empangan bergantung kepada tiga tugas utama, iaitu; meramal parameter pecahan, menganggar hidrograf banjir pecahan dan mengesan perjalanan hidrograf ini di hilir tapak empangan. Di dalam kajian ini, lima pendekatan ramalan pecahan telah dilaksanakan untuk meramalkan geometri pecahan dan masa yang diperlukan untuk pembentukan pecahan. Di samping itu, mod kegagalan limpahan dan paip dipertimbangkan. Bagi setiap pendekatan, lapan paras air takungan, dari peringkat operasi minimum ke tahap penyimpanan maksimum dengan selang 5 m, telah dikaji. Analisis kepekaan dijalankan untuk menilai kesan parameter pecahan ke atas hidrograf banjir yang terhasil. Topografi kawasan kajian ditunjukkan dengan menggunakan Model Ketinggian Digital (DEM) 30 m × 30 m. Di dalam kajian ini, penyebaran banjir hiliran pecahan Empangan Mosul telah disimulasikan menggunakan model berangka dua-dimensi dikenali sebagai BASEMENT versi 2.5.3. Model berangka digunakan untuk Sungai Tigris antara Empangan Mosul dan selatan bandaraya Mosul sepanjang 87.8 km. Hidrograf banjir pecahan untuk setiap senario dianalisis dan dibincangkan. Keputusan menunjukkan



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bahawa mod kegagalan limpahan cenderung memberi nilai pelepasan puncak yang lebih tinggi daripada mod kegagalan paip sebanyak 1.8 hingga 19.6% dalam kes paras air takungan 330 dan 300 m masing-masing. Di samping itu, dapatan menunjukkan bahawa kaedah yang paling sesuai untuk menganggar parameter pecahan untuk empangan besar ialah pendekatan Froehlich (2008).

Tambahan pula, untuk empangan besar, seperti empangan Mosul, analisis kepekaan menunjukkan bahawa cerun di tepi pecahan tidak menjejaskan masa pelepasan puncak dan mempunyai pengaruh kecil terhadap nilai aliran keluar puncak. Sementara itu, masa yang diperlukan untuk pecahan membangun sangat sensitif terhadap kedua-duanya pelepasan puncak dan masa pelepasan puncak. Sebagai contoh, meningkatkan masa pembentukan pecahan sebanyak 50% membawa kepada pegurangan pelepasan puncak sebanyak 19.19% dan menganjakkan masa pelepasan puncak dari 6 jam kepada 9.5 jam. Berdasarkan keputusan simulasi, peta pembanjiran indikatif untuk pelbagai senario telah dikemukakan di dalam kajian ini. Ekoran masa antara permulaan kegagalan empangan Mosul dan ketibaan aliran puncak ke bandaraya Mosul untuk semua kes dinyatakan. Di samping itu, pelepasan puncak banjir, paras air puncak, dan masa ekoran pelepasan puncak di kawasan jangkauan Sungai Tigris bagi pelbagai nilai paras takungan air ditentukan dan dianalisis. Model empirikal baru berkenaan dengan kedalaman gelombang maksimum di sepanjang aliran utama dengan keadaan awal takungan dan dimensi pemecahan telah dibangunkan. Model empirikal baru ini mempunyai ketepatan yang ketara untuk menganggar kedalaman banjir maksimum berbanding kepntusan simulasi mengguna BASEMENT.

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This thesis was submitted to the Senate of Universiti Putra Malaysia has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy. The Members of the Supervisory Committee were as follows:

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**Declaration by graduate student**

I hereby confirm that:

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# LIST OF ABBREVIATIONS

## Abbreviations

| | |
|---|---|
| BASEMENT | Basic-Simulation-Environment |
| CFL | Courant-Friedrichs-Lewy (Courant number) |
| DEM | Digital Elevation Model |
| FDM | Finite Difference Method |
| FDS | Flux Difference Splitting |
| FEM | Finite Element Method |
| FVM | Finite Volume Method |
| HEC-RAS | Hydrologic Engineering Centre-River Analysis System |
| HLL | Harten-Lax-Van Leer |
| HLLC | Harten-Lax-Leer-Contact |
| SVE | Saint Venant Equations |
| SWE | Shallow Water Equations |
| USBR | United States Bureau of Reclamation |

## Notations

| | |
|---|---|
| $a$ | acceleration, m/sec$^2$ |
| $A$ | wetted cross section area, m$^2$ |
| $A_f$ | flooded area, km$^2$ |
| $B$ | breach width, m |
| $B_{avg}$ | average breach width, m |
| $C_b$ | reservoir volume coefficient |
| $CFL$ | Courant number |
| $D_{max}$ | maximum water depth, m |
| $F_n$ | force, N |
| $F_x$ | vector of the flux function in x direction |
| $F_y$ | vector of the flux function in y direction |
| $g$ | standard gravitational acceleration, m/sec$^2$ |
| $h$ | water depth, m |
| $H$ | reservoir level above embankment bed, m |
| $h_b$ | breach height, m |
| $h_{b*}$ | dimensionless breach hydraulic head |
| $h_d$ | dam height, m |
| $h_w$ | depth of water above the bottom of the breach, m |
| $k_o$ | mode of failure coefficient |
| $m$ | mass, kg |
| $M$ | momentum, kg m/sec |
| $Q$ | discharge, m$^3$/sec |
| $Q_b$ | breach discharge, m$^3$/sec |
| $Q_{b*}$ | dimensionless breach discharge |



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| | |
|---|---|
| $q_l$ | lateral discharge per meter of length, $m^2$/sec |
| $Q_p$ | peak discharge, $m^3$/sec |
| $RL$ | initial reservoir level, m |
| $S$ | vector of the source terms |
| $S_f$ | friction slope |
| $S_{fx}$ | energy grade line slope in x direction |
| $S_{fy}$ | energy grade line slope in y direction |
| $S_o$ | bed slope |
| $S_{ox}$ | bed slope in x direction |
| $S_{oy}$ | bed slope in y direction |
| $t$ | time, sec |
| $t_f$ | breach formation time, hr |
| $T_p$ | time of peak discharge, hr |
| $U$ | vector of the conserved variables |
| $u$ | depth averaged velocity in x direction, m/sec |
| $u_s$ | velocity in x direction at water surface, m/sec |
| $u_w$ | wave propagation speed, m/sec |
| $v$ | depth averaged velocity in y direction, m/sec |
| $V_{er}$ | volume of material eroded from the dam embankment, $m^3$ |
| $v_s$ | velocity in y direction at water surface, m/sec |
| $V_{out}$ | volume of water that passes through the breach, $m^3$ |
| $V_w$ | reservoir volume at the time of failure, $m^3$ |
| $w_s$ | velocity in z direction at water surface, m/sec |
| $x$ | distance along channel, m |
| $z$ | breach side slope |
| $\Delta t$ | time step, sec |
| $\Delta x$ | grid spacing, m |

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# CHAPTER 1

# INTRODUCTION

## 1.1 General

Dams are hydraulic structures built to store waters flowing in rivers, and provide many benefits including daily water use, irrigation, hydropower generation, and many other purposes. In early times, dams were constructed for water supply or irrigation. With time development, multipurpose dams were built for flood control, energy, sediment control, navigation, industrial uses, water supply, and irrigation as well. Dams provide numerous benefits to civilization; however, floods resulting from a dam break could lead to tremendous loss of lives and properties.

In spite of the efforts that are taken to ensure dam safety, dam failure may occur. Depending on the dam type, dam failure can take the form of collapse of the structure, or breach in the structure. Dam failures can occur as a result of one or a combination of the following reasons:

i. Runoff resulting from intense rainfall storms,
ii. Insufficient spillway capacity, which result an embankment overtopping,
iii. Seepage or piping through the embankment or foundation (Internal erosion),
iv. Inadequate dam maintenance,
v. Poor design or use of unsuitable construction materials,
vi. Failure of upstream dams, which may cause a sequent dam failure,
vii. Foundation structural defects,
viii. Landslides into dam's reservoirs, which may cause surges in the stored water that lead to overtopping,
ix. Significant wave action due to high winds, which can result in considerable erosion in the upstream face of the dam, and
x. Earthquakes, which may cause a liquefaction of earthen dams, or form cracks in the dam body.

Dam breaks result in an uncontrolled release of a mixture of water and sediment from the reservoir that lead to an unexpected and destructive flood wave spreading downstream dam site. The catastrophic event of dam break may cause tremendous loss of life, environmental and property damages. A damaging effect on power generation and water supply would be anticipated as well. Regardless of the reason, nearly all dam's failure initiate with formation of a breach (Xiong, 2011).

According to the failure consequences, dams can be classified into low, significant, and high hazard (FEMA, 2013; Singh, 1996; USBR, 1988). The hazard potential classification depends on the probable loss of human lives and the economic losses in



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the potential inundation area as consequences of a dam break. The economic losses would comprise damage to inhabit residences, agricultural lands, livestock, factories, commercial buildings, roads, highways, and state utilities.

The devastating consequences of dam failure necessitate the study of dam break flood propagation in urban areas, in order to provide the data for risk assessment and to develop a realistic emergency plan.

Essentially, the flow resulting from the dam break can be studied analytically, experimentally, and numerically. The analytical studies emphases on resolving the governing equations using the principle of mathematics. Solving the nonlinear flow equations require a number of assumptions in order to simplify the equations which narrow the applicability to a limited dam break cases (Singh et al., 2011; Zhang & Wu, 2011). Dam break experimental studies use physical models that built in laboratories and tested using advanced tools for measuring and recording the complicated dam break flow. The experimental studies investigate the dam break problems and provide reliable data for numerical model validation as well (Carrivick et al., 2011; Oertel & Bung, (2012). The dam breaks numerical studies overcomes the analytical and experimental methods limitation. With advanced computers and high processing capacity, simulations of dam break become more efficient and effective (Zhang et al., 2014).

## 1.2 Mosul Dam Condition

Mosul Dam (Figure 1.1) is the largest dam in Iraq and the fourth largest dam in the Middle East with reservoir capacity of 11110 $Mm^3$ at the maximum operating level (El. 330 m). The dam located on the Tigris River in the governorate of Ninawah about 60 km to the northwest of Mosul city. The dam is a multi-purpose earth-fill dam constructed for water supply, irrigation, flood control and hydropower generation, and was put into operation in 1986.

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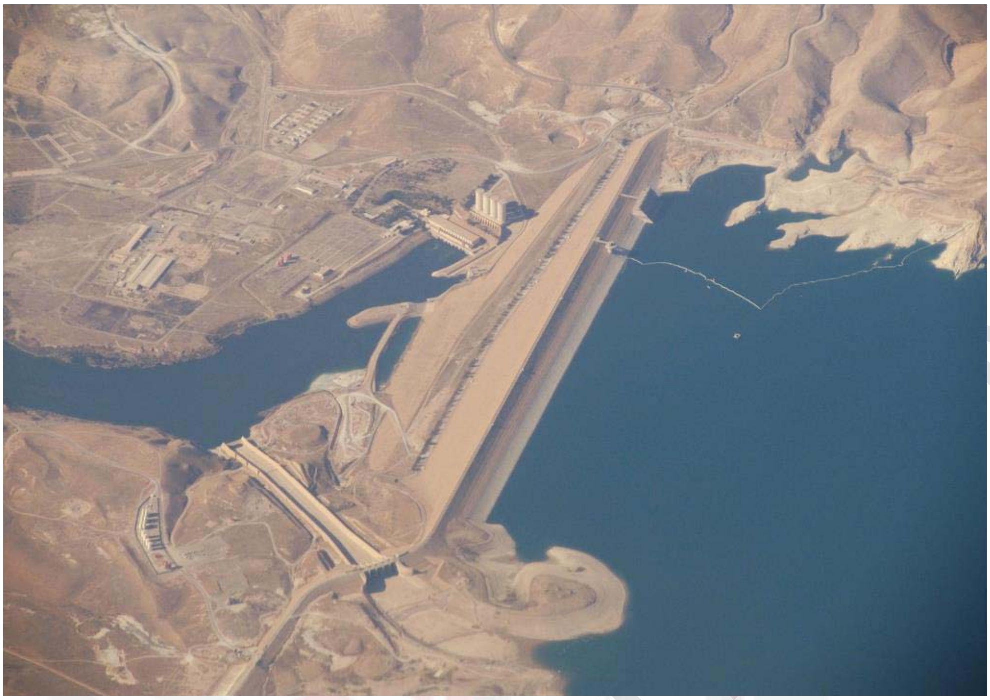

**Figure 1.1 : Aerial View of Mosul Dam, Mosul, Iraq**

The main problem of Mosul dam is the corrosion in the foundation due to the dissolve of its materials under seepage effect. The dam had been built on a weak foundation, which comprises a sequenced rock layers of marls, anhydrite, gypsum, and fractured limestone. These layers are subjected to dissolution forming fractures and leading to karst development under the dam body which appears as sinkholes at the surface (Al-Taiee & Rasheed, 2009; Kelley et al., 2007; SIGIR, 2007).

To overcome this problem and in order to reinforce the dam foundations, a continuous treatment must be provided by grouting and cement injections at the foundations. For this purpose, the designer includes a grouting gallery through the dam body to continue the grouting process of the foundation after completing the dam and during its operation (SIGIR, 2007). Although the grouting process is never stopped, some evidences of seepage near the left abutment, developing sinkholes (Figure 1.2 and Figure 1.3) downstream dam site have been recorded for the period from filling the dam reservoir until 2007 (SIGIR, 2007; Sissakian et al., 2014).

According to United States Army Corps of Engineers (USACE) 2006 report; “in terms of internal erosion potential of the foundation, Mosul Dam is the most dangerous dam in the world”. Moreover, USACE stated that the probability of Mosul dam failure is considered to be very high (SIGIR, 2007).

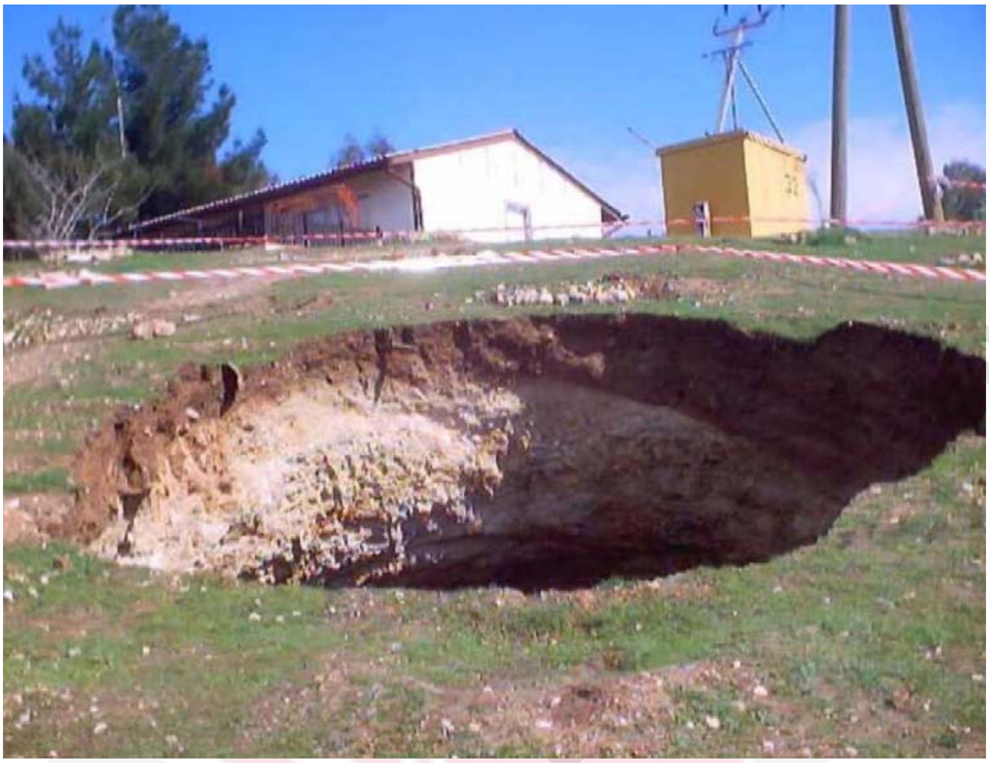

**Figure 1.2 : Sinkhole About 500 m Downstream from the Dam**
(SIGIR, 2007)

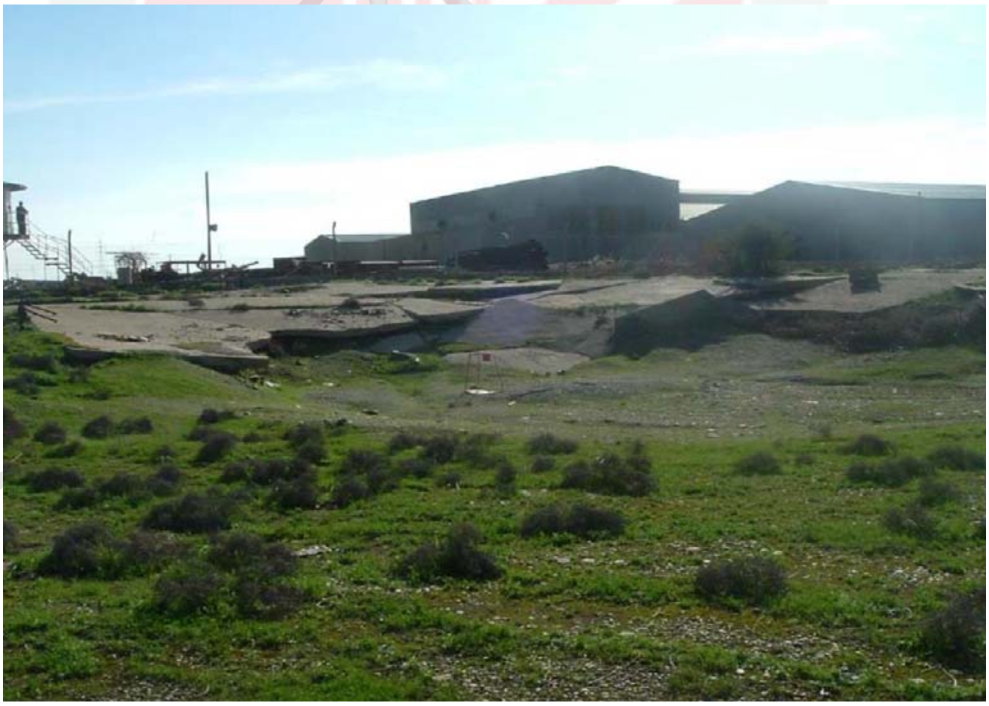

**Figure 1.3 : Sinkhole Below Concrete Paved Area**
(SIGIR, 2007)

## 1.3 Research Question

High capacity dams are constructed to achieve the balance between the growth in population and the demands for water supply, flood control and the hydropower as well. The higher capacity creates a higher hazard if the dam fails. Dams breaks are relatively rare but can cause enormous lives and economic losses when they occur.

Due to the defect in the Mosul dam foundation as described in Section 1.2, the dam is subject to probable failure. Therefore, there is a need to investigate the flood resulting from Mosul dam break and its consequences on downstream areas.

Based on the literature, very little works have been done in Mosul dam break simulation and its limited to one-dimensional models. The one-dimensional numerical models have a deficiency in simulating the flood wave in lateral diffusion compared to the two-dimensional models. Therefore, the current study attempts to analyze Mosul dam break in details using a two-dimensional model.

Different two-dimensional hydrodynamic models use different techniques to solve the Shallow Water Equation (SWE) numerically. This numerical solution is based on the Finite Difference Method (FDM), Finite Element Method (FEM), or Finite Volume Method (FVM). Furthermore, the computational mesh can be formed as structured or unstructured elements.

In the current study, the hydrodynamic model BASEMENT is employed to simulate Mosul dam break. This model solves the shallow water equations using a finite volume method on an unstructured mesh. In addition to that, BASEMENT model can handle one-dimensional, two-dimensional hydrodynamic models, slope collapse, sediment transport, model coupling, and many other features.

The advantages of using BASEMENT model are: Firstly, it uses unstructured mesh which has the ability to represent complex geometries accurately. Secondly, it provides a wide range of alternatives to control the simulation environment and the select the solver schemes. Moreover, it provides the ability to use the parallel calculation technique, which use the available processors on the multi-core computer. In addition to, the model has a unique ability to visualize and view the results during the simulation process.

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## 1.4 Objectives of the Study

The main objective of this study is to investigate the Mosul dam break and the possible effects to the areas located downstream dam site, which include Mosul city. The specific objectives of this study can be listed as follows:

1. To employ different methods to predict the breach parameters and evaluate the resulting flood hydrograph
2. To simulate the flood wave propagation numerically using the two-dimensional BASEMENT and HEC-RAS models for different dam break scenarios.
3. To investigate the effect of Mosul dam break on Mosul city in order to identify the zones under potential risk by developing inundation maps and providing the features of the flood wave.

## 1.5 Scope and Limitation

The scope of this research is to investigate numerically the Mosul dam break using a two-dimensional model. In order to achieve the study objectives, the present investigation has been concerned with:

i. Employing five common approaches to predict the breach geometry and time of breach development, considering the overtopping and piping failure modes. In addition to evaluating the breach parameters ($B_{avg}$, $z$, and $t_f$) by conducting a sensitivity analysis to check their effect on the resulting flood hydrographs,

ii. Estimating the flood hydrographs that resulting from the breached dam using the HEC-RAS model for different initial reservoir water elevations. The considered initial water elevation are: the maximum storage level (EL 335 m), the maximum operation level (EL 330 m), and the minimum operation level (EL 300 m), in addition to extra water levels (EL 325, 320, 315, 310, 305 m),

iii. Routing the flood hydrograph downstream dam site towards Mosul city, in Iraq using the two-dimensional hydrodynamic model BASEMENT. The numerical simulation considering the above breach methods with the initial reservoir water elevations. A total of fifty-six different cases simulated in the study,

iv. Applying the HEC-RAS 2D model to simulate the flood wave propagation and comparing the result with BASEMENT model, and

v. Employing the geographic information system software (QGIS) for preparing the required data for the simulation and for presenting the simulation results and the inundation maps.



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Due to the wide variety that can be considered in dam break studies, the current investigation is limited to the above-mentioned scopes. The considered river length of the study is up to 87.8 km, i.e. to the south of Mosul city, as the afterward areas are mostly agricultural areas with scattered small villages. In addition to that, the study is limited to the following points:

i. Since the study area is located far away from Tigris River estuary, there is no effect of the sea tide on the study, hence sea tide was not included in the simulation,
ii. The hypothesis Mosul dam break is considered to occur due to the foundation failure, i.e., a sunny day failure,
iii. Failure due to overtopping was set to occur when the water level in the reservoir exceeds the dam crest by 0.5 m,
iv. For piping failure mode, the elevation of piping initiation was set at ½ $h_w$,
v. The breach location was assumed to be at the dam centreline, and
vi. The final breach bottom elevation was set at the riverbed (reservoir bed).

## 1.6 Organization of the Thesis

This thesis is composed of six chapters. Chapter One, as shown above, presents a general background about dam break problems, the problem of Mosul dam, and the objectives of the study, together with the scope and limitations of the current research.

Chapter Two contains a review of the literature that related to the dam break, which cover the techniques and the components that used in dam break studies. This Chapter extensively reviews the causes and the modes of dam failures, the method that used in prediction of dam breach, dam break modelling types, such as physical and numerical which divided into one-dimensional and two-dimensional models. The Chapter also reviews the literature on sensitivity analysis of different dam break parameters. Finally, there is a summary of the literature review and the research gaps related to dam break studies.

Chapter Three is devoted to the theoretical fundamental of the numerical simulation which include the basis of the one-dimensional and two-dimensional unsteady flow equations, with their assumptions. The factors that accompany the numerical modelling of dam break flows have been discussed. In addition, the methods that numerically solve the Shallow Water Equations have been presented in this chapter.

The methodology to achieve the objective of the current study is described in Chapter Four. The information about the study area, Mosul dam, and Mosul reservoir are presented. For the development of the simulation model, the pre-processing preparation and the elements required for model building in BASEMENT have been described in details in this chapter.



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Chapter Five introduces the results and discussion of the Mosul dam break for different failure scenarios. The results presented and discussed as graphs, tables and maps for different cases. The flood hydrographs resulting from the breached dam for different method and scenarios have been compared and discussed. Moreover, validation of BASEMENT model for the case study had been included in this chapter. The effect of the flood hydrograph on Mosul city had been analysed. Multi types of inundation maps for different dam break scenarios have been presented.

Finally, Chapter Six presents a summary and conclusions of the study, as well as suggestions for some work in the future.

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“How to Write a Great Research Paper and Get Published”. February 23, 2017. Elsevier- UPM workshop, Universiti Putra Malaysia

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