Scientific Research Publishing

Engineering, 2021, 13, 105-124
https://www.scirp.org/journal/eng
ISSN Online: 1947-394X
ISSN Print: 1947-3931

Mosul Dam Problem and Stability

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How to cite this paper: Al-Ansari, N., Adamo, N., Al-Hamdani, M.R., Sahar, K. and Al-Naemi, R.E.A. (2021) Mosul Dam Problem and Stability. *Engineering*, **13**, 105-124.
https://doi.org/10.4236/eng.2021.133009

Received: February 8, 2021
Accepted: March 5, 2021
Published: March 8, 2021

Abstract

Mosul Dam is located on the River Tigris about 60 km northwest Mosul in Iraq. It is the biggest dam where its storage capacity reaches 11.11 billion cubic meters at normal operational level (330 m. above sea level). The dam was constructed on alternating beds of karistified limestone, gypsum and marl. This dam suffered from water seepage under its foundation since its operation in 1986. Grouting operations were implemented since that time to overcome this problem. This seepage is believed to be due to dissolution of gypsum beds under the foundation, which was not carefully considered by the designers. It was recommended by the international board of experts that the water level should be kept at or below 319 m.a.s.l. to minimize damages in case of the failure of the dam. ISIS occupied the dam site on 8 August 2014 and it was seized back from the hands of ISIS on the 16th of the same month. They did plenty of damage despite the short period they occupied the area. After that, the Iraqi Ministry of Water Resources rebuilt the damaged parts and used new grouting and maintenance program. Now, the dam looks very safe at 319 m water level at its reservoir. In addition, the impounding was raised 325 m.a.s.l. for few days and nothing abnormal was noticed.

Keywords

Mosul Dam, Grouting, Stability, Tigris River, Iraq

1. Introduction

Iraq is located in the northeastern part of the Arabian Peninsula (coordinates 33 00 N, 44 00 E) (**Figure 1**). It covers an area of 437,072 square kilometers and

Figure 1. Location of Iraq.

population of about 40 million. The climate is mainly continental, subtropical and semi-arid [1]. The Tigris and Euphrates Rivers form the main water resources of Iraq. Both rivers rise in Turkey and the water coming from Turkey to Iraq is about 71% while about 6.9% and 4% come from Iran and Syria respectively (**Figure 2**) [2] [3] [4].

To protect the country from floods, ensure the required quantities of water for irrigation and for power generation, number of dams, barrages and hydrological projects were implemented [5]-[15]. The long-term average of the flow of the Tigris River is 21.2 km^3 and its tributaries contribute 24.78 km^3. The Euphrates contributes 30 km^3 (which might fluctuate from 10 to 40 km^3) [16] [17] [18]. All the water of the Euphrates River comes from outside the borders of Iraq while 67% of the Tigris water also comes from outside source [19].

Iraq used to consume about 42.8 km^3 of water in 1990. Most of it is consumed for agricultural purposes (90%) while 4% and 6% are consumed for domestic and industrial purposes. [19] [20] [21] stated that 85% of the water withdrawal is used for agricultural purposes recently. All urban areas received safe water supplies while 54% of rural areas receive safe water supplies. After the Gulf war, the situation deteriorated for water and sanitation sectors and accordingly 1/3 of the population of Iraq do not have access to potable water [22].

Despite the fact that the Middle East is considered as arid to semi-arid area, Iraq used to be considered as rich in its water supplies until 1970. After that, the conditions changed due to climate change and construction of dams and irrigation projects by riparian countries [23]-[36]. In view of the current situation, it is of prime importance that Iraq should act to ensure water availability. One of the important measures to be taken in this context is the safety of the existing dams. In this context, Mosul Dam (the biggest dam in Iraq) experienced some problems [37]-[73]. This paper describes the problems of Mosul Dam and the measures taken to stabilize the dam. The goal of this work is to show the real status of the dam now.

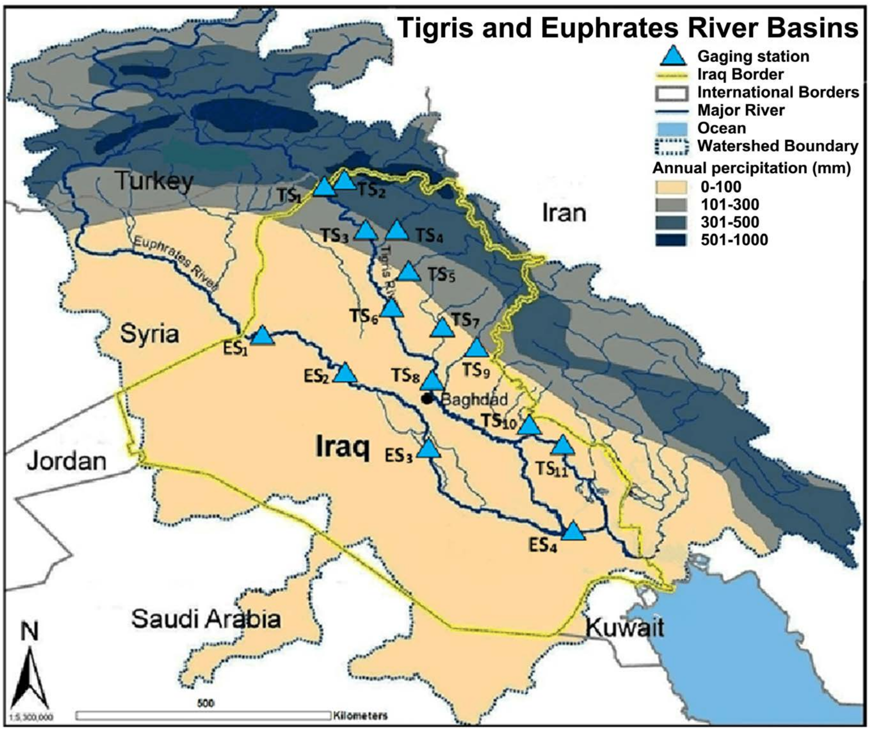

Figure 2. Sources of water for the Tigris and Euphrates Rivers (modified from [4]).

2. Mosul Dam Project

Mosul Dam is the biggest dam in Iraq and second biggest dam in the Middle East. It is located 60 km northwest of Mosul city (**Figure 1** and **Figure 3**) [37] [38]. The construction of the dam started on 25 January 1981 and it started operating on 7 July 1986. The dam is multi objective projects where it provides water for three irrigation projects, flood control and hydropower generation. It is 113 m in height and 3650 m long including its spillway. Its top width is 10 m at 341 meters above sea level (a.s.l.). The normal, maximum and dead storage levels 330,335 and 300 m (a.s.l.). It is an earth fill type with a mud core. The reservoir is designed to impound 11.11 km^3 at normal operational level (8.16 and 2.95 km^3 of live and dead storage respectively) (**Figure 4**). The dam has a concrete spillway located on the left abutment and has five radial gates measuring 13.5 m × 13.5 m giving a discharge of 12,600 m^3·sec^{-1} at the maximum reservoir level of 338 m (a.s.l.) and its crest elevation of the spillway is 330 m (a.s.l.) and its length is 680 m [38]. The power generation facilities are located on and in the right abutment of the main dam and at the crest of the nearby hill the hydropower pumping storage is located (**Figure 3**). At the toe embankment of the dam, the powerhouse is located (**Figure 3**) and includes four turbines with total generating capacity of 750 MW and the pumping storage generates 240 MW. At the northern part of the reservoir, North Al-Jazeera pumping station is located with a maximum water discharge 45 m^3·sec^{-1} (**Figure 3**) [38].

The reservoir of Mosul Dam is almost elongated shape where the River Tigris enters the upper zone and expands close to the dam site. Its length is about 45

Figure 3. Location of Mosul Dam with main facilities.

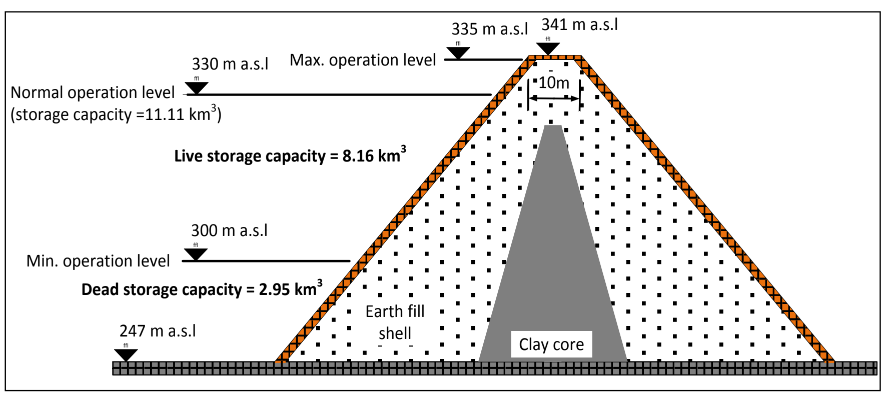

Figure 4. Schematic diagram of Mosul Dam cross section.

km and its width ranges from 2 to 14 km with a water surface area of about 380 km^2 at the maximum operation level of 330 m (a.s.l.). There are ten main valleys that feeding the reservoir (7 from the left side and 3 from the right side) [39].

3. Geology of the Area

The dam lies parallel to Butmah East anticline which is trending E-W with a gentle northern limb. The exposed rocks within the dam site and its reservoir area are the limestone and dolostone beds with soft marl beds of the Euphrates Formation (Lower Miocene) and the Fatha Formation (Middle Miocene) which consists of two members (Lower and Upper). The geology of the area is very complicated and for this reason number of investigations were carried out [40]-[49]. These members consist of cyclic sediments starting with green soft marl, hard limestone and hard gypsum (**Figure 5** and **Figure 6**). Due to the in-homogeneity of the rocks; in their mechanical behavior will certainly behave differently when are loaded.

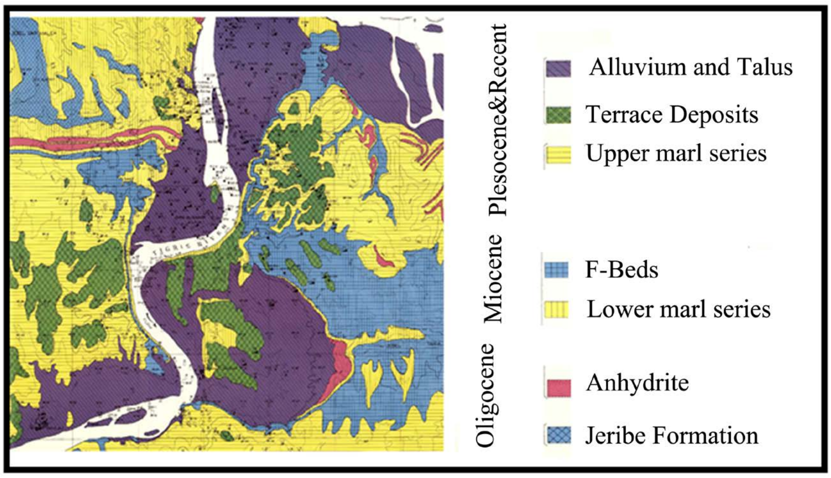

Figure 5. Geologic map of Mosul Dam site area (After [48]).

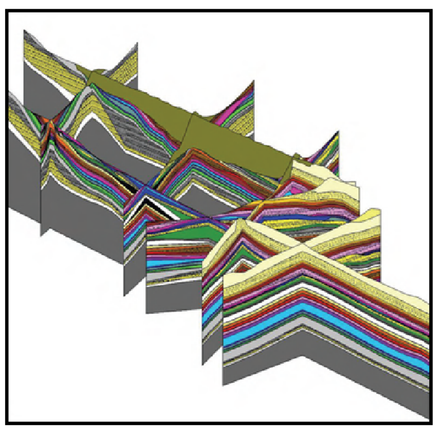

Figure 6. Intersecting cross sections from intermediate version of ERDC geologic conceptual model, showing complex stratigraphy and partial resolution of discrepancies in stratigraphy at intersections of the geologic panels from generated boreholes. (After [49]).

Gypsum and limestone beds are usually karstified, but the karstification is less in the Upper Member as compared to Lower Member of the Fatha Formation. This is due to the presence of more clastics in the Upper Member than that of the Lower Member of the Fatha Formation, besides that gypsum and limestone beds become thin in the uppermost parts of the formation. [50] [51]. The most influential geological feature is the karstification especially in the foundation's rocks [41] [45] [50]-[55].

4. Problem of Mosul Dam

The nature of the rocks (e.g. limestone and gypsum) within the abutments and foundations Mosul Dam site (**Figure 7**) have high dissolution ability, which are

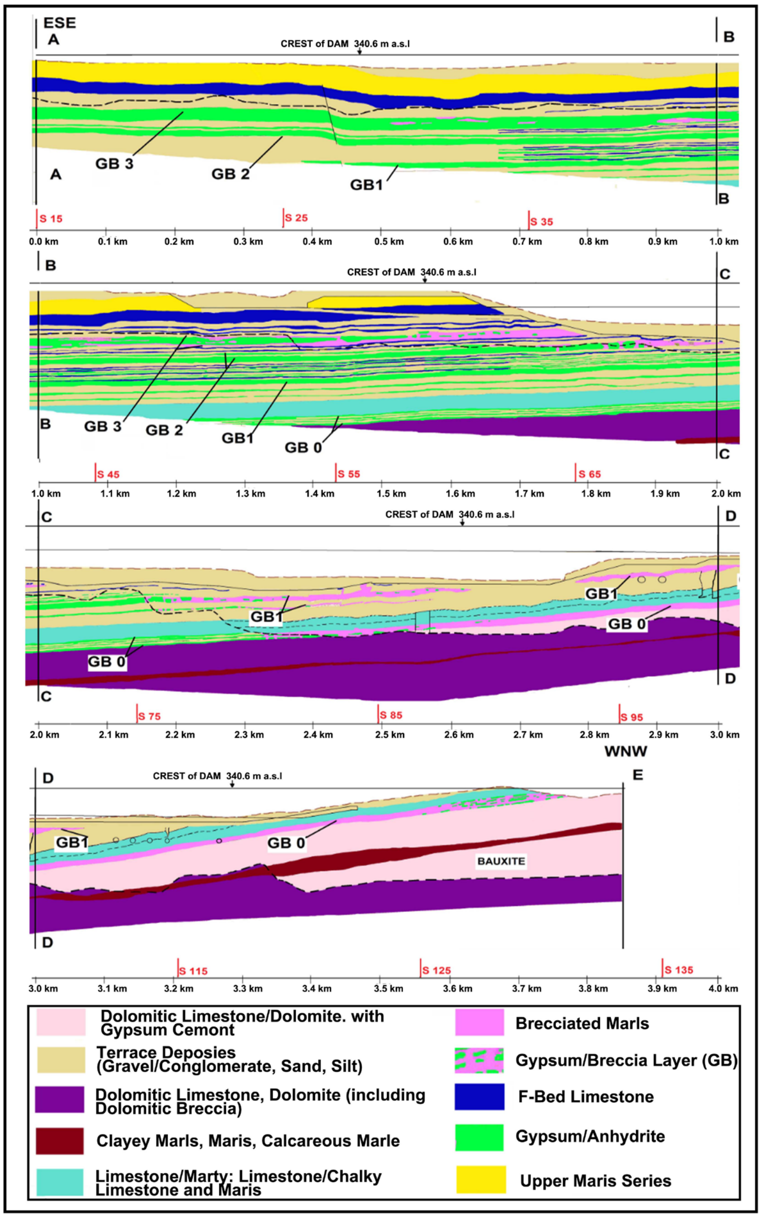

Figure 7. Geologic cross sections along the axis of the dam ([47]).

highly karstified [47] (Al-Ansari *et al.*, 2015). Most of the karst forms are sinkholes that were developed in gypsum and/or limestone [56]-[67] (**Figures 8-10**). The karst extends to a depth of about 100 m below the dam foundation (**Figure 8**).

Sinkholes in the downstream of the dam are believed to be developed due to fluctuations in the tail water level of the main dam during operation of the dam and the down-stream regulating reservoir [41] (Washington Group International, 2005). Before the impoundment of the reservoir, substantial flows of order of 360 l/s were noticed from a gypsum layer found during excavation of the tailrace tunnel for the pumped storage scheme. The seepage water had a high sulphate content, which was different from the reservoir water (**Figure 9(B)**). These

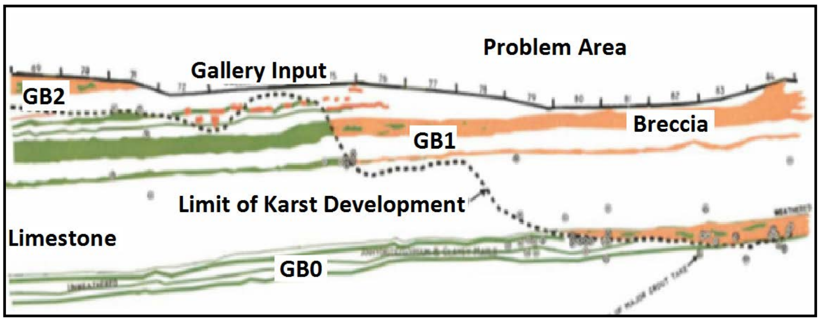

Figure 8. Location of the Karst line ([55]).

Figure 9. (A) One of the four sinkholes which had appeared in the 90's at the downstream right bank near the contractor yard. (B) Spring of discharge 360 l/s which is connected to the ground water aquifer connected to the reservoir ([47]).

Figure 10. An example of sinkhole that apeared in 2003. The left bank sinkhole after full development ([47]).

sinkholes are believed to be connected to the aquifer on the right bank of the reservoir. There are other forms of features such as Karren, shafts, channels also. When the reservoir was filled to its normal operational level (330 m a.s.l.) for the first time new sinkholes appeared downstream (**Figure 10**). In addition, many other seepages were observed with high sulphide water which indicates dissolution of the gypsum [57].

The operation of the reservoir had led to a new groundwater dynamic that accelerated the dissolution of gypsum under the foundation of the dam and within the reservoir area. A sediment and bathymetric survey was conducted during 2011 to the reservoir area and the bathymetric map (**Figure 11**) showed formation of sinkholes within the bottom of the reservoir [68]-[75].

In addition to the above, several researches were conducted to check the stability of Mosul Dam [76] [77] [78] [79] [80]. Settlite based work indicated that there is local differential settlement in the body of Mosul Dam. The results of different work published showed that the settlement varies from 5 - 15 mm/year [76] [77] [78] [79] [80]. This subsidence is believed to be mainly due to heterogeneous decline in the dictates of the dam and not in the foundations according to the consultants who designed the Mosul Dam.

5. Protective Measures

In view of the situation of Mosul Dam that has been discussed above, there were several measures taken to overcome the problem. These measures can be summarized in this section.

Grouting operations were carried out since the start of building the dam to overcome the problem of karstification and jointing of the rocks [56]-[67]. Blanket grouting was done under the core of the main dam. The purpose of this type of grouting was to make sure to fill all the openings due to karstification

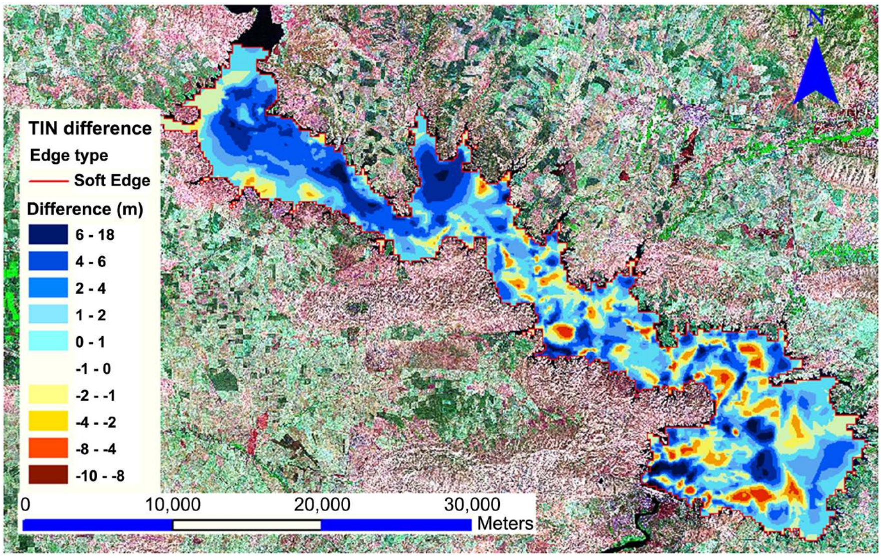

Figure 11. Holes noticed at the bed of Mosul reservoir [73].

and jointing. In addition, deep curtain grouting was performed to stop the seepage in the foundations under the dam, also to reduce the permeability of the grouted zone (see **Figure 8**). Lugeon tests were used to make sure that grouting operations fulfilled the engineering requirements. The aim was to close all the openings within the rocks under the foundation of the dam. Due to the dissolution of gypsum, there were openings created within the deep curtain. To close these openings, massive grouting operations were performed. Despite all the maintenance program, which was carried out seepage of water under the foundation, did not stop and in fact the situation was worsening.

To evaluate the conditions of Mosul Dam, the US Army Corps of Engineers [47] (Kelly *et al.* 2007) used the rock quality designation (RQD) (Deere and Deere 1989) as an index for the description of rock mass fractured state. This test was performed on samples taken in years of 1989 and 2006. The results showed that the samples were deteriorating where RQD results were 45% - 65% for the year 1989 and 0% - 20% for the year 2006. It should be mentioned however that these samples were taken within the vicinity of sinkhole SD5 and it does not reflect the real situation of Mosul Dam foundation. In addition, it was noticed that there were places that highly deteriorated within the deep curtain and the dissolution front had progressed 350 m toward the east *i.e.* an average of about 17 m/year. In view of this, the International Board of Experts for Mosul Dam decided to keep the water level within the reservoir at 319 m a.s.l. [57] [58]. This is to minimize the loses in case of dam failure and it will also decrease the quantity of dissolution of gypsum.

6. Islamic State of Iraq and Syria (ISIS) Occupation of the Dam Area

ISIS occupied Mosul Dam area on 8 August 2014 and they were seized back from the hands of ISIS on the 16th of the same month. ISIS destroyed the buildings, equipment, bridges, etc. on the site (**Figure 12**). As a result, the grouting

Figure 12. Destructions of buildings and bridge as an example of what ISIS did at Mosul Dam site.

operations were halted which had been taking place for more than 30 years and had consumed more than 95,000 tons of solid grout materials. In view of this, the number of work was done by the US Army Corps of Engineers in 2015 to carry out measurements, surveys and observations to follow developments that might lead to the dam failure [67]. The results of these investigations estimated that about 10,000 m^3 of gypsum were dissolved during the period 2014-2016 due to discontinuation of grouting works which was stopped for few months. All these indications led number of researchers to believe that the am is in very critical conditions [77] [78] [79] [81] [82]. Accordingly number of work was carried out [41] [77] [78] [79] [83] [84] [85] to find out the consequences of dam failure and if the work done by the Swiss Consultants was good enough [86] [87] [88].

7. Work after ISIS Occupation

After the defeat of ISIS from Mosul Dam area, the Iraqi Ministry of Water Resources started to rebuild and construct the destroyed parts of the site and started again the maintenance program for the dam (**Figure 13**). In addition, they signed a contract with an Italian company (Trevi) (contract No. 1002/2016) to do maintenance work at Mosul Dam area. The work mainly included the rehabilitation of one of the bottom outlet gates and grouting.

In addition to the above-mentioned work, the D.G. of Dams did a very good training program with Trevi in maintenance grouting and rehabilitation of bottom outlet for the personnel working (**Figure 14**) and another course with the US Army Corps of Engineers (**Figure 15**). After doing these training courses, the

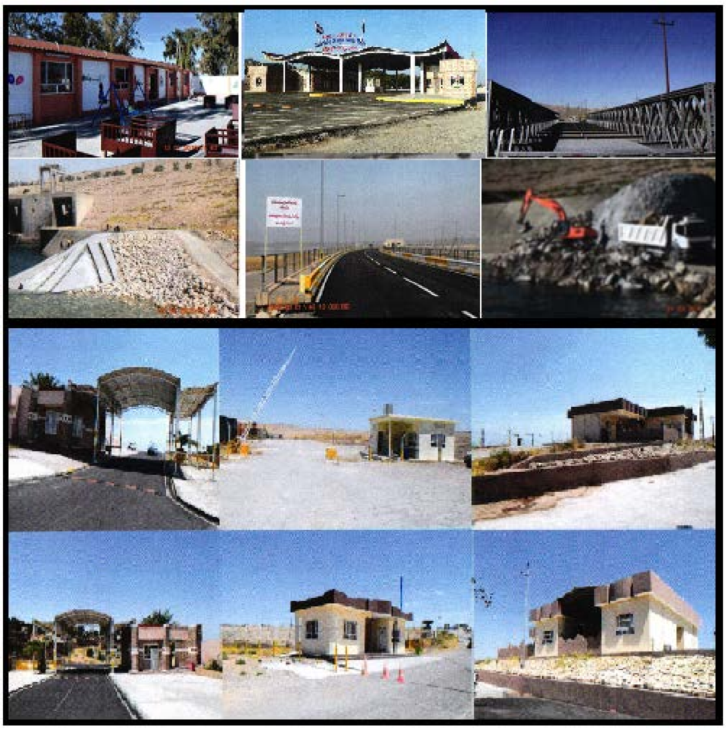

Figure 13. Reconstruction of different sites in Mosul Dam area after ISIS occupation.

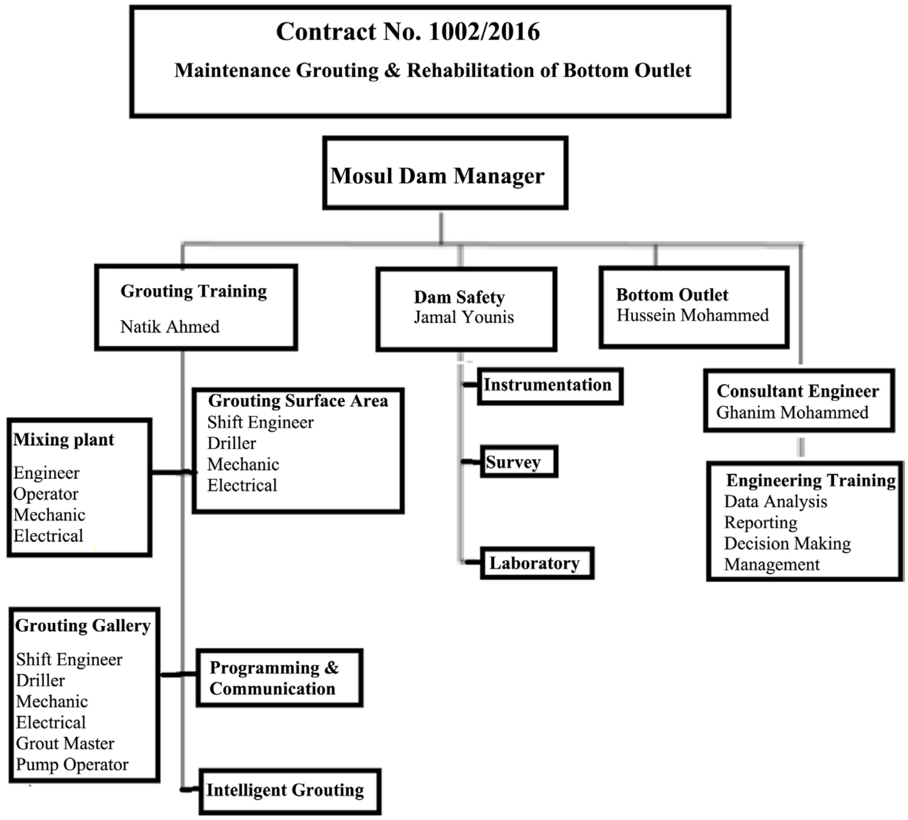

Figure 14. Flow chart of training program for engineers at Mosul Dam with the Italian company "Trevi".

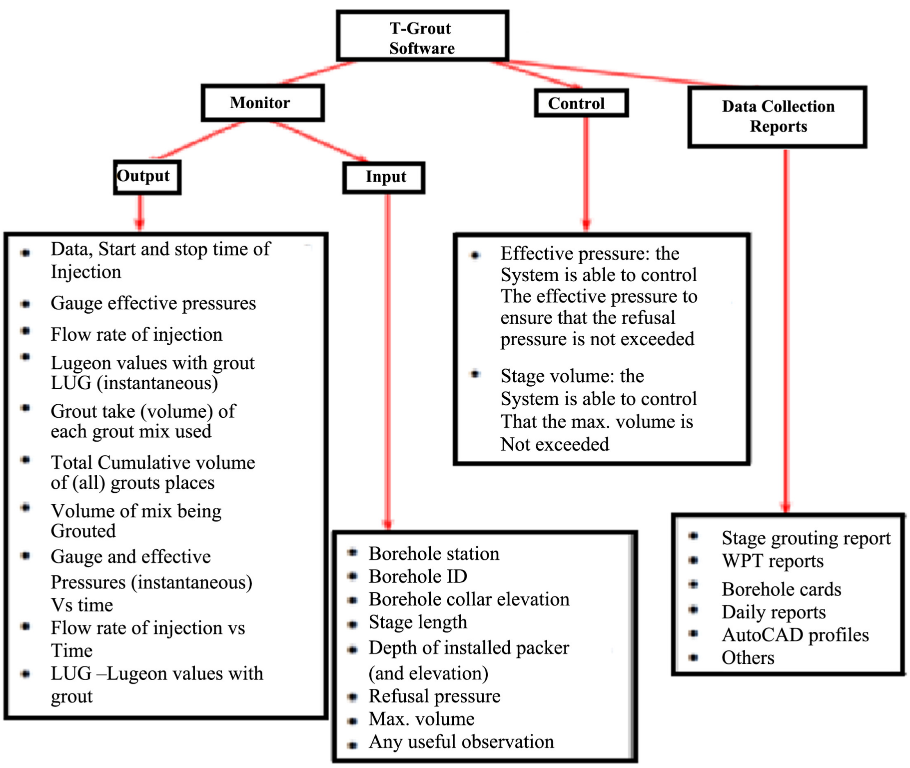

Figure 15. Grouting system used at Mosul Dam site.

staff at Mosul Dam project were qualified to take the responsibilities in maintenance, grouting and operation of the dam.

Grouting operations now follow very highly upgraded system (**Figure 15**). Furthermore, advanced stations and equipment for preparing and pumping grout mix are used now. All the operation is computerized. All electrical cables (98 km long) were replaced in grouting galleries. Pipes that are used for pumping grout mix (15 km long with 1.5-inch diameter) and water pipes (5.7 km long and 6 inches diameter) were all replaced (**Figure 16**).

New 18 drilling machine are used now where 11 of them are electric machines and the remainder are diesel-operating machines (**Figure 17**). All drilling machines are equipped with advanced technologies to register drilling speed, rotations per minute and liquid pressure. This gives accurate information about the beds and all data are displayed on the computer. Three preparation and grout pumping stations were installed that covers all the required areas (**Figure 18**) and there are 32 secondary grout-pumping stations (**Figure 19**). It should be mentioned however, that the grout mix is prepared using special computer program to ensure good required specifications (**Figure 20**). The overall grouting operation is controlled from the control room (**Figure 21**). From this room all grouting operations are monitored and can be controlled. In addition, all the

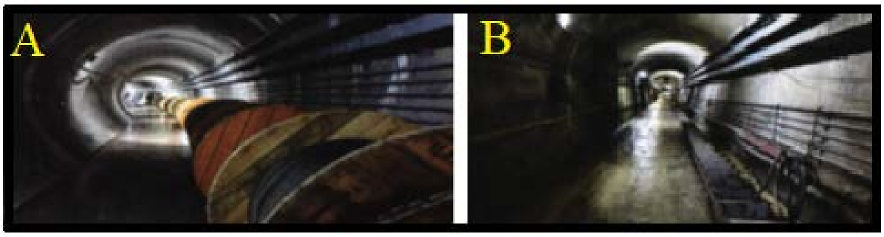

Figure 16. Electrical cables (A) and water pipes (B) were replaced in all galleries at Mosul Dam site.

Figure 17. Drilling machines used at Mosul Dam, (A) Small Diesel machine (B) large machine (C) Small machine for tight areas.

Figure 18. Grout mixing and pumping stations.

Figure 19. Secondary Grout mixing and pumping stations.

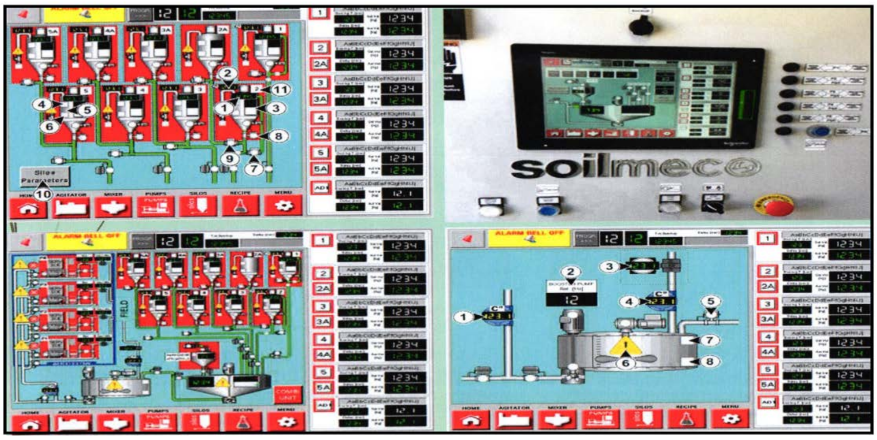

Figure 20. The grout mix is prepared using special computer program to ensure good specifications required.

Figure 21. Control room for Grout operations.

data concerning this operation is stored and data base is prepared for all grouting operations.

It is noteworthy to mention that different galleries and tunnels were cleaned and repaired from grout waste mainly Aljazera irrigation tunnel. This tunnel is 450 m long with 6 m diameter which is lined by concrete layer 1 m thick and another iron layer 18 mm thick (Figure 22).

Figure 22. Cleaning operations at Aljazera irrigation tunnel.

8. Conclusions

Mosul Dam was built on alternating beds of limestone, gypsum and marls. These rocks were highly karstified and jointed. It seems that there were some geological misinterpretations of the geological conditions of the site. These faulty interpretations can be summarized as follow:

1) The depth drawn by the designers to indicate the depth of grouting to fill all cavities ignored some of the gypsum beds that are present below that depth. It seems that these beds were affected by the water particularly one impounding started. Some of these beds were dissolved and cavities were developed. For this reason, grouting material was going down to these cavities, which are located below the curtain-grouting limit. It should be mentioned however, that if grouting operations for karstified rocks in dam sites are not performed correctly [89], or when performed by using miss interpreted data [42], the results will be negative.

2) Some samples collected from some boreholes were reddish brown clay described as bauxite. Actually, they are Terra Rossa, which is a very good indication for karst [90]. These were not grouted and neglected.

For the above reasons, seepage of water started once the reservoir was impounded. The process of karstification is an ongoing process and expected to continue with the limestone and gypsum beds and for this reason, grouting is to be performed continuously to minimize the seepage. In view of this situation, the International Board of Experts recommended to keep the water level at 219 m a.s.l. instead of the normal operation level (330 m.a.s.l.). This is to lower the pressure of impounded water on the dam and the rocks on the site to minimize the seepage and the damage will be minimum in case of dam failure.

It is noteworthy to mention that, the present grouting operations and performance of maintenance work by the Iraqi engineers in Mosul Dam site are excellent. This indicates that the dam is safe at its present water level within its reservoir at 319 m.a.s.l. In addition, the impounding was raised 325 m.a.s.l. for few days and nothing abnormal was noticed.

Acknowledgements

We would like to thank the Iraqi Ministry of Water Resources for providing the data and arranging field trips.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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