Research Article

The Status of Mosul Dam, NW of Iraq

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Access this article online		
Received on: August 30, 2021	**Accepted on:** September 27, 2021	**Published on:** December 28, 2021
DOI: 10.25079/ukhjse.v5n2y2021.pp56-61	**E-ISSN:** 2520-7792	

Abstract
Mosul Dam is located in the northwestern part of Iraq impounding the Tigris River; about 60 km north of Mosul city. This project is multipurpose project; to provide water for irrigation, flood control and hydropower generation. The dam is 113 m high and 3650 m long including the spillway. The dam is earth fill type with a mud core. The dam was designed to impound 11.11 km³ because it is based and underlain by gypsum beds alternated with limestone and marl. Therefore, it is planned to use continuous grouting to fill the karst caverns. The used quantity exceeded 95000 tons of solid grouting materials since 1986 up to 2014. After all, is the dam safe? The details are given in the current article.

Keywords: Foundation, Grouting, Gypsum, Karstification, Mosul Dam.

1. Introduction

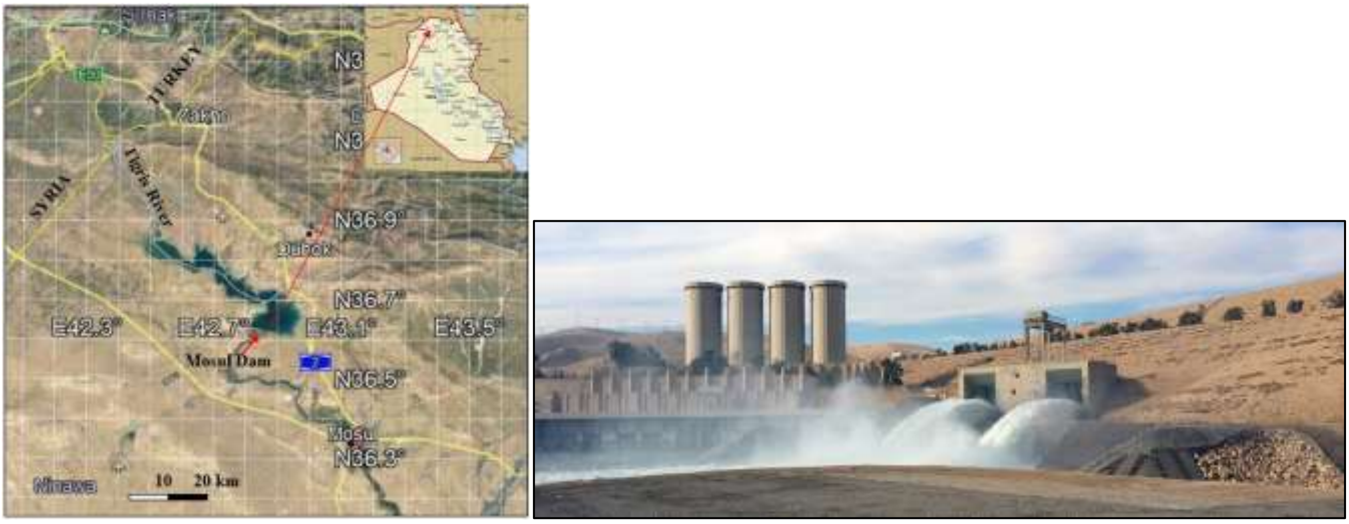
Mosul dam is an Earth-fill dam constructed to impound the Tigris River in the northwestern part of Iraq, 60 km northwest of Mosul city (Figure 1a). It is the largest dam in Iraq with clay core, its height is 113 m and length is 3650 m (Iraqi Ministry of Water Resources, 2012). The total cost of the dam was 2.6 billion US$. A general view of the dam is shown in Figure 1b. The maximum, normal and dead storage levels of its reservoir are 335, 330 and 300 m (a.s.l.), respectively. The dam was designed to impound 11.11 $x10^{9}$ m of water at normal operation level. The construction of the dam started on January 25th, 1981 and completed on 24th July 1986 (Al-Ansari *et al.*, 2015a).

The aim of this article is to give a brief review about Mosul Dam and to discuss its safety. The authors are well acquainted with the history of Mosul dam; they have contributed in an International Conference held in Stockholm, Sweden in 2016 by the Luleå University of Technology (https://www.ltu.se/cms_fs/1.148962!/file/Very%20Final%20Mosul%20Dam%20Workshop.pdf).

2. Geological Setting

The geological setting of Mosul Dam site and reservoir area is briefed hereinafter based on Sissakian and Fouad (2012). Mosul Dam is constructed parallel to the axis of Butmah East anticline which has E – W trend with steep southern limb. Karst forms are well developed, especially in gypsum rocks in form of sinkholes. The exposed rocks in the dam site and reservoir area belong to two main formations, these are:1) Euphrates Formation (Lower Miocene) consists of limestone and dolostone beds with soft marl beds, and 2) Fatha Formation (Middle Miocene) consists of two members

(Lower and Upper). Both members consist of cyclic sediments starting with soft green marl, hard limestone, and hard gypsum (Figure 2).



a b

Figure 1. Mosul Dam a) Satellite Image Showing Location Of Mosul Dam, b) General View of the Mosul Dam.

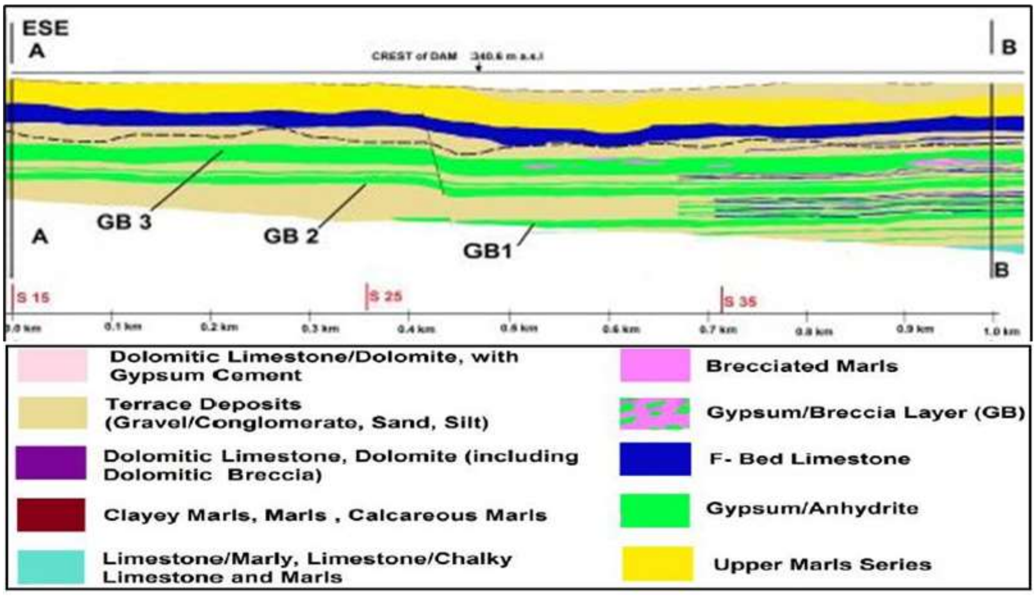


Figure 2. Cross Section on Mosul Dam Axis Showing the Cyclic Sediments of the Fatha Formation. The dashed line represents karstification level, GB = Gypsum bed (Al-Ansari *et al.*, 2015c).

3. The Main Problem of Mosul Dam and Indications

Karstification is the main dangerous problem in the dam site and reservoir area. Due to existence of thick gypsum beds at the dam site, Swiss Consultants (1979) designed the foundations to be grouted since construction until decommissioning of the dam to minimize the karstification. At the end of the 1986, the reservoir level reached 316.4 m (a.s.l.). The reservoir was filled to the normal operation water level of 330 m (a.s.l.) for the first time in 1988. Accordingly, the first sign of trouble appeared at the first filling in the spring of 1986 (Adamo & Al-Ansari, 2016). New sinkholes were observed downstream of the dam (Figure 3); many other seepages were observed too with high sulphate water which indicates dissolution of the gypsum. Moreover, many grouting boreholes along the foundation of the dam were found to be empty which means the grouting materials had disappeared. However, the dam body was inspected in different time intervals and found to be free of cracks, settlement, and dislocation (Mark & Wheeler, 2004; Milillo *et al.*, 2016).

It is worth mentioning that Othman *et al.* (2019) conducted remote sensing study to check the stability of Mosul Dam and they found that "Maximum deformation rate was found to be about 7.4 mm/ year at a longitudinal subsidence area extending over a length of 222 m along the dam axis. Whereas the mean subsidence was about 6.27 mm/ year and lies in the center of the dam.

Figure 3. A Recent Developed Sinkhole (Down-Stream) After Filling of the Reservoir (Al-Ansari *et el.*, 2015b).

After the first impounding of the reservoir in 1986, the dynamic of the groundwater was changed. The new created groundwater dynamic with the operation of the reservoir has accelerated the dissolution of the gypsum beds not only under the foundation but even in the reservoir area; accordingly, the development of the sinkholes was accelerated. Moreover, seepages and springs were observed downstream of the dam, as well as deterioration of the deep grout curtain under the dam. The curtain, during construction was suffering from deficiencies due to inability of closing certain areas in the curtain within the gypsum brecciated layers (Adamo *et al.*, 2015a).

To check and follow up the dissolution of gypsum beds, water samples were chemically analyzed continuously; moreover, seepage rates were monitored and found an increase from 500 l/ sec on February 10, 1986, to 1400 l/ sec on August 16, 1986; with increase in water head from 49 m to 65 m. The chemical analyses of the sampled water showed that the dissolution intensity increased from 42 to 80 t / day.

Issa et al. (2003) conducted bathymetrical survey in the reservoir of Mosul Dam to show the changes in the reservoir bottom morphology with time (1983 – 2001) due to erosion and sedimentation processes. Accordingly, an erosion and sedimentation map was generated (Figure 4). The erosional areas with maximum depth of 9.6 m are believed to represent sinkholes and gypsum dissolved areas (Kelley et al., 2007 ; Wakeley et al., 2007). Some of these sinkholes are about 15 m in diameter and more 15 m in depth (Washington Group International, 2005).

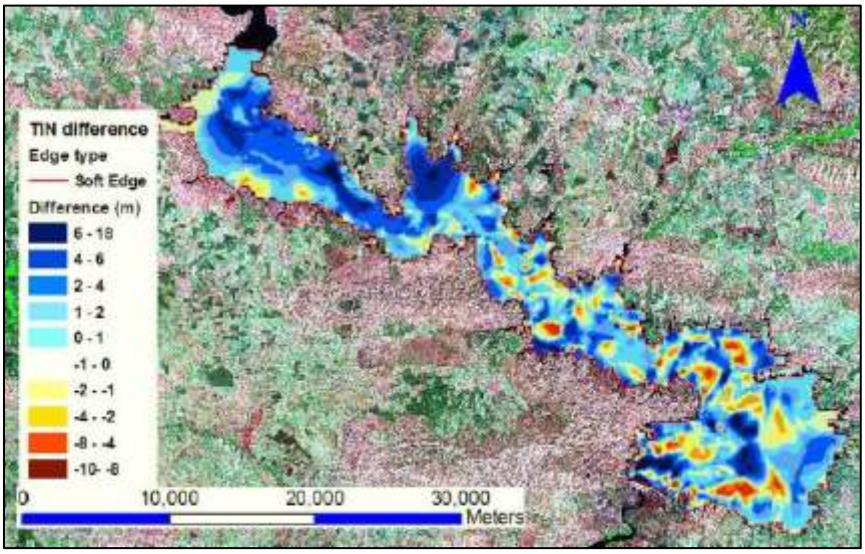


Figure 4. TINs for Survey 2011 and 1983 of Mosul Reservoir (Issa et al., 2003).

4. Protective Actions

Due to the mentioned observed cases and to avoid any possibility of the dam failure, extensive grouting program was performed in 1987 to strengthen the right bank grout curtain extension and to elongate the curtain further to the right side, while re-grouting continued in the river channel section as repair work. It is worth to mention that the grouting is continuous hitherto. The following actions were carried out and part of them is still ongoing.

4.1. Grouting Works

The treatment of the Mosul dam foundations as per design consists of two main elements: a) Blanket grouting, and b) Deep grout curtain. The deep grout curtain construction was completed on February 6^{th,} 1988. But maintenance and repair work which were started in the end of 1986 continues up to now (Adamo *et al.*, 2015b).

4.1.1. Blanket Grouting

This grouting was performed under the core of the main dam. The purpose of this grouting is to close the openings originally existing in the foundation rocks due to dissolution of gypsum beds (karstification). It was planned and designed to seal any seepage paths at the contact of the core with the foundation. To find out later efficiency of the blanket grouting, permeability tests were conducted using Lugeon test in exploratory holes before starting the grouting. Accordingly, high permeability zones were recognized with values 28.7 and 54.5 Lu on the right and left banks, respectively.

4.1.2. Deep Grout Curtain

This grouting was planned and designed to create a barrier to stop the seepage in the foundations under the dam, also to reduce the permeability of the grouted zone. The aim was to stop the dissolution of gypsum beds. Moreover, to seal all types of cavities; accordingly, to reduce the seepage flow in the foundations.

4.1.3. Massive Grouting

This was used in repair works of the grout curtain. Piezometric observation were carried out for checking of the conditions of the grout curtain and the detection of problematic areas where additional treatment was required. Piezometric observation continued and resulted in the repeated application of both normal and massive grouting works up to now, where the grout used from 1986 to 2014 reached 95657.43 tons.

4.2. Lowering Water Level

After 2006, where all grouting processes were almost in vain, an action was suggested to keep the safety of Mosul Dam. This was lowering the maximum normal operation water level in the reservoir to 319 m (a.s.l.) instead of 330 m (a.s.l.) (Adamo and Al-Ansari, 2016). However, this means the dam will operate in all its planned and designed aims to about 60%; including: 1) Water supply for irrigation, 2) Flood control, and 3) Electric power generation. Nevertheless, lowering the water level will decrease: 1) The dissolution rate of gypsum due to lowering the water head, 2) The exerted forces on the dam due to decrease of the water volume.

4.3. Works of the Italian Company

In June 2014, ISIS controlled Mosul Dam for about 2 weeks, during their control; the grouting processes were terminated, and all grouting equipment and materials were destroyed. After the ISIS was dismissed, the dam returned under the control of the Ministry of Water Resources. Accordingly, a new grouting attempt was restarted by an Italian Company named "Trevi". The task was performed and Trevi left the site in March 2018 after training of local engineers. Accordingly, the grouting processes were continued up to the most recent techniques.

5. Discussion

The safety of Mosul Dam is still a matter of debate. Keeping the dam from collapsing is a never-ending task (IWPDC, 2011). Although, the Italian company completed the task of the grouting in March 2018; however, the normal operation water level is still not 330 m (a.s.l.). In 2019, the Ministry of water Resources ventured to reach level 323 m (a.s.l.) but the level was lowered back quickly to level 319 m (a. s. l). This is a good indication that the dam's safety is still doubtful.

Grouting of the karstified rocks in dams can give reverse results when is not correctly performed (Bonaci et al., 2009) or when performed by using missinterpreted data (Sissakian *et al.*, 2017). Hereinafter are some missinterpreted data which led to an endless successful grouting.

5.1. Missinterpreted karstification line

Figure 2 shows the karstification line which was used to indicate the depths of the grouting boreholes, and it shows that there are many gypsum layers below the line. Those gypsum beds will dissolve, and voids and caverns will be developed, and the grouting materials will go down in the developed caverns below the karstification lines.

5.2. Miss Interpreted Terra Rossa

In some of the boreholes, bauxite is described. Actually, it is not bauxite; it is reddish brown clay called Terra Rossa; a good indication for karst (Merino *et al.*, 2006). But it was not considered as karst indication by the site geologists of the construction companies (GIMOD), and consequently no grouting was performed.

5.3. Dam Safety

From reviewing the missinterpreted data which was used in planning the depths of grouting boreholes and/or areas which need to be grouted, the grouting process will not be effective and will not be able to seal the caverns developed due to the karstification of gypsum and/or limestone beds because the karstification is an ongoing process. Accordingly, the seepages will continue from the foundations. Moreover, keeping the water level in the reservoir lower than the designed elevation (330 m, a.s.l.) means that the dam is still not completely safe.

Recently, the grouting operation is carried out using new technique. The area is connected with a grouting network that is computerized. It should be mentioned however, that the water level is kept at 319 m (a. s. l..). At this level the dam is stable.

6. Conclusions

From the reviewed and reinterpreted data, it is clear that the safety of Mosul Dam is still a matter of debate, and the dam requires continuous technical monitoring. It is very difficult and suspicious to conclude that Mosul Dam is in a safe status or otherwise. For this reason, the water level is kept at or lower than 319 m (a. s. l.).

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