Research Article

Karstification Problems in the Haditha Dam, West Iraq

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Access this article online		
Received on: January 2, 2021	**Accepted on:** April 24, 2021	**Published on:** June 30, 2021
DOI: 10.25079/ukhjse.v5n1y2021.pp111-118	**E-ISSN:** 2520-7792	

Abstract
Haditha Dam is constructed on the Euphrates River in the western part of Iraq completed in 1988 and located 14 km west of Haditha town. Haditha Dam is a combined earthfill and concrete dam with a total length of 9064 m. The maximum height of the dam is 57 m from the deepest point at the river channel and dam crest level is 154.00 m (a.s.l.). The storage capacity is 6×109 m3 at normal operation water level of 143 m (a.s.l.). The exposed formations in the dam site and reservoir area are the Euphrates (Lower Miocene) and Fatha (Middle Miocene) formations. Both formations are well known in Iraq to be karstified at different intensities. The right bank of the Euphrates River is severely karstified with tens of sinkholes of different shapes, dimensions and activities. The presence of the karstified rocks is the main reason the dam has a very long grout curtain which extends along its entire length and includes the concrete powerhouse and spillway structure in the river channel, and the right and left bank extensions. The right bank extension of the grout curtain is exceptionally long due to the extent of the sinkhole area. Grouting was performed here in boreholes drilled at one-meter spacing to reduce water penetration and movement through the flank of the dam. The grout curtain under the embankment in the river section was done in two rows, while under the concrete structure it is comprised of three rows of holes. The left bank extension has two rows. The depths of all parts of the curtain varied following the karstification zones and intensities. The main aim of the current study is to elucidate and discuss the influence of the karstified rocks at the dam site and reservoir on the design and especially the length of the dam and the need for side extensions.

Keywords: Haditha Dam, Karstification, Grouting, Grout Curtain, Sinkholes, Euphrates River.

1. Introduction

Haditha Dam is constructed on the Euphrates River near Haditha town. It is a combined earthfill and concrete dam with total length of 9064 m, the maximum height of the dam from the bed of the river channel is 57 m, the dam crest level is 154.00 m (a.s.l.) with storage capacity of 6×10^9 m^3 at normal operation water level of 143 m (a.s.l.). The investigation and preparation to construct the dam started in 1977 by ex-Soviet firms and the filling of the reservoir was completed in 1988 (Adamo and Al-Ansari, 2016). The width of the main channel during construction was 350 m, whereas the secondary channel was 50 m wide. The hydroelectric power station and spillway combined structure is located in part in this secondary channel. Hadith Dam (Previously called Al-Qadisiyah Dam) embankment was designed by the ex-Soviet Union's "All Union Consultants-Hydroproject", whereas the power station equipment was designed, supplied and erected by various firms under the umbrella of Hydropgradinja Co. which at the same time had retained Energoproject Co. as civil works designers; all were from ex- Yugoslavia. The dam was planned as a multi-purpose project that would generate hydroelectric power, regulate the flow of the Euphrates River, provide water for irrigation for the southern part of Iraq and provide security against the Euphrates River floods. The filling of the reservoir started from 1985 and was completed 1988 Figure 1.

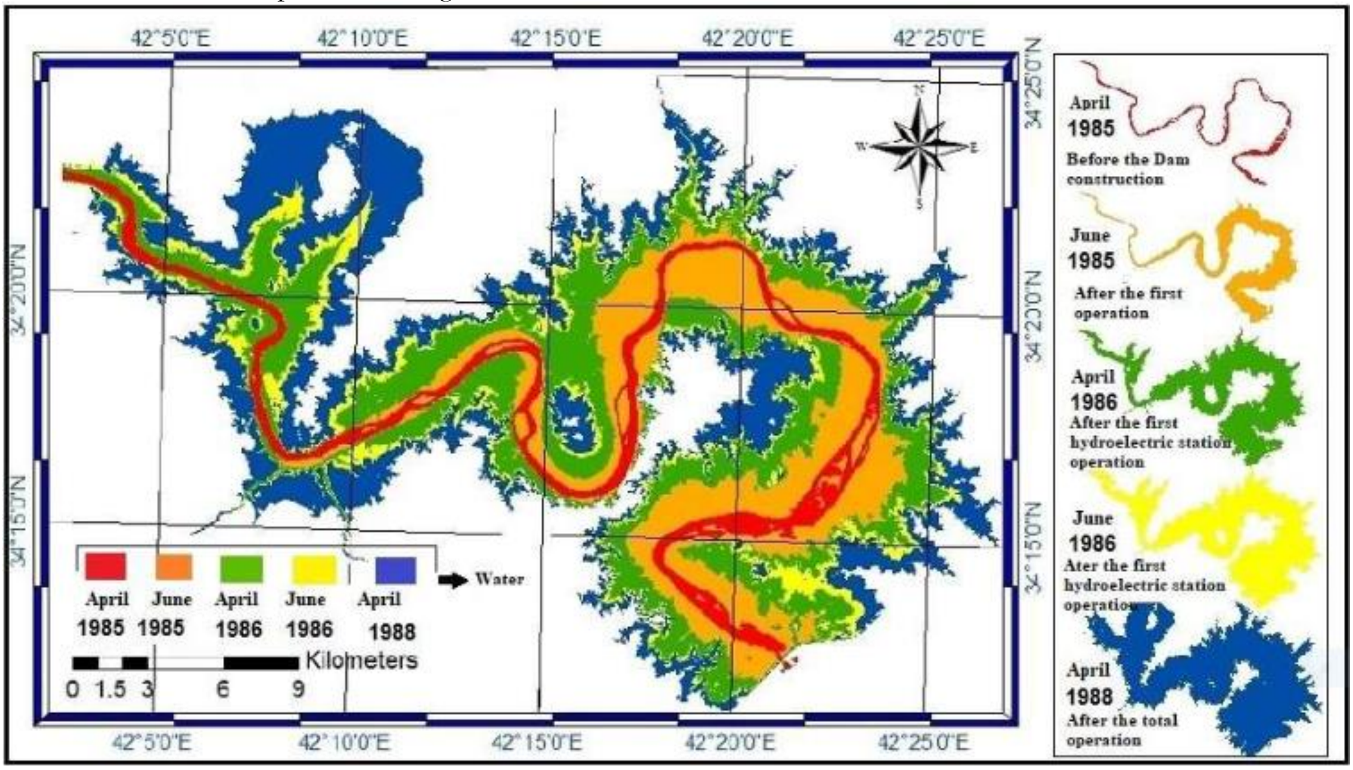

Figure 1. Variation of water surface area of Haditha Dam Lake, 1985-1988 (After Hason et al., 2020).

1.1. Location

Haditha Dam is located in the central western part of Iraq, 14 km north west of Hadith town, see Figure 2. The dam impounds the Euphrates River and the reservoir covers about 500 km² at maximum flood water level of 147 m (a.s.l.) with 100 km of shoreline, and has inundated two main towns; Anah and part of Rawa.

1.2. Previous Studies

Different studies were carried out on Haditha Dam and its near surroundings, among them are: Hamza (1997) which compiled the geomorphological map of Iraq and described Anah – Haditha vicinity as one of the most karstified areas in Iraq. Sissakian et al. (1984) studied different geotechnical properties of the exposed rocks at the dam site and its near surroundings. Mahdi et al. (1984) conducted detailed geological mapping of the dam site and part of the reservoir area. They presented geological maps at a scale of 1:25000 and described the exposed rocks, structural, and geomorphological aspects of the area under consideration. Sissakian et al. (1986) studied the existing sinkholes in Anah – Haditha vicinity and they recognized 55 sinkholes of different types, dimensions and activities. Sissakian et al. (2015) considered the karstification problems in Haditha area as one of the major issues facing thethe Haditha Dam.. Still further, Sissakian et al. (2017) figured out that miss-interpretation of karst fill sediments as one of the main problems in the treatment of dam foundations. Adamo et al. (2018 a) described the foundation treatments of Hadith Dam, and Adamo et al. (2018 b) also described the construction materials used, in addition to the specifications of the dam work. Al-Ansari et al. (2018) narrated in details the water resources of the Euphrates River, especially those feeding Haditha Dam reservoir. Danboos et al. (2018) studied the effect of the evaporation from Haditha reservoir on the ecological system. They concluded that water lost in the reservoir is about 60%, and was due to pumping of the groundwater. The current authors' observation on the water loss indicates that the reservoir recharges the groundwater and this is a good indication for intensively karstified area of the reservoir.

Li et al. (2018) performed a dynamic analysis of the Haditha earthfill dam, integrated with a hydropower plant system containing six vertical Kaplan turbines. They concluded that understanding the effects of running hydropower plant turbines on the dam body is one of the major safety concerns for the earthfill dam, besides other safety concerns such as karstification. Sissakian et al. (2018) described the general geology of Haditha Dam, and Hason et al. (2020) conducted change detections study over the impounded area of Haditha Dam reservoir for many years, see Figure 1.

The main aim of the current study is to elucidate and discuss the influence of the karstified rocks at the dam site and reservoir on the design and especially the length of the dam and the need for side extensions.

Figure 2. Location of Haditha Dam and reservoir.
(Dam location and old Anah and Rawa towns are added by the authors).

2. Materials and Methods

Different materials have been used to perform this study; among them are: geological maps of different scales, satellite images, tens of published articles which have dealt with Haditha Dam and karstification problems. Besides, field observations during construction of the dam at different periods were referred to during 1973 onwards, when the dam site was still under study and evaluation, and in 1984 when the dam was under construction. Some of the authors have contributed detailed discussions with the Soviet engineers and geologist to explain the geology of the area and the presence of tens of sinkholes and their effect on the dam. The effect of the karstified rocks; as indicated by the presence of these sinkholes near the dam site and reservoir area along the length of Haditha Dam and the foundation's treatment, are discussed hereinunder.

3. Geological Setting

The geological setting of the Haditha Dam and reservoir area is briefed hereinafter. Three main aspects are dealt with;

3.1. Stratigraphy

Figure 3 presents the exposed geological formations at Haditha Dam site and near surroundings as complied by Sissakian and Qanber (1993). The following geological formations are exposed at the dam site and reservoir area:

- **Anah Formation** (Upper Oligocene): The formation is exposed south of the reservoir area, it consists of massive and thickly bedded and hard dolomitic limestone and cavernous limestone. The formation plays effective role in development of the sinkholes; this is attributed to the presence of thick conglomerate bed between Anah Formation and overlying Euphrates Formation. The conglomerate bed acts as groundwater passage, and accordingly contributes to the development of sinkholes.

– **Euphrates Formation** (Lower Miocene): The formation is exposed at the dam site and reservoir area. The formation consists of two members. The Lower Member consists of basal conglomerate, the pebbles are all derived from the underlying Anah Formation cemented by fairly hard cement. The conglomerate is overlain by well bedded and hard dolomitic limestone, dolomite and limestone; and followed upwards by thickly bedded chalky dolomitic limestone. This member forms the flat areas in the dam site and near surroundings and all the sinkholes are developed within it. The Upper Member consists of brecciated, highly undulated dolomite with thin marl horizons; overlain by well thinly bedded and hard undulated limestone.

– **Fatha Formation** (Middle Miocene): The formation is exposed only in the left bank of the reservoir area. see Figure 3. The formation is divided into two members: The Lower Member, consists of cyclic sediments, each cycle consists of green marl, limestone and gypsum. The Upper Member consists of cyclic sediments, each cycle consists of green marl, red claystone, limestone and gypsum. Locally, the uppermost cycles include fine reddish brown sandstone beds. The formation is highly karstified; exhibiting solution sinkholes.

– **Nfayil Formation** (Middle Miocene): The formation is exposed as isolated hills and/or plateaus southwest of the dam site only, see Figure 3. The formation consists of cyclic sediments; each cycle consists of green marl and limestone; maximum of three cycles were observed (Sissakian et al., 1994 and 1996).

– **Quaternary Sediments** (Pleistocene and Holocene): The Quaternary sediments at the dam site and reservoir area are: Terraces of the Euphrates River, three levels were recorded before inundation of the river valley. Slope sediments are well developed along main cliffs, banks of main valleys. Flood plain sediments of the Euphrates River, in which two levels were recorded. Finally, valley fill sediments, where the main valleys are observed to have considerable amount of such sediments.

3.2. Geomorphology

The study area, including Haditha Dam and reservoir, is located in two different physiographical provinces; these are Western Desert and Al-Jazira Provinces (Sissakian and Fouad, 2012). Both provinces are characterized by flat terrain dissected by large valleys, especially the former province, see Figure 4. The main geomorphological aspects are briefed hereinafter.

3.2.1. Geomorphological Units

The geomorphological units belong to the following origins (Sissakian and Qanber, 1993):

Alluvial Origin: This includes two units: 1) River terraces consisting of gravels of different rock types, sizes and shapes cemented by sandy materials and are locally gypsiferous. The thickness varies from (3 – 5) m. 2) Flood plains consist of sand, silt, and clay. The thickness varies from (1.5 – 3) m.

Karst Origin: The most common karst forms in the dam site and reservoir area are the sinkholes. They are developed in different shapes, dimensions, and activities.

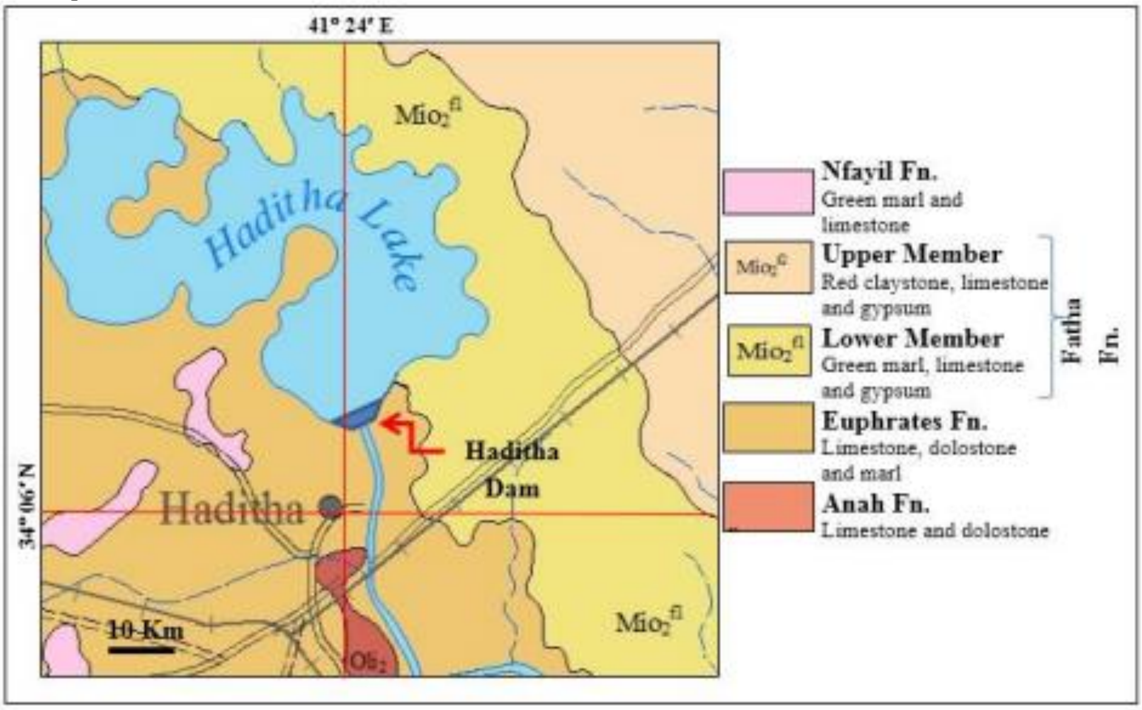

Figure 3. Geological map of Haditha Dam site and reservoir area (From Sissakian et al., 2018).

3.2.2. Weathering

The main weathering types that have developed and are active in the study area are: Chemical weathering, which is continually reacting on gypsum and limestone beds. Mechanical (Physical) weathering is less active; as indicated from the weathering grade of the rocks, especially of the Euphrates Formation, which are slightly weathered, whereas claystone and marl beds of the Fatha and Nfayil formations are moderately to highly weathered (Sissakian et al., 1984).

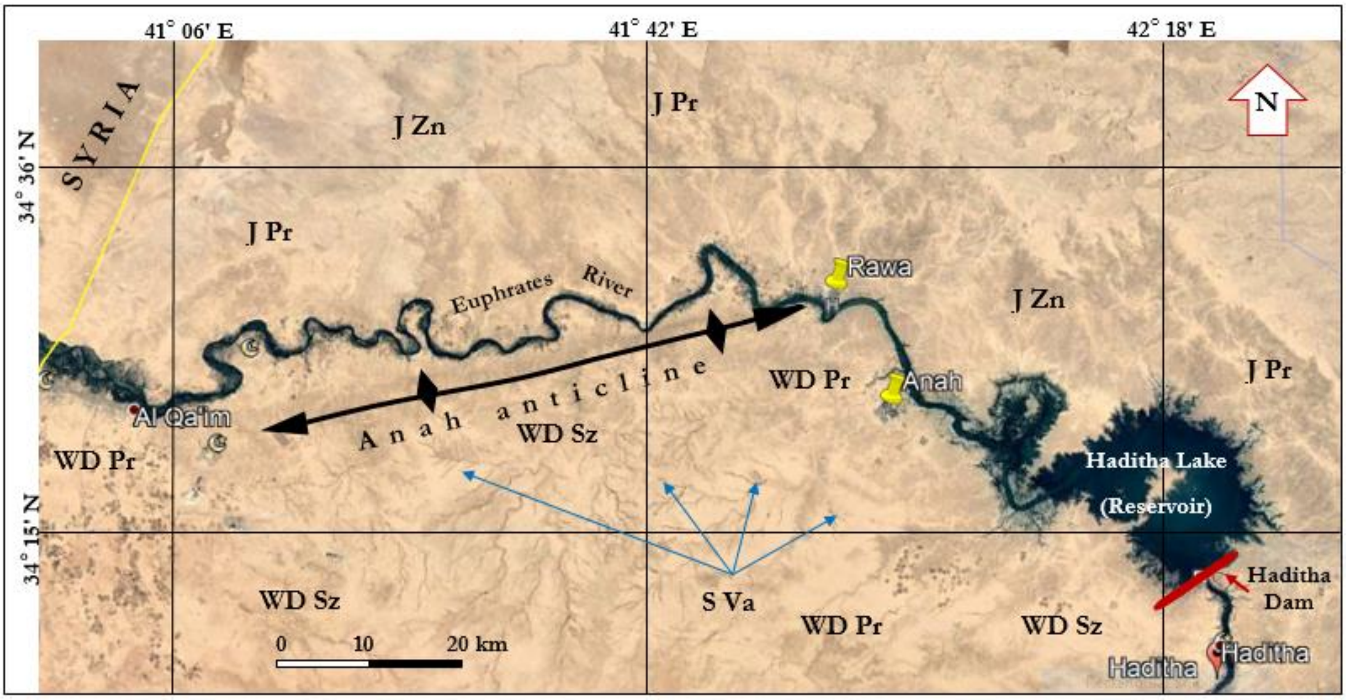

Figure 4. Satellite image showing Haditha Dam and Lake. Note that the coverage of the lake is decreased due to drought, normally it reaches to Rawa town.
Geomorphological Provinces: JPr= Jazira province, WD Pr= Western Desert Province.
Tectonic zones: JZn= Jazira Zone, WDSz= Western Desert Subzone. S Va= Straight valley
Geomorphological provinces are after Sissakian and Fouad (2012), Tectonic zones are after Fouad (2012).

3.2.3. Erosion

Three main types of erosion are developed in the study area; these are: 1) Gulley erosion is highly active in large valleys like Wadi Fhaimy, Wadi Al-khdher, Wadi Haqlan, where the courses of the valleys are deep with steep banks, 2) Rill erosion can be recognized also on the slopes of main cliffs, and 3) Sheet erosion can be recognized on the flat areas that are covered usually by residual soil (Sissakian et al., 1984).

3.3. Tectonic and Structural Geology

The study area, of Haditha Dam site and its reservoir are located within two different tectonic zones, see Figure 4. The area north of the Euphrates River belongs to the Jazira Zone that is part of the Mesopotamia Foredeep of the Outer Platform. Whereas the area south of the Euphrates River belongs to the Western Desert Subzone of the Inner Platform. Both Outer and Inner Platforms belong to the Arabian Plate (Fouad, 2012).

The main characteristic of the Jazira Zone is the absence of surface structural features, which is the main reason it is a flat area with slight undulations. However, many subsurface anticlines were recorded by geophysical studies; all being originally inverted grabens (Fouad, 2012). It is worth mentioning that the Jazira area is characterized by Neotectonics evidence (Sissakian and Abdul Jab'bar, 2009). The Western Desert Subzone also lacks tectonic features indicating tectonic rest. However, Anah anticline shown in Figure 4, forms the tectonic boundary between the Inner and Outer Platforms and is the only structural form in the whole subzone that is far from the dam site, but within the reservoir area at the higher elevation levels.

Different Neotectonics evidence in different forms are present in different parts of the subzone, but all of them are not near the dam site (Sissakian and Deikran, 2009). Some fine branches of large valleys with straight trends, which are oriented in WNW – ESE trend can be seen west of the dam Figure 4; they indicate Neotectonic evidence (Sissakian, 2002). It is worth mentioning that all those structural and Neotectonic features have no significant effect on the stability of the dam. This is due to: 1) their small size, and 2) they are located far from the dam site.

4. The Dam

4.1. Overview

The Haditha Dam is characterised by a total length of 9064 m, maximum height of 57 m from the deepest point at the river channel, dam crest level was fixed at 154.00 m (a.s.l.). The width of crest is 20 m, and width of the dam at the deepest river section is more than 300 m, whereas the storage capacity is 6×10^9 m^3 at elevation 143 m (a.s.l.) The total length of the dam includes 8875 m of the earthfill part and 189 m of the hydropower station and spillway combined concrete structure, which is located at part of the river channel. The earthfill part of the dam includes 3310 m and 4985 m as the right and left abutments, respectively, and 580 m in the river channel, see Figure 5 (Adamo et al., 2018 b).

The site of the Dam is located in a narrow part of the Euphrates River valley, which is 10.5 km upstream from Haditha town as shown in Figure 2 and 4. This selection was based on the geological and topographic conditions, besides the mode of occurrence of karstified limestone and gypsum beds in the right and left abutments of the dam, respectively, see Figure 3. Moreover, to the availability of different types of construction materials alongside the Euphrates River, and the suitable conditions of performing the construction work.

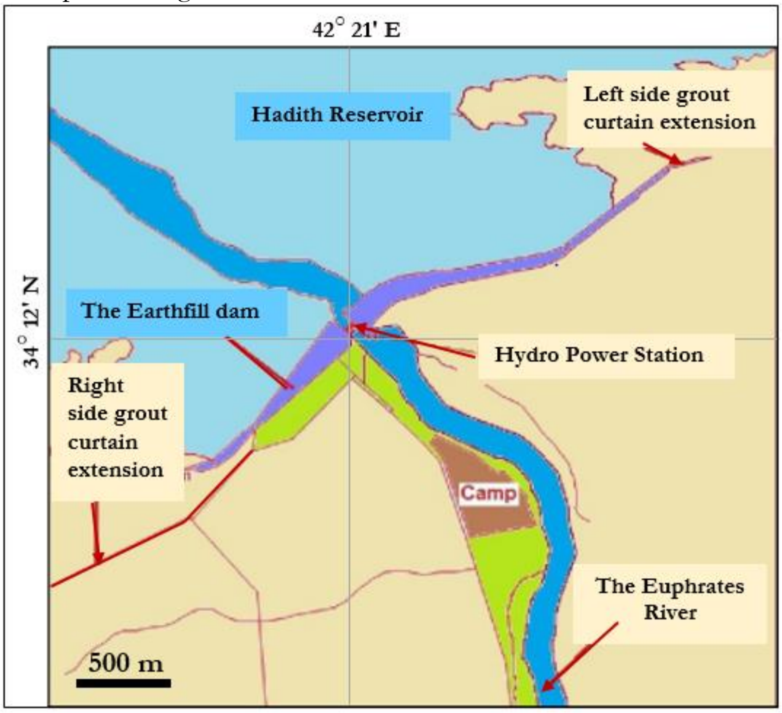

Figure 5. An illustrative map showing the length of Haditha Dam, the earthfill left and right banks, and left and right side grout curtain extensions (Adamo et al., 2018b). The authors added approximate scale and coordinates.

4.2. Materials of the Dam Construction

The design of Haditha earth fill embankment and the used methods for construction were governed by the availability of local materials at the site or close to it, and the severely karstified rocks, especially along the right bank of the river, in addition to, the available technology. Topographical and geological conditions required the embankment dam to be of large length (8875 m); accordingly, huge amounts of different types of construction materials were needed. The total volume of materials required for the filling was 30 million m^3. For the dam core, for which clay was virtually non-existent at any suitable distance from the site dolomite was therefore used in addition to installing vertical asphaltic diaphragm as the sealing element. However, 77 million m^3 of mealy dolomite (the powdered dolomite used instead of clay in the core of the dam) was available within the Euphrates Formation along the right bank of the Euphrates River, see Figure 3. Moreover, about 36 million m^3 of sandy gravel materials in the riverbanks; as flood plain sediments, long sand bars in the river, and terraces, were available for the dam shells, besides 8.8 million m^3 dolomitic limestone and dolomite rock were also available for the downstream protection. Upstream protection was achieved by reinforced concrete slabs placed on porous concrete as a filter. (Kamenev et al., 1983 in Adamo et al., 2018b).

5. Results

The following results were obtained in the current study from reviewing the presented data.

5.1. Karstification

One of the main problems that normally cause a lot of damage to engineering structures in Iraq and elsewhere is karstification (Sissakian and Al-Musawi, 2007; Sissakian et al., 2015). The karstification process is defined as "A topography formed from the dissolution of soluble rocks such as limestone, dolomite, and gypsum. It is characterized by underground drainage systems with sinkholes and caves (Julia, 1997). The most dangerous and active process affecting Haditha Dam and reservoir area is karstification (Sissakian et al., 1984, 1986 and 2015). The karstified materials and infilling sediments in caverns when encountered in drilling may cause serious problems to the planners and designers of dam foundations, especially when they are miss-interpreted as being different materials (Sissakian et al., 2017). The foundations of the Mosul Dam are an excellent example for such a case (Adamo et al., 2018a).

One of the main and well-known karst areas in Iraq is Anah – Hadith – Heet (Hit) vicinity; including Haditha Dam site and the reservoir area (Hamza, 1997; Sissakian et al., 1984). The number of the documented sinkholes of different shapes, dimensions, and activities at the right side of Haditha Dam site and near surrounding is 54 sinkholes. The maximum and minimum diameters of the sinkholes are 110 m and few meters, respectively. Whereas the maximum and minimum depths of the sinkholes are 55 m and 2 m, respectively

Majority of the sinkholes are of active type; as they can discharge exceptionally large amounts of water through the existing fractures at their floors (Sissakian et al., 1984 and 1986). One of the sinkholes which is located at the floor of a wadi near the dam site has a diameter of about 35 m and depth of 18 m; it was tested by Soviet engineers during the study phase of the dam site and was found that it can discharge an amount of 5500 m^3 per hour (field observation in 1973).

5.2. Length of the Haditha Dam

The total length of the dam is 9064 m which includes 189 m for the concrete structure in the central part. The earthfill parts of the dam are: 3310 m on the right abutment, 4985 m on the left abutment and 580 m in the river channel. Karst prevails in the foundation of the whole length of the dam and for long distances on its both sides. This is attributed to: 1) Exposures of the Euphrates Formation on the right side of the river, 2) The rocks of the Euphrates Formation (Limestone and dolostone) are highly karstified, and 3) Presence of long and deep wadis near the dam site which can work as discharging zone from the reservoir to the downstream. Whereas, on the left side, it is attributed to: 1) Exposures of the Fatha Formation on this side of the river, 2) The rocks of the Fatha Formation (Gypsum and limestone) are highly karstified, and 3) Presence of long and deep wadis near the dam site which can work as discharging zone from the reservoir to the downstream and to the Tharthar reservoir. The presence of this extensive karstification added to the dam works the necessity of extending the grout curtain under the dam for additional 10260 meter, and 635 m extensions on the right and left sides of the dam respectively.

6. Discussion

The intensively karstified rocks at the dam site of the Haditha Dam (limestone and dolostone along the right side and river channel, and gypsum and limestone along the left side) have caused the designers of the dam to construct long grout curtain under the whole earthfill dam and concrete structure and extended it in both banks for long distances beyond the dam body as extensions to the main curtain under the dam itself. Grouting boreholes were drilled in the curtain extensions of the dam at an interval of one meter. Each borehole has consumed different quantity of grouting material as compared to others. However, those on the right side have consumed more grouting materials than those on the left. One of the right-side extension boreholes has consumed about 500 tons of grouting materials, whereas two boreholes on both sides of the concerned borehole have consumed normal amounts of grouting materials. This is due to the presence of a large cavern below the concerned borehole; as it is clear from the existing sinkholes in the right side of the dam and reservoir; starting from Anah town of different sizes and shapes; the majority of them are active, which means they can engulf huge quantities of surface run-off water.

The grouting curtains under the dam and both abutments and its extensions have successfully kept the safety of the dam despite the tens of sinkholes occurring on both sides of the dam and the indications of the development of many new ones, which have not reached the surface (Sissakian et al., 1986). The grout curtain has successfully sealed all karst cracks and dissolution channels in the abutments and river section and along the dam axis in both right and left sides for considerable distances. This is clear from the absence of water leakage in the downstream. Apart from normal quantities of seepage, there is not any single indication that the dam suffers from settlement.

7. Conclusions

The Haditha Dam is constructed in a highly karstified area. Tens of sinkholes occur in long reaches on both sides of the dam due to the exposure of limestone and dolostone on the right side and gypsum and limestone on the left side. Karstified and dissolution channels are also present in the dam foundations. The constructed long grout curtain on both sides of the dam succeeded in reducing seepage flow under and around the dam to safe limits. The abnormal length of this grout curtain is attributed to the extensive karstification in the site. A single row curtain was needed in most parts of the right and left grout curtain extensions with one-meter spacing; however, along the dam and river sections the grout curtain was constructed in two or three rows of grout holes with spacing's either one or one and half meter spacing's as needed, which depended on the intensity of the karstification and the sizes of the subsurface caverns developed due to the dissolution of limestone and gypsum beds; both on surface and subsurface.

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