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Badush Dam, NW Iraq: A Geological Study

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Abstract

The river Tigris flows from Turkey towards Iraq in its northwestern part dissecting the whole Iraqi territory. During 1981– 1986 a very large earth fill dam was constructed, which is Mosul Dam impounding the flow of the Tigris River. It is the largest dam in Iraq and one of the largest in the Middle East. The geological conditions of the dam site and surroundings, however, are not suitable due to thick exposures of the Fatha Formation, which consists of marl, clay, limestone and gypsum. The gypsum and limestone beds are highly karstified causing severe problems to the dam foundation. Mosul dam suffers from serious problems due to the presence of karstified rocks; therefore, the Ministry of Irrigation in Baghdad, decided to construct a protection dam downstream of Mosul Dam; it is called Badush Dam. The geological conditions at Badush Dam site are the same as those at Mosul Dam site, which means the foundations of the dam are located on karstified rocks. Therefore, grouting works were planned and designed and it was partly performed from the beginning of the construction in 1988. The construction of the dam; however, stopped in 1991 due to the consequences of the First Gulf War. The constructed parts of the dam are (30 – 40) %. In this study, we have presented the main problems, which will cause real danger to Badush Dam, if its construction is re-started, and we have suggested many requirements to avoid any hazard that may cause the collapse of Badush Dam.

Keywords: Badush Dam, Mosul Dam, Karstification, Gypsum rocks, Grouting, Iraq.

1 Introduction

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Badush Dam is planned, designed and located NW of Mosul city at about 16 Km, and 40 Km downstream from the existing Mosul Dam (Fig. 1). Badush Dam is a protection dam to protect the lives of the people living downstream and to keep the infrastructures safe, in case of the collapse of Mosul Dam which could occur due to severe karstification problems existing at the dam site and its foundations.

The main aim of the current study is to present the most updated study on the geological conditions, which exist in Badush Dam site, besides giving suggestions to enhance the safety of the dam in case the Iraqi Ministry of Water Resources (which has replaced the Ministry of Irrigation) decides to continue the construction of the dam, which was started in 1988 and stopped in 1991 due to the consequences of the First Gulf War.

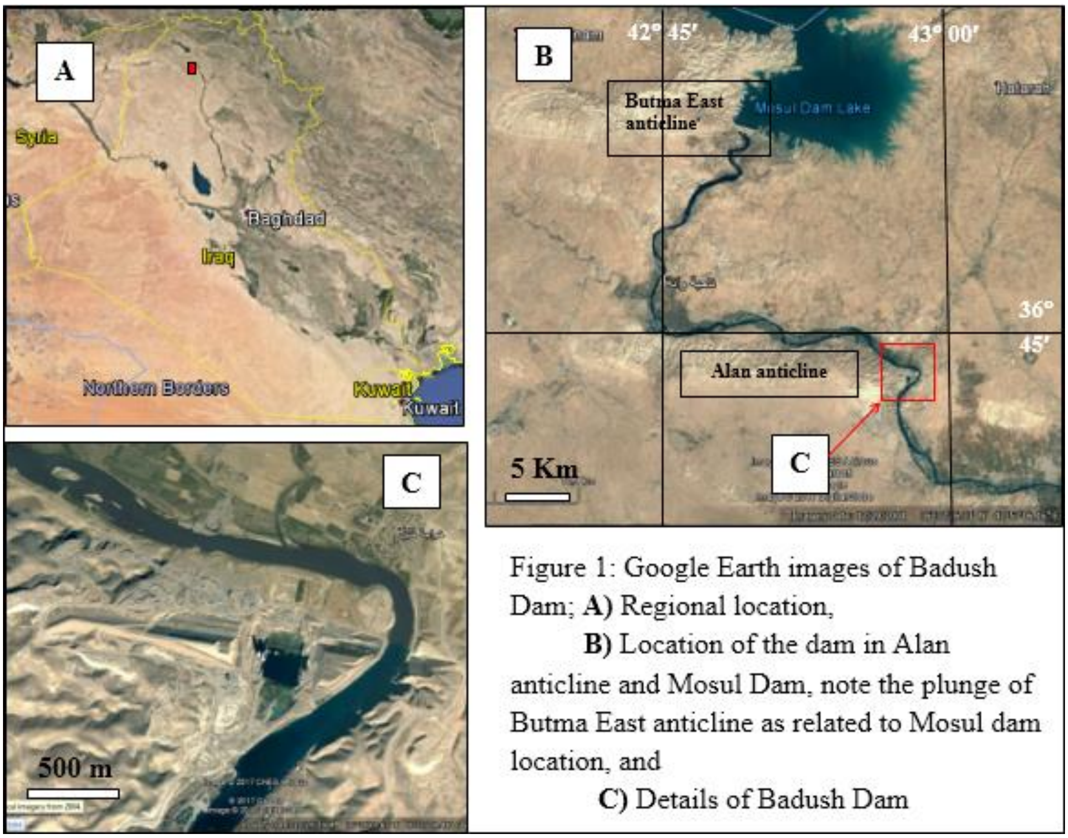

Figure 1: Google Earth images of Badush Dam; **A)** Regional location, **B)** Location of the dam in Alan anticline and Mosul Dam, note the plunge of Butma East anticline as related to Mosul dam location, and **C)** Details of Badush Dam

Figure 1: Badush Dam Location

2 Materials Used and Methods

In order to achieve the main aim of this study the following materials were used:

- Topographic and geological maps of different scales of the studied area and near surroundings.
- Google Earth, FLASH Earth, and DEM images.
- Many different reports and published articles concerning Mosul Dam.

The geological maps and reports were used to indicate the geological conditions in Badush Dam site and its foundations. The reports and published articles, which were concerned with Mosul Dam were reviewed to indicate the main problems in Mosul Dam site, and they were compared with those of Badush Dam site. The knowledge of the authors in the details of the dam present problems was useful also. In addition, the geological conditions of both dam's sites are utilized in conducting the current study.

3 Previous Studies

The following are the main geological works carried out in the site of Badush Dam and near surroundings:
Muhi Al-Deen et al. [1] conducted geological mapping of Badush Dam site and far surroundings. They indicated that the dam site is covered by the rocks of the Fatha Formation, which includes karstified gypsum beds. Fouad et al. [2] conducted detailed geological survey of Badush Dam site and surroundings and reported about the details of the karstified gypsum beds of the Fatha Formation. Sissakian and Ibrahim [3] compiled the Geological Hazards Map of Mosul Quadrangle at a scale of 1:250000 and considered that the dam site area and near surroundings are within the karstified areas. Al-Ansari et al. [4] presented different geological data about Mosul Dam, which has the same characters and geological conditions as Badush Dam. Sissakian et al. [5, 6] gave more details on the geology and karstification of Mosul Dam site. Adamo et al. [7, 8] wrote about the grouting techniques and existing problems in Mosul Dam site. Al-Dabbagh and Al-Naqib [9] reported about different scientific aspects of Mosul Dam. Moreover, many articles and scientific reports are conducted, which deal with different safety aspects of Mosul Dam; all are the same as those in Badush Dam. Among them are, but not limited to; Washington Group International [10], Wheeler et al. [11], Wakeley [12], and U.S. Army Corps of Engineers [13].

4 Geological Setting

The geological setting of Badush Dam site and surroundings are briefed hereinafter, using the best available data including Geomorphology, Tectonics and Structural Geology, and Stratigraphy [2, 14, 15, 16]. The geological map of the dam site is presented in Fig. (2).

- Geomorphology: The main geomorphological units are those of Alluvial Origin; flood plain and river terraces, the sediments of both units are used in the construction of the dam. Within the Structural – Denudational units, the depositional and erosional glacis are rich in gypsiferous cement. Also anticlinal ridges and flat irons are well developed in the Fatha Formation. Within the Solution Units, sinkholes of different shapes, sizes and activities are well developed in both the Euphrates and Fatha formations. Due to the very active karstification, the limestone beds of the Fatha Formation exhibit false dipping towards the karst forms; due to collapse of the beds towards the existing caves and fractures.

- Tectonics and Structural Geology: The studied area is located in the Low Folded Zone of the Outer Platform, which belongs to the Arabian Plate. It is a part of the Zagros Thrust – Fold Belt [15]. Alan anticline on which Badush Dam is located is a double plunging anticline with almost E – W trend (Figs. 1 and 2), the southern limb is slightly steeper and the eastern plunge is located east of the Tigris River, i.e. east of Badush Dam (Fig. 2).

- Stratigraphy: The exposed geological formations and main Quaternary sediments are briefed hereinafter and presented in Fig. (2).

Euphrates Formation (Lower Miocene): The formation is exposed in the core of Alan anticline; it consists of well bedded, hard limestone and marly limestone. The rocks are highly karstified. The thickness of the formation ranges from (26 – 50) m. The foundation of the dam rest on the rocks of this formation; therefore, the foundations will suffer from karstification, which will increase in activity after filling of the reservoir.

Fatha Formation (Middle Miocene): The formation forms the bulk of Alan anticline and surrounding areas; it is divided into Lower and Upper Members. Both members consist of cyclic sediments of green marl, limestone and gypsum, with reddish brown claystone in the Upper Member. The gypsum and limestone beds are highly karstified. The foundations of the dam rest on these karstified rocks. The thickness of the formation ranges from 117 m at the left bank and 350 m at the right bank.

River Terraces (Early Pleistocene): The terraces are accumulated in different parts, especially north of the Tigris River. Three levels are developed. The pebbles of the terraces consist of limestone, silicate and igneous and metamorphic rocks, cemented by gypsiferous and sandy cement **Residual Soil (Holocene):** The residual soil covers large parts of the surroundings of Badush Dam. It is reddish brown, clayey and gypsiferous soil.

Flood Plain Sediments (Holocene): The flood plain sediments are developed along the Tigris River. The sediments consist of sand, silt and clay.

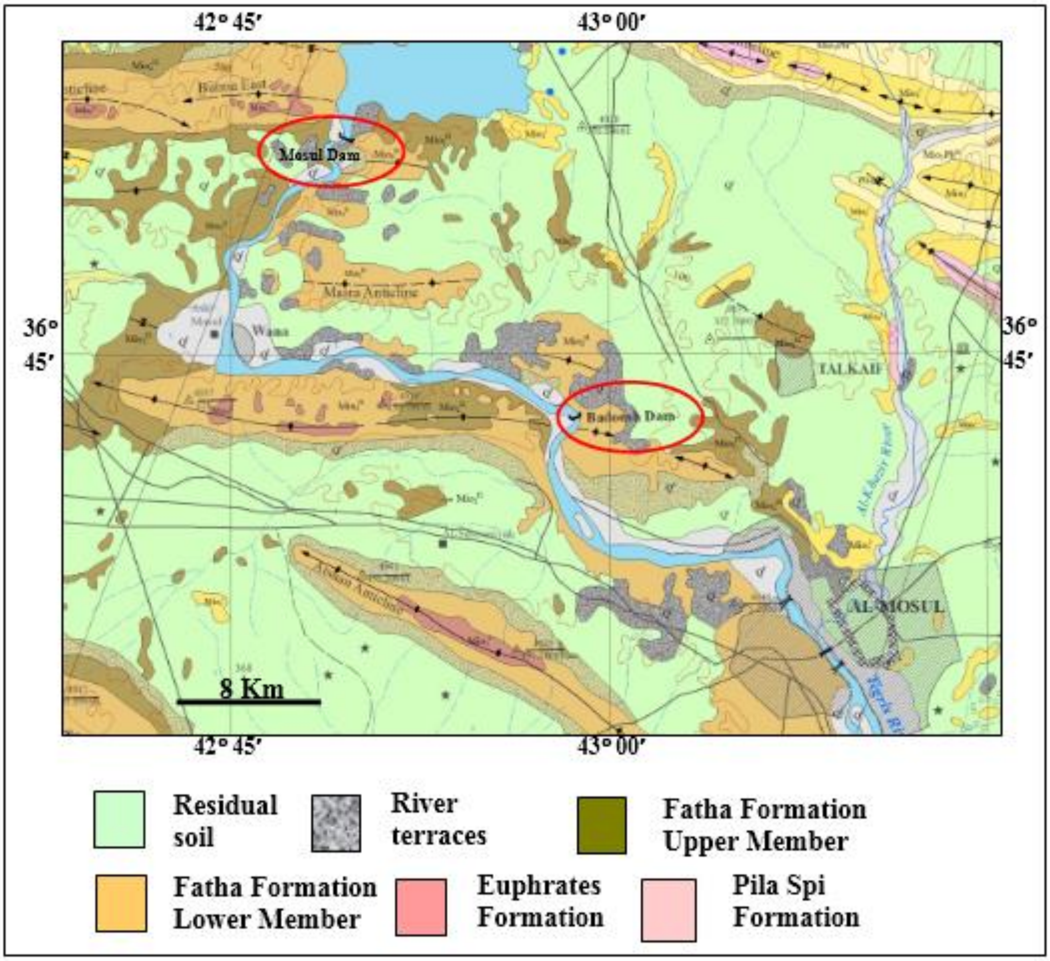

Figure 2: Geological map of Badush Dam site and near surroundings (After [16])

5 Badush Dam

- Historical Review

During the first filling of Mosul Dam reservoir, large amount of seepages appeared from under the main dam in the river section and the saddle dam at the left bank. Seepage water showed heavy dissolution of gypsum from dam foundations [17]. The Ministry of Irrigation received in 1985 the report of a flood wave study in case of Mosul Dam failure, indicated the colossal volume of the wave and the unprecedented dimensions of the catastrophe that could follow [18]. The decision was taken, therefore, in 1987 to build a dam downstream of –Mosul Dam as a protection dam from this wave. The selected site at 40 km south of Mosul Dam was called Badush which was the name of a nearby village

The basic design considerations were to build the dam to be high enough to have a reservoir with a capacity of 10 billion cubic meters which is equal to the volume of the Mosul Dam flood wave [19]. This resulted in proposing a dam crest level of 312 m (a.s.l.). The design of the earth fill dam indicates clearly the temporary nature of its use [19].

- Characteristics of Badush Dam

Badush Dam is an unfinished multi-purpose combined earth fill and concrete buttress gravity dam on the Tigris River. The percentages of the completed works range between (30 – 40) % (Fig. 3). If completed, the dam's designed main purpose is to provide protection from the failure of the unstable Mosul Dam upstream [4]. The dam has a height of 103 m, length of 3730 m, volume of earthfill of 6.1 x 10^6 m^3, and reservoir capacity of 1.0 x10^7 m^3. Badush Dam is designed by Enerjoproject according to a contract with the Iraqi Ministry of Water Resources. At its maximum level, Badush reservoir can hold 1.0 x $10^7 m^3$, enough to absorb and pass Mosul Dam wave, according to the flood wave study completed in 1985 [18].

Figure 3: The constructed concrete part of Badush Dam

6 Badush Dam Expected Problems

The problems of Mosul Dam site have been presented in many previous papers [4, 5, 6, 7, 20, 21]. The same problems which exist in Mosul Dam site may exist in Badush Dam site too, as the geological conditions are the same at both dam sites (Fig. 2). If the re-construction of Badush Dam is to be started again, then the same problems that exist in the site of Mosul Dam will be faced in Badush Dam site if the suggestions and the recommendations given by Sissakian et al. [22] are not considered. The recommendations emphasize on the importance of detecting the true depth of the deepest karstified gypsum and/ or limestone beds.

The main problems are briefed hereinafter.

1) ***Karstified Rocks***: The main problem in Badush Dam site as well as in Mosul Dam site is the karstification. The gypsum and limestone beds in both Fatha

and Euphrates formations; respectively are highly karstified as may be seen in Figs. (3 and 4) [4, 5, 6, 21, 22, 23, 24, 25, 26].

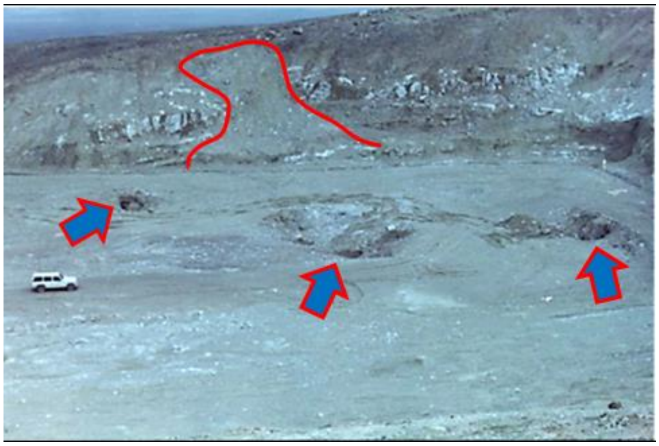

Figure 3: Karstified gypsum beds in an industrial site south of Badush Dam site, about 15 Km. Note the absence of the gypsum bed (white colored) in the facing cliff; surrounded by the red line. The three arrows point to three sinkholes found in the floor of the site.

2) ***Lithological Succession***: To design a relevant and good grouting program or a diaphragm wall, it is necessary to know the true lithological succession in the dam site. Accordingly, to know the deepest karstified rocks in order to decide on the required depth of the grouting boreholes or the diaphragm; whichever is constructed. The thickness of the Fatha Formation in the left side is about 100 m [27]; whereas, in the right side of the dam it is about 300 m [1]. This large difference in thickness should be taken into consideration in the adopted design solution, otherwise the same grouting problems which exist in Mosul Dam site will be faced in Badush Dam site also.

Figure 4: Karstified gypsum beds, south of Badush Dam site, about 15 Km.
Note the absence of the gypsum beds (white dashed line) due to karstification limited by the red line. The arrow point to circular feature on the surface, it indicates the presence of karst blow the circular feature.

3) Grouting Program: One of the significant actions taken to overcome the karstification in engineering sites is grouting [13, 28]. However, negative effects of grouting on the engineering structures are also common [29,30].

Construction of large grout curtains is always accompanied with the building of dams in karstified areas. Thousands of tons of materials are injected into the underground karsts. Some of the used materials in grouting may be toxic, neurotoxin or carcinogenic; therefore, their use should be done with care. Accordingly, intolerable leakage of karst reservoirs can occur over the lifetime of a dam site [30].

In Mosul Dam, grouting programs were implemented at different parts in at different depths and following different grouting techniques and using different materials [4, 7, 8, 17, 20, 31]. The implemented grouting in Mosul Dam; however, has not been successful hitherto, although extremely large quantities of different grouting materials and grouting mixes and techniques were used [4, 7, 12, 17]. This is attributed; mainly to the miss-interpretation of the true karst line depth [17], in addition to lack of knowledge of the true nature of the brecciated gypsum beds present in the foundation. The authors understand that the same grouting materials and techniques were used in Badush Dam as in Mosul Dam [8]. Accordingly, the same negative results may occur at this dam site if the construction is to be continued with the present design without further investigations and examination, especially after filling of the reservoir and in the same manner; as it happened at Mosul Dam [7].

7 Results

The dam is planned to be a protection dam in case of the failure of Mosul Dam, which is 40 Km upstream from Badush Dam as its main function.

The geological conditions of Badush Dam are exactly to the same of those existing in Mosul Dam, although Badush dam axis is almost parallel to the axis of Allan anticline (E – W) and dam is located in its axial part, at its eastern plunge area (Figs. 2 and 5). Therefore, the same existing karstification problems in Mosul Dam will face in Badush Dam if the construction is completed using the same type of foundation treatment without further investigations and examination as recommended by Sissakian et al. [22]. The most significant thing is to discover the true depth of the deepest karstified rocks, in order to design the grouting boreholes or diaphragm wall according to the depth, which should be deeper than the deepest karstified beds.

Figure 5: Google Earth image facing south. Note the uncompleted Badush dam and its location in the axial part of Allan anticline

8 Discussion

Badush Dam is planned and designed in a karst region. Therefore, gypsum and limestone beds of the Fatha and Euphrates formations will continue in dissolution forming subsurface caverns of different shapes, sizes and depths; as it is the case in Mosul Dam. Such problems induced in engineering structures are well known and their solutions are as very risky tasks [32]. A typical example is Mosul Dam and if Badush Dam's construction is resumed, it will be, then, another typical example of a bad design, unless careful considerations are given to the foundation problems. Even though, very detailed geophysical and geological investigations are normally carried out, the possibility for dam failures cannot be eliminated [32]. It is worth mentioning that Fouad et al. [2] have conducted detailed geological survey in Badush Dam site and surroundings aiming for investigation of sulphur deposits. Among their significant findings were the tilting and/ or collapsing of the limestone beds of the Fatha Formation in different directions; apart from the local dip. This was attributed to the collapsing of the limestone beds towards the subsurface existing karst forms leading to hindering of the karstified gypsum beds (Fig. 6). This finding was mentioned by Sissakian and Abdul Jab'bar [25]. The presence of such phenomena gives a first impression that no gypsum beds exist in the area and may be misleading for the absence of the gypsum in the considered site.

In the karst environment, with its highly random distribution of dissolution features, some uncertainties always remain. Mosul Dam is a good example, since leakage problems started even before completion of the impounding [7]. According to one of the geologists who had worked in the Grouting Department of Badush Dam (Personal communication with Mr. Basman Zadoian, 2017), the average depth of the drilled grouting borehole was 100 m. It is worth mentioning that the thickness of the Fatha Formation in the eastern side of the dam is 100 m [27], whereas in the western side is 300 m [1]. It is clear from the mentioned thicknesses that the depth of the karstified gypsum beds is more than the depth of the drilled grouting boreholes. Accordingly, the used grouting materials did not reach to the deepest karstified beds. The dissolution problem in such case will continue and the used grouting materials will fail in filling the caverns in the deepest dissolved beds of the karstified gypsum and limestone beds below the grouting level.

If the Iraqi Ministry of Water Resources decides to resume the construction of Badush Dam as a protection dam; just to store and pass the initiated wave from the collapse of Mosul Dam, then the current design of the dam is relevant. Otherwise, the dam will face the same existing problems in Mosul Dam. Therefore, the recommendations stated by Sissakian et al. [22] apply here and should be considered carefully. The most significant recommendation is to know the accurate depth of the deepest karstified gypsum and/ or limestone horizon bellow the foundations of the dam. Accordingly, to design the depth of the grouting boreholes to penetrate the last karstified bed at least by 10 m in the case of using the dam for permanent storage and not as a protection dam only.

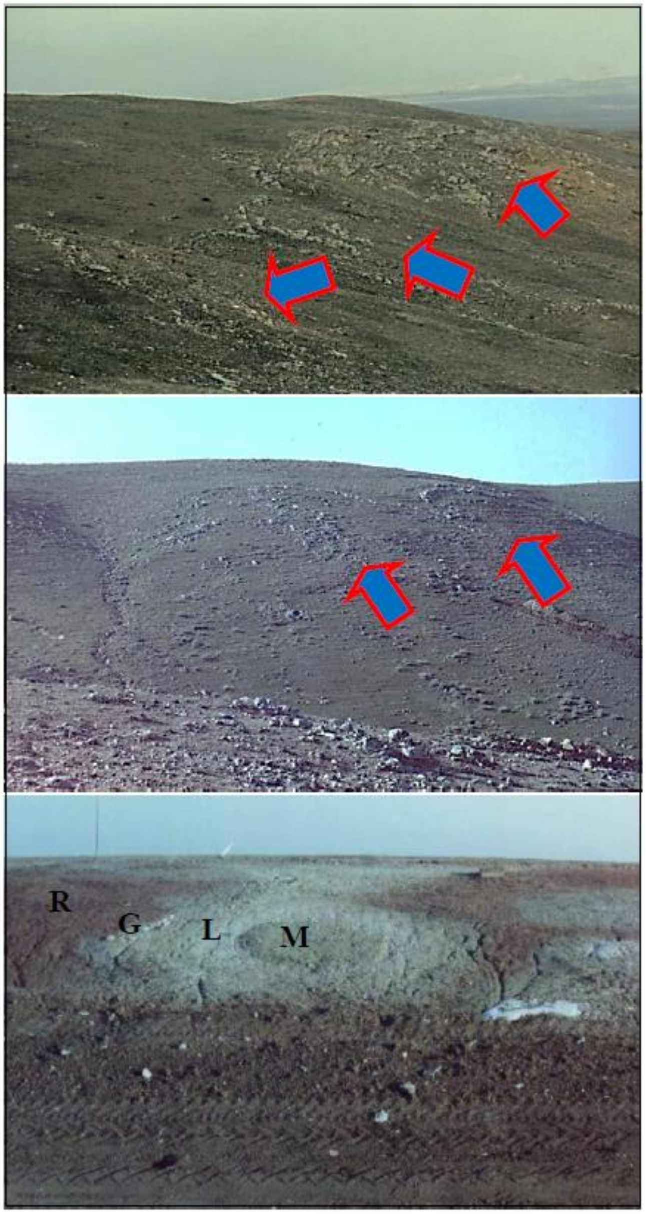

Figure 6: Three scenes of karstified region 15 km south of Badush Dam site. **Top:** Collapsed limestone beds hindering the karstified gypsum beds. The arrows point to collapsed limestone beds with crescent like forms. Note that no gypsum beds can be seen. **Middle:** Slope showing collapsed limestone beds in form of crescent shapes. Note there are no gypsum beds along the whole slope due to the collapse of the limestone bed. The arrows point to the collapsed limestone beds. **Bottom:** A small sinkhole filled by green marl (M), followed by limestone (L), karstified thin white gypsum (G), and followed by red claystone (R); as appeared due to a road cut along a road to Badush village. Compare the size with the traces of shovels tire.

9 Conclusions

1. If Badush Dam will perform as a protection dam only, then the present design is relevant.
2. If the decision is taken to resume works in Badush Dam as a replacement of Mosul Dam, then intensive geological investigations must be carried out to obtain the depth of the deepest karstified gypsum and limestone beds accurately. This cannot be done unless the lithological column in the dam site and near surroundings is accurately known.
3. The designed grouting boreholes of 100 m depth will not be sufficient to seal the existing karst caverns, because the thickness of the Fatha Formation is more than 250 m, especially in the right side of the Tigris River.
4. The location of the axis of Badush Dam almost coincides with the axis of the symmetrical Allan anticline. This is a positive factor since the distribution of the exerted forces by the water of the reservoir will be distributed almost equally on both sides of the dam.
5. Badush Dam and Mosul Dam have the same type of geology and foundation conditions. Both are located within the Fatha Formation and both foundations are characterized with dense karstic conditions. These foundations are prone to dissolution within the karst and possible formation of sinkholes under the dam and in the reservoir and can lead to the failure of the dam.

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Badush Dam: Controversy and Future Possibilities

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Abstract

Badush Dam is believed to be the first dam in the world which is designed to protect from the flood wave which could result from the collapse of another dam; in this case Mosul Dam. Badush Dam construction was started in 1988 but it was stopped two years later due to unexpected reasons. From that time on many attempts were made to resume construction without success. Its value was stressed in a multitude of studies and technical reports amid conflict of opinions on how to do this. The original design of the dam as a protection dam was intended to have a large part of the reservoir empty to accommodate the volume of the expected flood wave for only a few months during which time it's content are released in a controlled and safe way to the downstream. The lower part of Badush Dam which has a limited height continues before and after this event to act as a low head power generation facility. Among the later studies on the dam, there were suggestions to introduce changes to the design of the unfinished dam which covered the foundation treatment and also asked for constructing a diaphragm in the dam. A long controversy is still going on with many possibilities but with no hope to reach a final solution soon. Any rational solution must consider both Badush Dam and Mosul Dam together as the safety issue involves both of them. This paper may be seen in six paragraphs. The first three describe in brief the history, the outline design and foundation treatment of the dam, therefore, setting the background to follow the conflicting views over its purpose and future which is discussed in the following two paragraphs. The final paragraph is devoted to discussion and our conclusions.

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1 History of the Dam

Badush Dam located 40 kilometres south of Mosul Dam, was conceived as a protection measure against the catastrophic flood wave that could result from the failure of Mosul Dam. The idea of building such dam was circulated first within the Ministry of Irrigation (MOI) in 1987 when Mosul Dam construction had passed the non-return point. It became clear that this dam was suffering from foundation problems resulting from the unsuccessful completion of the deep grout curtain under it. This meant the possibility of dam failure due to the continuous dissolution of gypsum and the formation of sinkholes and new cavities under the dam. The fear of such catastrophe was justified by a study of the Mosul Dam flood wave which can occur due to the dam failure. This study was completed in 1985 by the Swiss Consultants Consortium who had designed the dam [1]. The concept of building a "Protection Dam" did not find complete acceptance and there were engineers and experts who argued to spend more money to fortify Mosul Dam instead of wasting it on such a dam. One member of the Mosul Dam International Board of Experts, namely the World Dams Expert the late Mr. Pierre Lond (ex. ICOLD president) even refused to take any part related to the suggested dam saying; "Nobody on earth builds a dam to protect from the failure of another dam; Why not fortify or decommission the problematic one?" [2].

The Ministry, however, went ahead with its plan and invited consulting firms to submit studies, designs and plans to construct the dam. Fast Track Method was followed by overlapping the investigation stage with the studies and design phases, while more designs were done during construction. This was done and construction started on 1st January 1988. The construction went ahead at a very fast rate but it came to a halt at the end of 1990 due to the invasion of Kuwait by Iraq and the UN economic sanctions on the country which followed. Works were not resumed up to this moment and the completed percentages of the various items then were (30%- 40%). Many attempts have been made since that time to resume construction but they did not materialize in any fruitful action so far. The chronic problems, however, in Mosul Dam continue and the need for a solution is an urgent matter.

2 Original Design of the Dam

The basic design considerations of Badush Dam were to have a dam which is high enough to contain the full volume of Mosul Dam wave of 10 billion cubic meters when routed through its reservoir, but to improve the economic indices of the dam, the available head between the Mosul reregulating power station and the Badush site would be utilized to produce electric power before and after the failure of Mosul Dam [3] [4]. The final design was that of a high dam with a crest at elevation 312 m (a.sl). The capacity of the proposed volume of the reservoir was checked by mathematical modelling and was verified on a physical model. The main characteristics and design parameter were as shown in Table (1).

The eight bottom outlets were to be used during, river diversion, normal operation and also for the passage of normal floods up to 8000 m^3 /sec, which is the routed maximum anticipated flood from Mosul Dam. The top ungated spillway operates only in the event of water level rising due to the flood wave and exceeding its sill level of 294.7 m (a.s.l) in which case it can pass up to 4000 m^3/sec and limits the maximum water level to 307 m (a.s.l), leaving a freeboard of 5 meters without causing the danger of the dam's collapse.

The main dam was designed in two distinct parts. The first was the earthfill embankment that extends on the right bank, the left bank and part of the river channel and the second part was the concrete hollow gravity and buttress dam which was formed of two sections. The first section houses the bottom outlets and the ungated spillway at the top, while the second section contains the power penstocks that lead to the powerhouse building at the toe of the dam. More can be found on this type of dams in reference [5]. The earthfill embankment adjoins the abutments of the concrete dam from both sides. Figure (1) shows the layout of the main dam. In addition to the main dam, there were also two small saddle dams with maximum heights of 11 and 22 meters in the left bank to contain the flood wave completely and prevent it from spilling over as seen in Figure (2) [3].

The design of the earthfill dam indicates clearly the temporary nature of its use from elevation 260 m (a.s.l) upward; which is reflected in the thin inclined clay core and other embankment details as indicated in the typical cross-section of the dam in the river channel shown in Figure (3). The assumption made by the designer was that the upper part of the dam above elevation 260 m (a.s.l) was meant to function for few months only, in which time the reservoir would be emptied quickly. The same thing was also very clear in the design of the foundation treatment works, which are discussed later on in this paper. This was based on the assumption that the deep rock layers would not be affected by the very limited hydraulic head during the normal operation of the dam, and the high rise in the hydraulic head in the case of the flood wave impounding will be temporary and will not last very long. So the foundation treatment concentrated much more on the normal operation case.

Table1: General data of the proposed Badush dam.

General data of the dam	Units
Annual average discharge	667 m^3/s
Maximum Probable Flood (Mosul Dam)	27000 m^3/s
Flood with (0.1%) Probability at Mosul Dam	12000
Design flood during operation (Routed through Mosul Dam to be passed through Badush Dam)	8000 m^3/s
Maximum reservoir level (in case of Mosul Dam failure)	307 masl
Design flood level for the normal case	250 masl
Normal operation level for the normal case	245,5 masl
Minimum reservoir level for the normal case	243,8 masl
Spillway capacity	4000 m^3/s
No. of bottom outlets	8
Total bottom outlets capacity	8000 m^3/s
Dam crest level	312 masl
Maximum height of the main earthfill dam	92 masl
Length of the Dam crest	3,730 km
Crest level of the Concrete Dam	294,7 masl
Maximum height of the Concrete Dam	102 m
Length of the Concrete Dam	248 m
Installed capacity of the power station	170 Mw

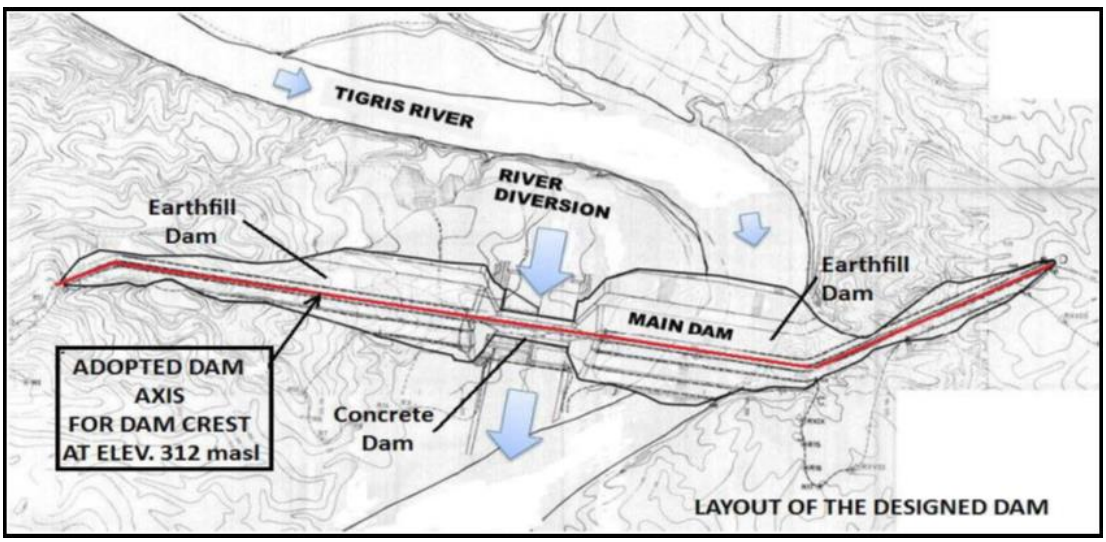

Figure 1: Main Badush dam General Layout [3].

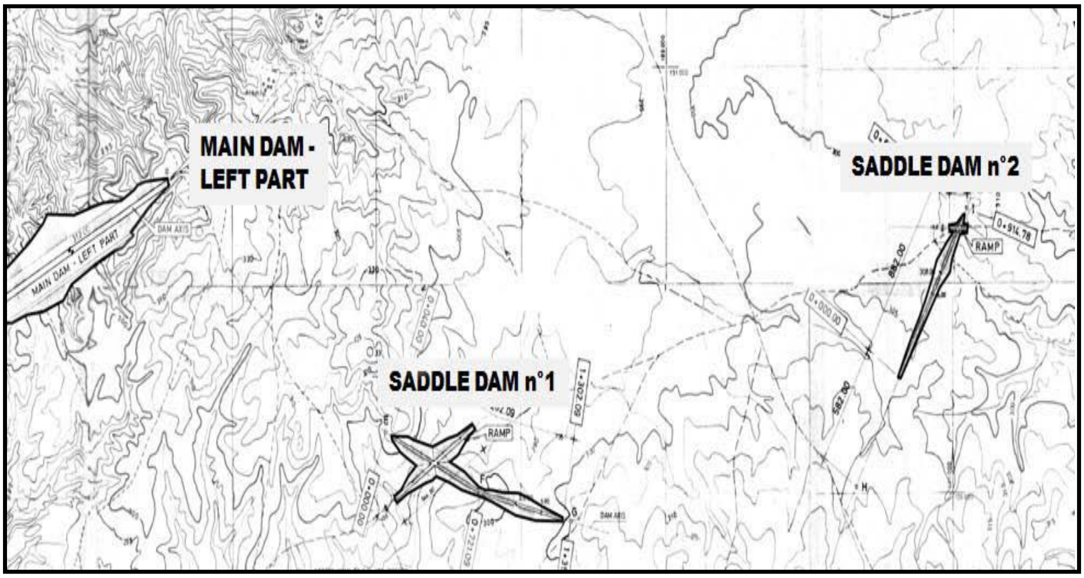

Figure 2: Badush Saddle Dams on the left bank [3].

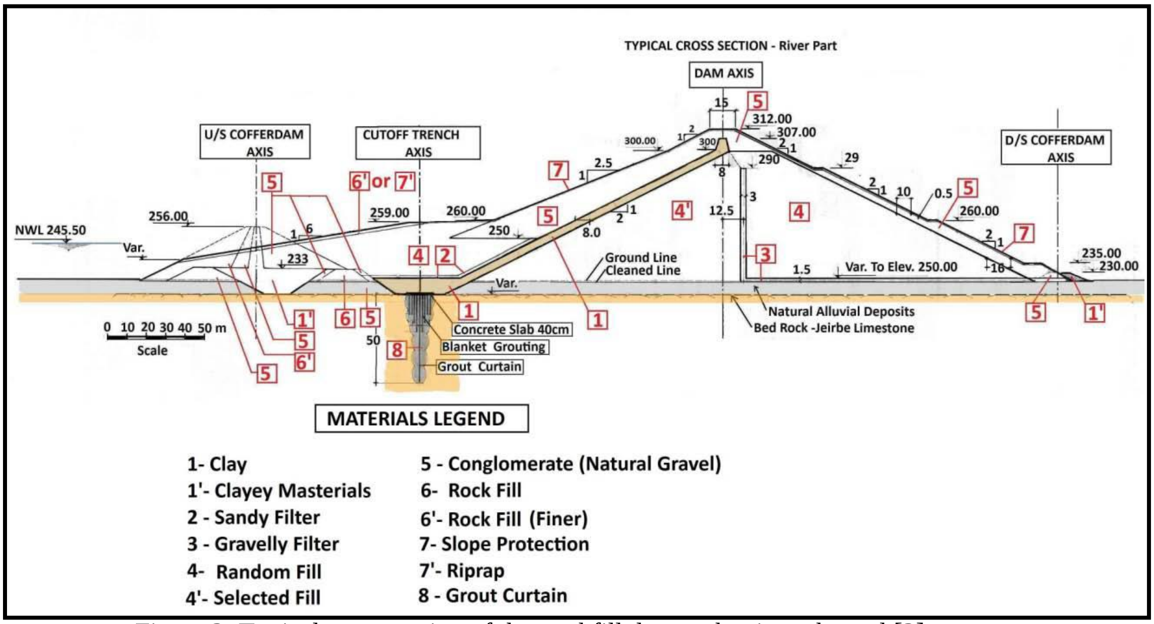

Figure 3: Typical cross section of the earthfill dam at the river channel [3].

3 Foundation treatment

During 1987-1988 geological investigations were carried out at the selected site which was located to have the axis of the dam coinciding with that of Alan anticline. This is a double plunging anticline extends at the right bank of the Tigris River and its eastern plunge is located at the left bank. While the dominant geology around the site is the Fatha Formation, the foundation of the dam was to be placed mainly on the Limestone Formation (which follows the Fatha Formation) and which is exposed at the core of this anticline [6]. It is a known fact that the Fatha Formation is characterised by heavy gypsum karsts and its presence in Mosul Dam foundation is causing the safety problems of this dam today [7] [8]. The investigation campaign included geological mapping of the site, drilling 83 deep drill holes some of which exceeded 100 meters in depth and totalling 5732 meters in total length with full core recovery, testing and analysing the properties of the recovered rock samples [9,10]. In this paper, however, we call for an additional geological investigation to be completed before attempting any further work in the Badush Dam construction in order to remove any doubt on the performed foundation treatment, and the need of any modification or other special treatments if required.

The design philosophy of the foundation treatment as adopted by the designers was as follows:

a. The effective hydraulic head in Badush dam is represented by the operation of the dam as a low dam for power generation. This head ranges between levels 245.5 m (a.s.l) and 250.0 m (a.s.l) at the upstream side and the corresponding levels of 227.7 m (a.s.l) and 233.20 m (a.s.l) at the downstream side. So the adopted value for the head was 20 meters. This is comparable to the hydraulic head at the Mosul Dam Re-Regulating Dam which is located in similar geology. The treatment works at Badush Dam need not be therefore much different if only this head is considered. This may consist of a blanket grouting with defined depth and a grout curtain of a very limited depth.
b. The high hydraulic head which would be realized during the impounding of Mosul Dam flood wave at an elevation of 307 m (a.s.l) would be a transient case which would take place for a very short period while the reservoir is emptied. It follows in such case that the only required additional treatment is to safeguard the dam against uplift forces. At the same time no appreciable change would occur to the deep rock formations under the dam during this short period. This is reflected in the final design of the dam by adding a single row grout curtain under it.

So, the following details may be given of the foundation's treatment as indicated in the final design:

1. With respect to the earthfill embankment, a cut-off trench under the clay core would be excavated down to the limestone formation to be filled with clay after performing dental concrete treatment to its bottom and its downstream surface. This trench is placed on the limestone formation for 1280 meters measured from the right river bank, after which it would continue through the Fatha Formation for another 200 meters to the point where the grout curtain is terminated. On the left bank, the trench would be excavated down to the limestone rock for the most of its

length and only for a small part through the Fatha Formation and would finish at the end of the grout curtain approximately 250 meters from the left river bank.

2. Blanket grouting was to be applied after excavating the cut-off trench from a concrete slab 0.4 meters thick placed at the bottom. The blanket itself would be formed from 8 rows of grouting holes at 1.5 meters spacing between rows. The holes are set at 1.5 meters spacing in a staggered form and have depths of 10 meters at the edge of the blanket which increases to 20 meters at the centreline. This would bring the width of the grouted zone to 12 meters. The central row holes in the blanket are extended down another 30 meters to form the deep grout curtain which has a total depth of the 50 meters under the base of the cut-off trench.

3. With respect to the concrete dam, the foundation excavation was extended down to the sound limestone rock after removing all the cracked and badly fissured upper layer of about 10 meters in thickness, which was filled afterwards with mass concrete up to the level of the bottom of the foundation slab. Grouting works consisted of blanket consolidation grouting and a deep grout curtain. Consolidation grouting was to be applied to the whole area of the foundation slab with the grout holes drilled in a grid of 3x3 meters and depths of 10 meters and 5 meters as shown in Figure (5). The 50 meters deep grout curtain was to be constructed from a grouting gallery with a similar specification to that under the embankment.

4. Additional to these grouting works under the concrete structures, two drainage curtains were envisaged to relief uplift pressure build-up at the concrete structure foundation joints. The first one would be at a distance of 6.67 meters downstream from the grout curtain and have 30 meters depth under the foundation joint. The second would be placed at 60.9 meters behind the grout curtain with the depth of holes of 5 meters below foundation level. All holes were to be at 3 meters spacing and to have a diameter of 146 mm. Perforated plastic pipes which were to be wrapped by two layers of plastic mesh filter would be inserted in these holes and would have taps at their tops so to discharge the drainage flow into two drainage galleries as shown in the Figure (5). This drainage water would then be collected in a common sump to be pumped out by the central pumping station in the powerhouse.

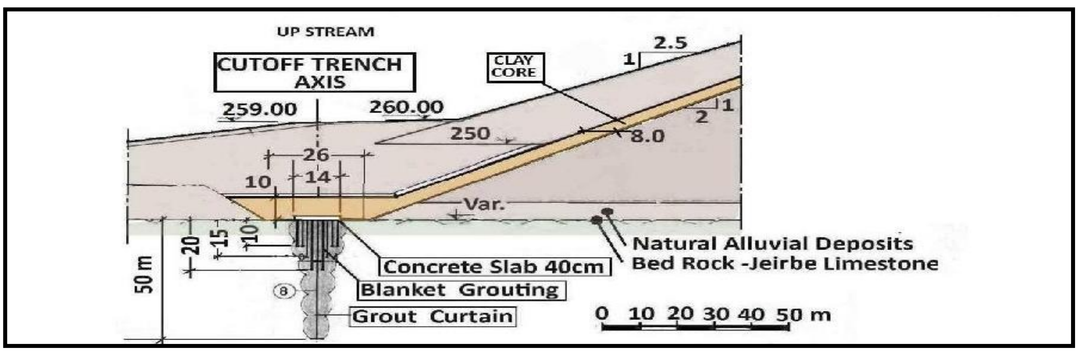

Figure 4: Details of grouting works under the embankment.

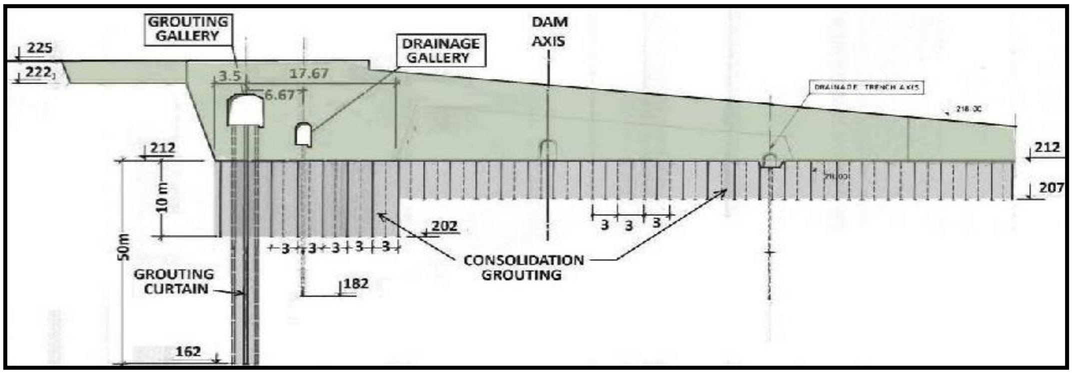

Figure 5: Details of grouting works under the concrete structure.

4 Further Studies and Conflict of Opinions

In 2004 the condition of Mosul Dam was thought to have reached such critical stage that it warranted complete engineering and safety reviews. The evaluation of the worth of the ongoing grout curtain maintenance program was necessary. This maintenance grouting had started since 1987 and continued till that time without tangible results. The total quantity of grouting materials used was about (93000) tons according to the safety review report [11]. In another word, dissolution of gypsum was continuing within the grouted zone and new seepage paths were opening in the same locations or in new ones. The report was completed in 2005 by Washington Group International &Black and Veatch [11] who carried out this safety evaluation. The Panel of Experts which examined Mosul Dam within the scope of this study highlighted the need to continue the maintenance grouting in Mosul Dam as long as possible but, considered that the completion of Badush Dam was necessary to protect the downstream population from the imminent collapse of the dam sometime in the future. The panel overruled the possibility of construction of any diaphragm in Mosul dam on the grounds that such diaphragm was technologically not feasible, its construction posed dangers to the integrity of the dam, and it would be much more expensive than the completion of Badush Dam [11]. No action was taken however to resume the construction of Badush Dam.

The question of Mosul Dam safety versus Badush Dam completion was then considered again in 2006 when another Panel of Experts was commissioned by the Ministry of Water Resources (MOWR) which had replaced the (MOI) to study Mosul Dam conditions. This panel was formed mainly from specialists working with Harza Engineering Company, a principal partner of MHW Global since 2001.The panel in the report of its third meeting held in May 2007 recommended the installation of a diaphragm in Mosul Dam, in addition to transforming Badush Dam from a high protection dam to a low dam for power generation only [12].

These recommendations were the complete reverse of the previous panel recommendations. The same panel in its first report in 2006 had recommended lowering the normal water operation level at Mosul Dam from 330 m (a.s.l) to 319 m (a.s.l) to reduce the possibility of the development of dangerous sinkholes downstream of the dam as had repeatedly happened especially with the last one appearing in July 2005.

In following this matter, MOI awarded a new contract to a joint venture of consultants which was formed from Elconcord (Jordan), Paul Rizzo (USA), Energoprojekt (Serbia), and MEDINGEGNERIA (Italy) to study and present designs of a low Badush Dam for power generation only with the understanding that a diaphragm wall was to be implemented in Mosul Dam. The new consultants prepared and submitted in the following years, many reports which covered two phases, [13] [14]. The tender documents for the required works were submitted later on in 2010 and they included among other things the works for the suggested modifications on the concrete structures, earthworks and foundation treatment. One of the most striking things in these designs and documents was the unnecessary removal of 450000 m^3 of heavily reinforced concrete that were placed already in the dam abutments. The other matter which may be criticized strongly in these documents is the provision in the design for all the requirements as if the dam is to be raised to elevation of 312 m (a.s.l) in a second stage of work but knowing well at the same time that such second stage would not be needed if a diaphragm is to be constructed in Mosul dam which was hypothesized originally [12]. These modifications were to build the dam in two stages. The first stage was to construct the dam to elevation 260 m (a.s.l) as designed by Energoprojekt to operate the hydropower plant with a head of 18.5 meters. Then a second stage to follow was to raise the crest level of the dam to elevation 312 m (a.s.l) in order to enable the retention of the flood wave from possible failure of Mosul Dam, but no clue was given by these consultants on the proper time to start this second stage. The height increment to the final stage was designed as a Roller Compacted Concrete (RCC) dam to fit with what remains of the original concrete.

Regarding the earthfill embankment, the consultants relied upon an inner vertical core instead of the designed thin inclined core. Diaphragm wall was proposed to be implemented in the first stage under the dam foreseeing that it would be necessary for the final stage. Grouting was anticipated under the concrete structures on the same lines as those prescribed previously by Energoprojekt. The total estimated cost to complete the dam exceeded 1.45 billion dollars. This was considered by the employer as totally unacceptable high cost for getting only 170 Mw electric power facility. In addition to the fact that the start and completion of the second stage were not defined in any time frame and this decision must rest in the owner’s hands.

Following this, the feasibility of the dam itself was put to the question, and for that matter, it was referred to yet another new group of consultants formed from EDR GmbH (Germany) and Cedre Team International (Lebanon) in a new contract which was signed in the beginning of 2013. The study report was submitted in October 2014 in which, these consultants expressed their belief that the protection from Mosul Dam flood wave should take precedence over all other considerations due to the ongoing grave threats of Mosul Dam, and treating the power generation question as a secondary matter. Economic analysis outlined in their report showed that power generation alone did not justify constructing Badush Dam [15], and they considered that the total human and material losses in case of Mosul Dam failure were beyond reckoning and this would justify giving priority to flood protection over power generation, and would also justify the high cost required in such case. The report states in a concluding remark the following:

"Although Badush dam is not profitable project, we should focus on its second, but very important purpose (Protection from Flood Risk). Consequently, it is inhuman and even uneconomical to consider the project as just electrical plant generating 170 Mw. MOWR is the concerned party or employer to be obligated by the government to complete it"

In May 2016 an International workshop on Mosul dam safety issue was held in Stockholm which was sponsored by Luleå technical university. A large number of leading world experts and dam engineers in addition to grouting contractors and diaphragm machines manufacturers were invited. The workshop examined Mosul Dam problems closely and came up with a wide range of recommendation with respect to the required future actions (Lauleå Technical University, (2016) [16]. Three alternatives with respect to Mosul Dam future were suggested for further study, analysis and evaluation; these were:

1. To study the question of installing diaphragm wall through Mosul Dam,
2. To complete the construction of Badush Dam as a protection dam and, in the meantime continue grouting at Mosul dam.
3. Use a "hybrid approach" by which Badush Dam would be completed and used as a protection and storage dam.

The third alternative means to complete Badush Dam according to a new design and not wait for the Mosul Dam to fail. The Mosul Dam storage can be then released in a controlled manner into Badush Dam reservoir which will act then as storage dam replacing Mosul Dam and completely decommission it.

5 Evaluation of the suggested options: their Pros and Cons

From the proceedings, it is clear that many options for Badush Dam future were suggested and discussed. All of these options were considered in the context of providing safety to the population and infrastructure downstream from the threatened Mosul Dam and the protection from the catastrophic consequences of the expected flood wave that could result from Mosul Dam failure. In the following, these options may be summarized and investigated for their value, reliability, required scope of work and economic and technical feasibility;

Option (0): This option is to do nothing more than what is being done so far. That is to keep grouting in Mosul Dam and do nothing on Badush Dam. This option does not recognize the continuous deteriorating conditions in the foundations of Mosul Dam which was not so clear in 1989 [17], but which became evident after carrying maintenance grouting for so many years afterwards. It was evident during all these years, however, that not much improvement on the foundation conditions could be obtained by this maintenance grouting, which is only sustaining the dam for unknown more years. The possible collapse without previous warning is still a scare up to now [18]. We may say, therefore, that this solution by itself is of temporary nature and cannot be relied upon to save the dam or secure the downstream reach of the river. It should be noted also that this option was adopted in (1987) after the submittal to the Mosul Dam Board of Expert of a report by the main contractor of the dam construction works (GIMOD) which was prepared by his consultants Binne and Partners [19] at a time when Badush Dam construction was under discussion within (MOI) and the idea of building it was not fully crystallised.

Option (1): This option required the continuation of the maintenance grouting in Mosul Dam by using the improved intelligrout techniques, but at the same time to resume the construction of Badush Dam as per the original design as a protective dam [11]. It was argued that continued grouting undoubtedly would elongate the service life of Mosul Dam and produce the intended benefits for more years, but it would not save the dam itself in the long run. It follows that the only possible way to protect the population and infrastructures downstream would be the completion of Badush Dam.

In formulating this option the Panel of Experts was not in favour of constructing a diaphragm wall through the dam body down to reach the required depth on the ground that no hydromill machine was manufactured at that time which can excavate to the required depth of 240 meters as the work had to be done from the crest of the dam, and even if such machines were available then there was no guarantee that the diaphragm wall panels would have the exact vertical alignments and so there will be wide open gaps in the wall at depth.

Option (2): This suggested option can be seen in terms of two intrinsically related and interconnected parts. Part (a) calls for stopping grouting in Mosul Dam foundation and constructing instead a diaphragm wall from the crest of Mosul Dam reversing the previous panel’s recommendation, and; Part (b) to construct Badush Dam as a low dam with a maximum height at level 260 m (a.s.l), therefore, stripping it from the protection function and only to use it as a power facility [12]. This was again in complete contrast to the previous panel’s recommendations.

As regarding Part (a), the construction of diaphragm, in fact, faces many more technical problems than just the required depth or keeping the wall panel alignments vertical; these two problems however, may have been solved today. As seen from recent technological progress such depths are attainable now as indicated from the following website which claims the ability to reach a depth of 250 meters and keeping all panels to the true vertical with no deviation.

http://www.soilmec.com/en/soilmecworldrecord250meterdeephydromilltechnologydiaphragmwallslurrywall

But the real problem which remains as seen by us is in the karstic nature of the soft rock in the foundation which would result in slow progress of the hydromill machine and the need for a large number of such machines adding up to the total cost.

Additionally, the karstic and cavernous nature of the foundation poses also the possibility of losing the excavating slurry and the collapse of the excavated trench. In the simplest case this means the loss of the hydromill itself but in the worst scenario, the collapse of the trench could endanger the dam integrity and stability of the dam especially at high water levels of the reservoir. A possibility of pre-grouting ahead of excavating the trench may be considered as a solution, or even emptying the reservoir may be another one. These solutions, even if they prove their usefulness they add up to the total cost of the work, either as direct costs in the case of pre-grouting or indirect cost in the form of lost benefits for many years in case of reservoir emptying. Moreover, the diaphragm construction raises many other technical problems that may need serious attention and solution, such as avoiding the grouting gallery beloew the dam base, solving the problem of crossing the power and bottom outlet tunnels.. etc.

In Part (b) of this option, which is the transformation of Badush dam to a run of the river power station as suggested [12], the appointed consultant went ahead to design a second stage of construction to raise the dam back to its original designed height without stating when such work would be required and ignoring the fact that the construction of diaphragm in Mosul Dam as contemplated in Part (a) of this option eliminates the need for such second stage.

Our judgment on this option is that it fails engineering and economic norms and lacks engineering logic in addition to its abnormally unjustified high cost.

Option (3): This option, while it does not spell the grouting matter clearly aims at continuing grouting in Mosul Dam and at the same time calls for resuming the construction of Badush Dam and completing it as a high protection dam. This option is very much similar to option (1) but it calls for introducing some design modifications to the original design to remove any doubt on its proper functioning or safety and it emphasizes the value of the dam as a protection dam [15]. The suggested modifications were to cover both the earthfill dam and the concrete dam. It stipulated the installation of a diaphragm wall under the dam to replace the grout curtain which may not satisfy all the requirements under the full head which was even admitted in the original design, raising the concrete sill of the water conveyance structures by 3.5 meters to avoid clogging these conduits by debris which could accumulate due to Mosul Dam collapse, and finally limiting the removal of the old concrete to an absolute minimum while incorporate the rest in the finished structure. This option seems logical, but more detailed studies are needed to put it in a final shape.

Option (4): This option calls for continuing the grouting works in Mosul Dam for a limited period of time, but also to start immediately the works in Badush Dam as a Storage Dam in this case, and after completion the gradual decommissioning of Mosul Dam must be started, whereby Mosul Dam reservoir is to be released into the new Badush Dam reservoir in a controlled manner and to take Mosul Dam out of service completely. This was one of the options discussed in Stockholm World Mosul Dam Workshop (2016) [16]. In studying this option, we examined its implications on the design of Badush Dam and the far-reaching results on the other projects connected with Mosul Dam. These may be explained as follows: First; the design of Badush Dam must be changed drastically to allow using it for permanent storage and not only for the few months that were envisaged originally as a protective measure. The changes should cover the details of the earth dam cross section by enlarging the clay core and the gravel and sand filter zones from elevation 260 m.a.s.l upwards; the water outlets structures i.e. bottom outlets and the ungated spillway must be re-examined and reassessed. The question of eliminating four of the eight bottom outlets and at the same time lowering the sill of the spillway and equipping it with radial control gates should be addressed to get more flexible operation. The design of the power conduits and power plant should be changed completely to take the much higher head into consideration. The main challenge to the designer in all this is how to elaborate these changes and incorporate them into the final design together with some parts of the already completed works. The anti-seepage foundation work is the other crucial matter that should be studied carefully. A new campaign of geological investigation must be done adding much deeper drill holes, and not to be limited to the dam location but it shall cover the surroundings and the reservoir area, and must extend to include the saddle dams' foundation and the periphery of the reservoir to locate possible sinkholes and other karst phenomena. Second: The impacts on the projects related to Mosul Dam as a result of its decommissioning should be carefully studied. These may be outlined by the following:

1) the required removal of the re-regulating dam of Mosul Dam which will be flooded by the Badush high reservoir.

2) the necessary remodelling or changing of the pump storage power intake which is located about two kilometres downstream from Mosul Dam.

3) Other changes which affect the three Jazira Irrigation projects must be considered, namely; First, relocating, redesigning and refurbishing the existing pump station feeding the North Jazira irrigation project and moving it southward from its present location north of Mosul Dam to a new site making use of the new Badush reservoir; Second, relocating the intake of the East Jazira irrigation

project to be fed from Badush Reservoir instead of the Mosul Dam Reservoir, and; Third, finding an alternative location for the intake of the South Jazira irrigation project which is presently incorporated in Mosul Dam itself, and also finding a new route for the feeder canal of this project and review the need for the Jebal Sheikh Ibrahim tunnel which is part of the origional route of the main canal.

Fortunately, the last two projects are planned and not implemented yet which make room for carrying out the required designs, and if needed enough time for completing.

6 Final Conclusions and Recommendations

The final conclusions of this study may be stated as follows:

- From all the previously performed studies it is very clear that the problem of Mosul Dam safety cannot be separated from Badush Dam construction issue. Badush Dam was suggested as a protective measure from the consequences of Mosul Dam flood Wave in case if the dam would fail. But unfortunately, the works in Badush Dam were abandoned unfinished due to the reason explained previously. The calls for its resumption have continued up to now, either as it was originally designed or by introducing some design changes, and at the same time with the inclusion of diaphragm wall in Mosul Dam. It seems that the continued interest in Badush Dam reflects its importance and value.
- It is a much-known fact that the geology of Badush dam site is very similar to Mosul Dam site. Fatha Formation is dominating the depth of foundation around the Badush Dam although the dam axis itself is located on the Alan anticline in most parts which is a favourable factor. It was known that some of the drill holes completed during the investigation stage were about 100 meters deep without reaching the lower boundary of the karstified rock.In the light of all this, any plan for the resumption of works of Badush Dam, whether, according to the original design or otherwise must take the complexity of the geology into considerations and a thorough and new campaign of geological investigations must be performed. If the decision is taken to build the Badush Dam as a high dam, then such investigation should go as deep as 400 meters or even more in order to obtain the depth of the deepest karstified gypsum and limestone beds accurately
- In the case of high Badush Dam, grouting will not work for simillar reasons as in Mosul Dam case. A diaphragm wall offers then a good solution and it can be constructed from the ground surface and can, therefore, go down to much deeper levels than in Mosul Dam. Moreover, the work will be much easier in such case as there is no full reservoir to worry about. If the decision is taken to go for low Badush Dam the revision of grouting is also necessary. Such revision may result in deepening the curtain and making it wider but, the changes will not be

very extensive due to the low hydraulic head sustained by the dam. Such head is similar to the head at the re-regulating dam downstream of Mosul Dam which was constructed in similar geology without any known trouble so far.

– From the analysis of the various options available at our hands and discussed so far, it looks that all options have their pros and cons. In our opinion the more logical solutions seem either, to construct a diaphragm in Mosul dam after drawing down the reservoir so not to cause any danger to the dam stability and integrity, and at the same time convert Badush Dam to a low dam with absolutely minimum changes to the original design. Or, to decommission Mosul Dam after completion of a high Badush Dam according to a completely new design. Such design shall take care of all the requirements necessary in a high storage dam and shall include no doubt the construction of a diaphragm in this dam.

These solutions must be examined by thorough and rigorous future studies. The economic factors must not be overlooked and should be given prime considerations as the two solutions involve very large investments, in addition to such indirect costs such as the lost benefits which result from emptying the Mosul Dam reservoir which is necessary for the first solution, and the cost of relocating and constructing new feeding facilities to the three Jazira irrigation projects in the second solution.

- There seems also a strong need that the owner of Mosul and Badush Dams (MOWR) should take a more serious and firm policy towards the Mosul- Badush question. We can observe a lack of resolve to finalize this matter which is clear from the long years the discussions have taken from 2005 till now, and from the many panels of Experts appointed, and in the many consulting contracts which have been awarded during these years, only to get a lump sum of conflicting design requirements and ideas which do not help in drawing clear roadmap to resolve this matter. Another example of (MOWR) blunders is clear from signing in 2011 a letter of understanding with a major hydromill manufactures to produce many units and construct the diaphragm at a cost of 2.6 billion US dollars. This was done when the Ministry did not have the slightest clue on the technical specification and requirement of such a huge and delicate work. According to *Reuter News Agency* the following was reported on Nov 4, 2011;

"Construction and engineering company Bauer said it signed a letter of understanding on a $2.6 billion [3.1 trillion Iraqi dinar] contract to refurbish a dam in Iraq. "We expect the contract to be ready for signing within the next few months after some final details have been clarified," Chief Executive Thomas Bauer said in a statement on Thursday. The project, the company's biggest ever, is scheduled to take about six years to complete It will involve Bauer building a cut-off wall to seal the Mosul Dam in northern Iraq. The ground beneath the 3.6-kilometre-long dam has become increasingly water-permeable, Bauer said" [20].

This letter of understanding (or rather misunderstanding) was shelved and no one knows what has come of it so far.

In a final statement, we can only hope that a serious action to end this controversy will be taken before it is too late. Once Mosul Dam was described as "Iraq's Ticking Bomb" [21].

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A Comparative Study of Mosul and Haditha Dams, Iraq: Geological Conditions

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Abstract

Mosul and Haditha Dams are the largest dams on the Tigris and Euphrates Rivers in Iraq, respectively. Both dams are of earthfill type and constructed on sedimentary rocks, but have different geological conditions. Both of them suffer from karstification problems. The former; however, suffers from intense karstification, which has endangered the stability of the dam and possible failure.
The karstification in both sites is of different origins, types, shapes, sizes and depths, as well as in different rocks and geological formations. In Mosul Dam site, the highly dissolved gypsum beds of the Fatha Formation has formed solution type sinkholes with cavities of different shapes and sizes at different depth; attaining to about 250 m upon which the foundations of the dam are located. In Haditha Dam site, the karstification occur in the limestone beds of the Euphrates Formation, the developed sinkholes are of collapse type with regular shapes; either circular or oval apertures. The thickness of the karstified sequence in the foundations is not more 50 m.
This research work is to highlight the role of the geological conditions, especially when the karstification in the safety of both dams is concerned and its effect on the foundations of the dams

Keywords: Mosul Dam; Haditha Dam; Dam site geology; Karstification, Gypsum and Limestone beds.

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1 Introduction

Mosul and Haditha Dams are the two largest dams of Iraq, whether according to the volume of materials used in their construction or the volume of their storage. They impound the Tigris and Euphrates Rivers, respectively.

The two dams were constructed during the eighties of the last century although the investigation works and studies had taken much of the fifties, sixties and the seventies. Mosul Dam is located at 42° 13′ Longitude and 36° 37′ Latitude at a distance of 70 km northwest of Mosul city, which is about 400 kilometers north of the capital Baghdad. Haditha Dam is located at 34° 12′ Latitude and 42° 21′ Longitude, about 8 km northwest of Haditha town, which is about 270 kilometers northwest of Baghdad (Figure 1).

The two dams share together many similarities. In both dam sites karsts are present, but the karst forms; however, are of different characteristics and origin, which result in different approaches towards foundation treatment.

This paper seeks to highlight the important topics involved and to present a comparative study of the geology of the two dams with emphasis on the role of the karstification on the foundations of the two dams and their effect on their stability. Moreover, to highlight the failure possibility of Mosul dam; in spite of the enormous attempts of grouting that were carried out since the first year of the construction which still continues as an ongoing process.

A wealth of information on both dams is available; the bulk of it is from published papers, geological reports and maps, relevant books and the accumulated experience of the authors.

The Construction of Mosul Dam was started on the 25th January 1981 and completed on 24th July 1986. Finally, at 1978 the Swiss Consultant Consortium of Zurich- Geneva was selected to produce the planning report, final design and contract documents, perform the general supervision and, share with Energoprojekt of Belgrade the daily supervision on the works. Mosul Dam is an earthfill dam with total length of 3400 m, the maximum height of the dam is 113 m from the deepest point in the river channel; accordingly, the crest level was fixed at 341.6 m (a.s.l.). Normal Operation Water level is 330 m (a.s.l.), Maximum Operation Water is 335 m (a.s.l.) and Maximum Flood Water Level is 338 m (a.s.l.). The storage capacity is 11.11×10^9 m^3 at elevation 330 m (a.s.l.) [1].

Figure 1: Location of Mosul and Haditha Dams, Iraq

The Construction of Haditha dam was begun in 1977 and it was completed in 1988. Investigation works and preparation of the general design and specifications were initiated by Soviet organizations in contracts with the Iraqi Government. Haditha Dam is an earthfill Dam with 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 Normal Operation Water level is 143 m (a.s.l.), Maximum Operation Water is 147 m (a.s.l.) and Maximum Flood Water Level is 152.2 m (a.s.l.). The storage capacity is 6×10^9 m^3 at elevation 143 m (a.s.l.) [1].

2 Comparison of Geological Conditions

2.1. General

Mosul and Haditha Dams are located in sites of different geological conditions; although both have one common aspect that is the karstification. The karstification; however, is quite different in the two sites in many forms, the only common aspect is that in both sites the karstification is an active process and it is still ongoing.

The main geological conditions in both Mosul and Haditha Dams are compared to each other in order to show the main differences between the main geological aspects and indicate their effects on the stability of both dams. A very brief comparison between the main geological aspects in both dams is presented in Table (1).

The main geological aspects; geomorphology, tectonics and structural geology and stratigraphy of the two main dams are described; systematically. The used data is based mainly on the published maps and reports by Iraq Geological Survey (GEOSURV); however, other published data is used too when needed. The systematic description style is chosen to enable easier comparison between the dams; whenever a certain geological aspect is concerned. Those aspects, which are more significant; as far as the dam safety is concerned, are emphasized more; such as the origin of the karstification, features, forms, sizes, reasons, type of the rocks and geological formations, as well as the age of the karstification.

2.2. Geomorphology

The main geomorphological units and features of Mosul and Haditha dams are described in details; hereinafter.

2.2.1. Geomorphology of Mosul Dam

Mosul Dam and the reservoir area are located; physiographically within the Low Mountainous Province [2]. It is characterized by hilly terrain that rises to low mountainous area. The mountains form anticlines, which trend mainly in NW – SE direction and change~~s~~ westwards almost to E – W direction.

A) Geomorphological Units: The main geomorphological units and forms in the area under consideration belong to the following origins:

Structural – Denudational Origin: The main units are the anticlinal ridges, which form the limbs of the existing anticlines formed either by limestone, and/ or gypsum of the Fatha Formation (Figure 2). Another geomorphological form is the flat irons formed either in limestone and/ or gypsum beds (Figure 2); however, in the outer areas of the limbs, sandstone beds of the Injana Formation form cuestas and hogbags; due to their alternation with soft claystone beds [3, 4].

Table 1: Brief comparison between the main geological aspects at both Mosul and Haditha Dam sites

Aspects	Mosul Dam	Haditha Dam	Remarks
Tectonic And Structural Characters	Within the Low Folded Zone of the Outer Platform. The dam is located in the plunge of Butma East anticline.	Within the Inner Platform. The dam is located in an unfolded area; therefore, the beds are almost horizontal.	Both dams are located; tectonically, within the Arabian Plate.
Geomorphological Aspects	Anticlinal ridges, karst forms, flat irons and intensive weathering.	Residual soil, Karst forms, moderate to intensive weathering.	The only common feature is the karst forms
Stratigraphy and Type of the rocks	The dam site is within the Fatha Formation, which consists of cyclic sediments, each cycle includes marl, limestone and gypsum.	The dam site is within the Euphrates Formation, which consists of basal conglomerate, hard dolomite, chalky limestone and undulated limestone.	Both dams are located within sedimentary rocks sequence; almost all rocks are highly karstified.
Karstification	The main karst form is the sinkholes, majority of them are within the gypsum beds. The sinkholes are of solution type. The thickness of the karstified rocks is about 300 m.	The main karst form is the sinkholes, majority of them are within the limestone beds. The sinkholes are of collapse type. The thickness of the karstified rocks is about 50 m.	The karstification is an active process and still ongoing.

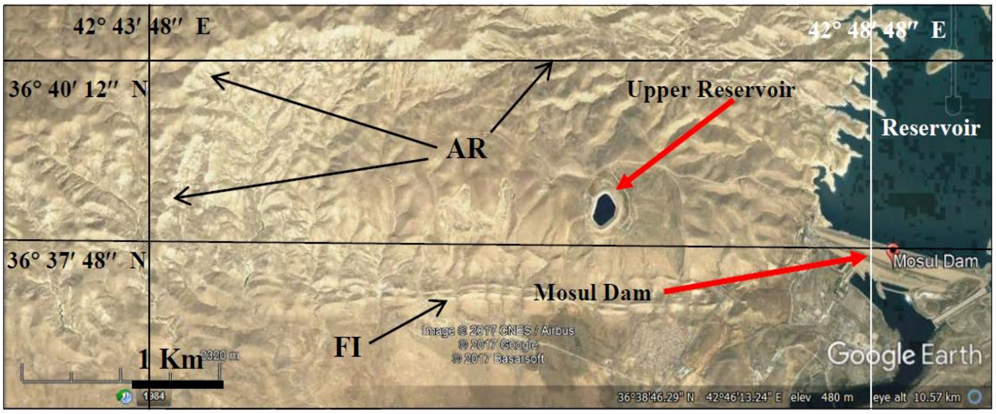

Figure 2: Google Earth image of Mosul Dam site. Note the anticlinal ridges (**AR**) and the Flat irons (**FI**)

Alluvial Origin: Two main units are developed. **1)** River terraces consisting of gravels of different rock types, sizes and shapes, cemented by gypsiferous material; usually (3 – 4) levels are developed, the thickness of each level varies from (5 – 8) m. **2)** Flood plain consisting of sand, silt and clay; usually two levels are developed. The thickness of each level varies from (1.5 – 3) m.

Karst Origin: Sinkholes are the most common karst forms in the dam site and reservoir area. They are described latter on separately.

B) Weathering and Erosion: The following weathering and erosion types are acting in the area under consideration.

Chemical Weathering: Is more effective and common; as indicated by the presence of solution sinkholes formed mainly in gypsum beds.

Mechanical (Physical) Weathering: Is less active; as can be seen on the weathering grade of the rocks, especially the hard limestone and dolomite beds within the Fatha Formation, which are slightly weathered, whereas the soft rocks like claystone and marl of the Fatha and Injana formations are moderately to highly weathered.

Rill Erosion: Is the most common erosion type; as can be seen on the slopes of soft to moderately hard rocks.

Gulley Erosion: Is usually acting in deeply incised valleys, especially in meandering of the valley courses.

Sheet Erosion: Is the less abundant type and acting on almost flat areas, which are very rare in the concerned area.

C) Mass Movements: The most common types are:

Toppling: This is the most abundant phenomenon, where the alternation of hard and soft rocks exhibit toppling of blocks of the hard rocks, which are underlain by soft rocks, such as sandstone overlying claystone (Injana Formation), limestone and gypsum underlain by marl and/ or claystone (Fatha Formation).

Landslides: These are very rare phenomena, especially along the banks of Mosul Lake. The sizes are small with no significant effect on the stability of the slopes.
Mud Flows: These are very rare phenomena developed within claystone beds of the Fatha and Injana formations, especially along steep slopes.

2.2.2. Geomorphology of Haditha Dam

Haditha Dam and the reservoir area are located; physiographically within the Western Desert and Al-Jazira Provinces [2]. Both provinces are characterized by flat terrain dissected by large valleys, especially the former province (Figure 3).

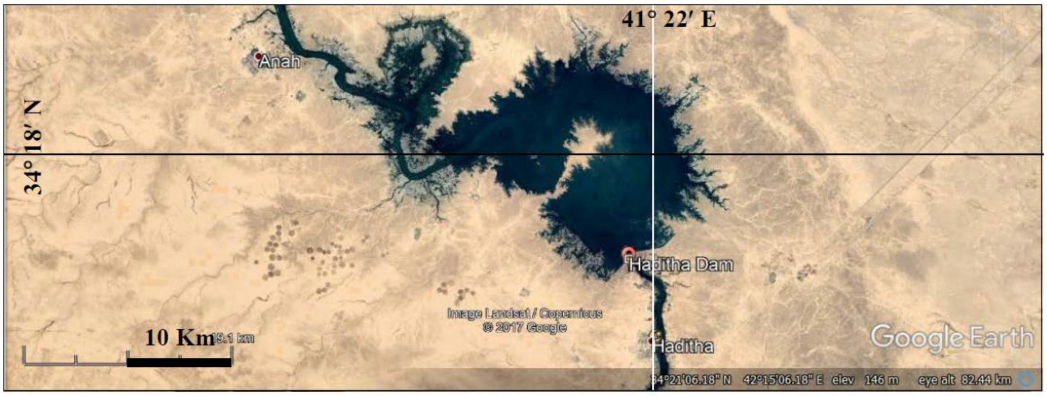

Figure 3: Google Earth image of Haditha Dam and lake. Note the flat terrain and large valleys; south of the lake

A) Geomorphological Units: The main geomorphological units and forms in the area under consideration area belong to the following origins [5]:

Alluvial Origin: Two main units are developed. **1)** River terraces consisting of gravel of different rock types, sizes and shapes cemented by sandy and clayey materials and rarely gypsiferous, especially those north of the river. Usually (2 – 3) levels are developed, the thickness of each level varies from (3 – 5) m. **2)** Flood plain consist of sand, silt and clay; usually two levels are developed. The thickness of each level varies from (1.5 – 3) m.
Karst Origin: Sinkholes are the most common karst forms in the dam site and reservoir area. They are described latter on separately.

B) Weathering and Erosion: The following weathering and erosion types are acting in the concerned area.
Chemical Weathering: Is more effective and common; as indicated by the presence of sinkholes formed in limestone beds.
Mechanical (Physical) Weathering: Is less active; as can be seen on the weathering grade of the rocks, especially the hard limestone and dolomite beds of the Euphrates Formation, which are slightly weathered, whereas the soft rocks like claystone and marl are of the Fatha and Nfayil formations are moderately to highly weathered.

Sheet Erosion: Is the more abundant type and acting on almost flat areas, which are very common in the area, especially south of the river.
Rill Erosion: Is the less abundant erosion type; as can be seen on the slopes of soft to moderately hard rocks.
Gulley Erosion: Is usually acting in deeply incised valleys, especially in meandering of the valley courses.

C) Mass Movements: The most common types are:
Toppling: This is the most abundant phenomenon, where the alternation of hard and soft rocks exhibit toppling of blocks of the hard rocks, which are underlain by soft rocks, such as limestone and dolomite overlying claystone (Euphrates and Nfayil formations), limestone and gypsum underlain by marl and/ or claystone (Fatha Formation).
Mud Flows: These are also very rare phenomena developed within claystone beds of the Fatha Formation, especially along steep slopes.

2.3. Tectonics and Structural Geology

The main structural features of the both Mosul and Haditha dams and tectonic zones are described in details; hereinafter.

2.3.1. Mosul Dam

Mosul Dam site and reservoir area are located within the Cham-Chamal Subzone of the Low Folded Zone; within the Unstable Shelf of the Arabian Plate [6]. The updated tectonic framework of Iraq [7]; however, has considered that the dam site and reservoir area are located within the Low Folded Zone, within the Outer Platform of the Arabian Plate, all belong to the Zagros Thrust – Fold Belt.

The Low Folded Zone of Iraq is characterized by long and narrow anticlines; mainly with exposed Miocene rocks in their cores, and wide and deep synclines, which are usually filled with Quaternary sediments. Mosul Dam is located within Butma East anticline, which has almost E – W trend with steeper southern limb (Figure 2).

Many anticlines surround the reservoir area of Mosul Dam and many others are located nearby to the reservoir and the dam site. Some of them exhibit strange shapes and local dislocations due to a major deep seated fault called Sasan – Bekhair Fault [7] (Figure 4), which passes NW of the dam with clear dislocation of the axes and beds of many anticlines (Figure 4). Moreover, many other small faults of different types and different dislocations were mapped in the dam site and reservoir area [8]. It is worth mentioning that all structural disturbances have no any significant effect on the dam, since there is no any evidence of neotectonic activity.

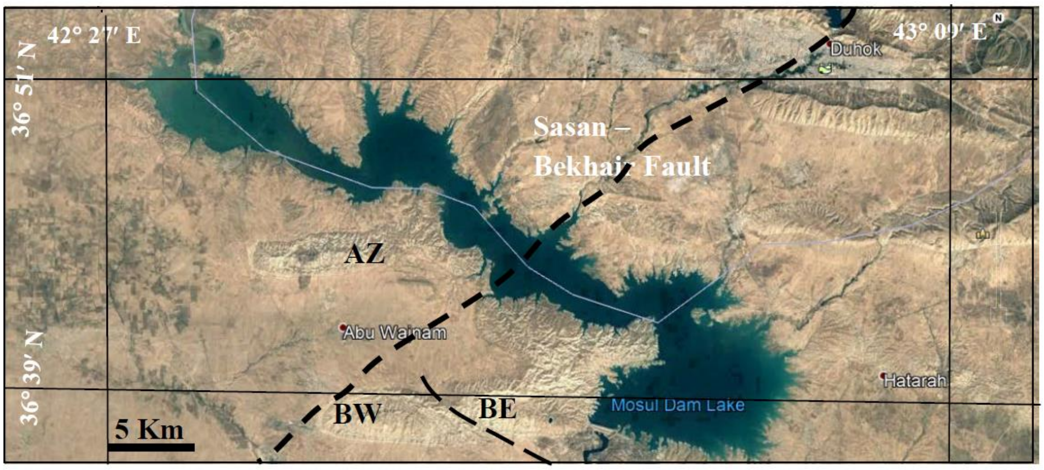

Figure 4: Google Earth image of Mosul Dam and Lake. Note the deep seated Sasan – Bekhair Fault. Anticlines: BE = Butma East, BW = Butma West, AZ = Ain Zala,

2.3.2. Haditha Dam

Haditha Dam site and reservoir area are located within two different tectonic zones. The northern part of the dam (left abutment) and reservoir belongs to the Jazira Zone within the Mesopotamia Foredeep of the Outer Platform. The southern part of the dam (right abutment) and reservoir; however, belongs to the Western Desert Zone of the Inner Platform. Both Outer and Inner Platforms belong to the Arabian Plate [7].

The Jazira Zone of Iraq is characterized by the absence of surface structural features; however, many subsurface anticlines exist; all are originally inverted grabens. Nevertheless, the area is rich in Neotectonic evidences [9]. All those structural features have no significant effect on the stability of the dam.

The Western Desert Zone of Iraq is characterized by tectonic rest as evidenced from the absence of any structural features; apart from Anah anticline, which is far from the dam site (Figure 5). Neotectonic evidences; however, are present in different parts in different forms, but not near the dam site [10, 11]. However, some structurally controlled straight fine branches of valleys, which are oriented in WNW – ESE trend west of the dam (Figure 5) indicate neotectonic evidence [12].

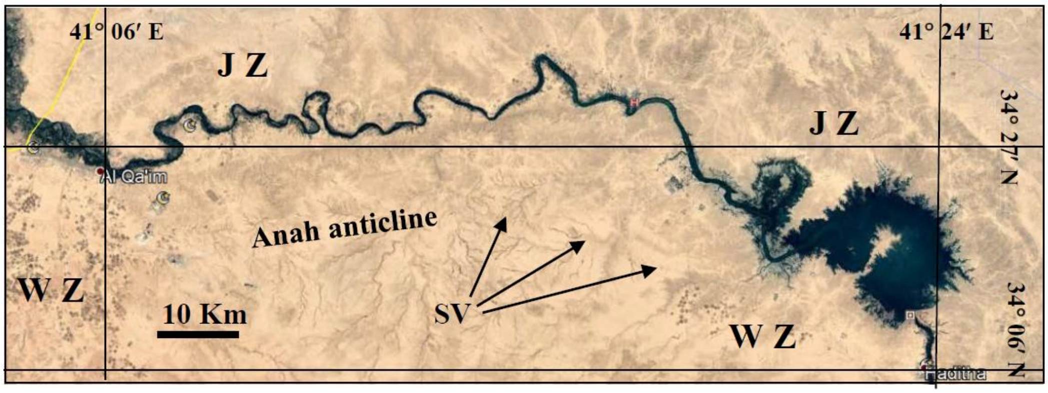

Figure 5: Google Earth image showing regional tectonic frame work of Haditha Dam site. JZ = Jazira Zone, WZ = Western Desert Zone, SV = Straight valleys

2.4. Stratigraphy

The main lithological constituents of the exposed geological formations at both Mosul and Haditha dams are described; hereinafter.

2.4.1. Mosul Dam

The exposed geological formations at Mosul Dam site and near surroundings are shown in (Figure 6). The exposed geological formations are described from the oldest to the youngest; hereinafter.

– **Pila Spi Formation** (Upper Eocene): The formation consists of well bedded and hard dolomitic limestone, dolomite and limestone. The formation exposed far from the dam site (Figure 6).

– **Euphrates Formation** (Lower Miocene): The formation consists of well bedded and hard dolomitic limestone, dolomite and limestone. The formation is exposed east and south of the dam site (Figure 6). Part of the foundations of the dam is located on this formation, which exhibit intense karstification.

– **Fatha Formation** (Middle Miocene): The formation is divided into two members: **Lower Member**, consists of cyclic deposits, each cycle consists of green marl, limestone and gypsum. **Upper Member**, consists of cyclic deposits, each cycle consists of green marl, red claystone, limestone and gypsum. The uppermost cycles include fine reddish brown sandstone. The formation is widely exposed in the dam site and along the southern and northern banks of the reservoir (Figure 6). The foundation and abutments of the dam are located in this formation, which exhibits intense karstification, which is very active hitherto.

– **Injana Formation** (Upper Miocene): The formation consists of cyclic deposits; each cycle consists of sandstone, siltstone and claystone. All rocks are reddish brown in color. The formation is exposed along the northern bank of the reservoir (Figure 6).

– **Mukdadiya Formation** (Upper Miocene – Pliocene): The formation consists of cyclic deposits; each cycle consists of sandstone; some are pebbly, siltstone and claystone. All rocks are grey in color. The formation is exposed east of the dam site only (Figure 6).

– **Bai Hassan Formation** (Pliocene -Pleistocene): The formation consists of conglomerate beds alternated with reddish brown claystone with rare sandstone beds. The formation is exposed in a very restricted area east of the dam site only (Figure 6).

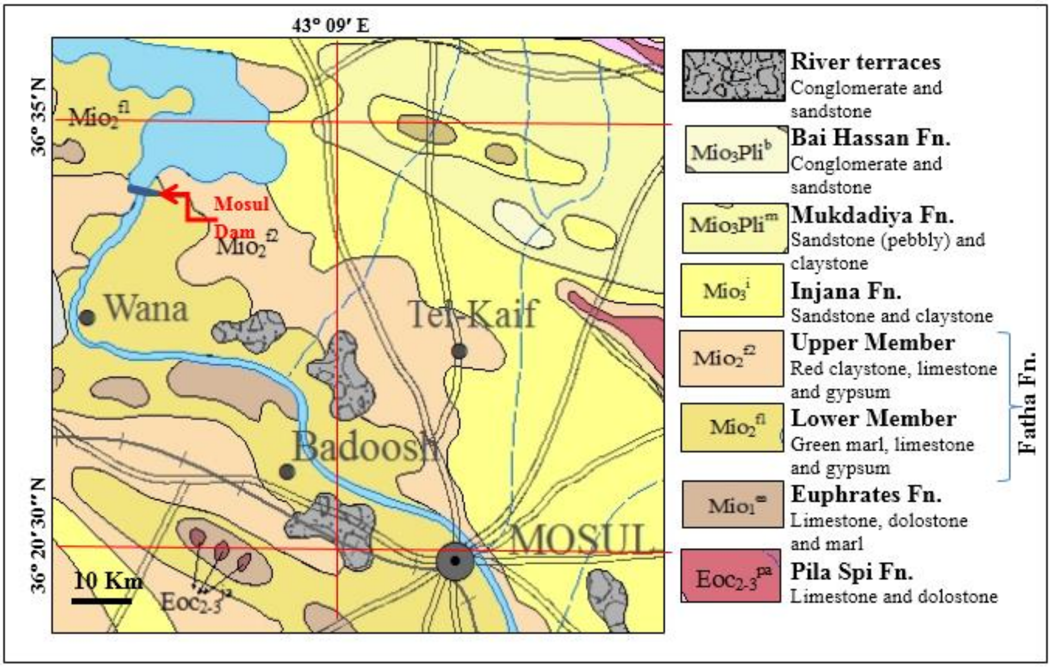

Figure 6: Geological map of Mosul Dam site and near surroundings [2]

2.4.2. Haditha Dam

The exposed geological formations at Haditha Dam site and near surroundings are shown in (Figure 7). The exposed geological formations are described from the oldest to the youngest; hereinafter.

– **Anah Formation** (Upper Oligocene): The formation consists of massively bedded and hard dolomitic limestone and cavernous limestone. The formation is exposed south of the dam site and some valleys and plays effective role in development of the sinkholes (Figure 7).

– **Euphrates Formation** (Lower Miocene): The formation consists of two members. **Lower Member** consists of basal conglomerate~~,~~ which plays a big role in water circulation and development of the sinkholes. The conglomerate is overlain by well bedded and hard dolomitic limestone, dolomite and limestone; followed by thickly bedded chalky limestone; upwards become thinly bedded. This succession forms all the flat areas in the dam site and near surroundings and all the sinkholes are developed in the succession. **Upper Member** consists of brecciated dolomite with thin marl horizons; overlain by well bedded undulated limestone. The formation is exposed in all sides of the dam site and reservoir area (Figure 7). It is worth mentioning that the Soviet Geologists working in the dam site, during the geological investigation stage have considered the undulated limestone unit as part of the Fatha Formation and it is spread over all other formations, which is not true, because it means there is a break in the deposition between Lower and Middle Miocene.

– **Fatha Formation** (Middle Miocene): The formation is divided into two members: **Lower Member**, consists of cyclic deposits, each cycle consists of green marl, limestone and gypsum. **Upper Member**, consists of cyclic deposits, each cycle consists of green marl, red claystone, limestone and gypsum. The uppermost cycles include fine reddish brown sandstone. The formation is widely exposed in the northern part of the dam site and along the northern bank of the reservoir (Figure 7). The formation is highly karstified; exhibiting solution sinkholes.

– **Nfayil Formation** (Middle Miocene): The formation consists of cyclic deposits; each cycle consists of green marl and limestone. The formation is exposed as isolated hills southwest of the dam site (Figure 7).

2.5. Karstification

Karstification is the most dangerous and effective process as far as the stability of both Mosul and Haditha dams are concerned; especially in Mosul Dam. The genesis, types and sizes of the existing karst forms at both dams are described; hereinafter.

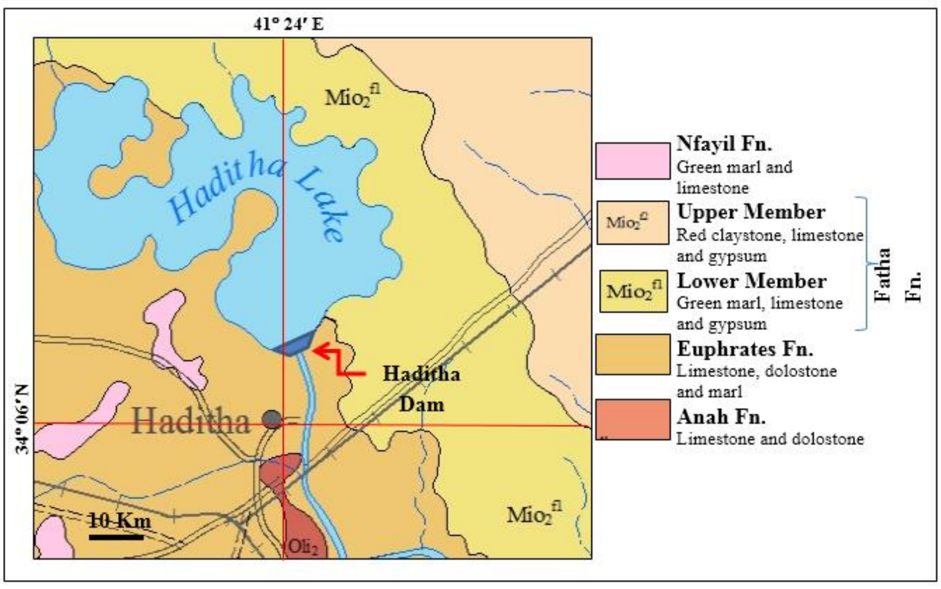

Figure 7: Geological map of Haditha Dam site and near surroundings [2]

2.5.1. Mosul Dam

The karstification is a very active process in the dam site and extends to its foundations and reservoir area [13, 14, 15, 16, 17 and 18]. The main karst feature is the sinkholes, which are developed mainly and intensively in gypsum beds and less abundant in limestone beds. Those developed in gypsum beds have irregular apertures with clear dissolving indications, the diameter of the sinkholes ranges from (< 1 – 3) m, whereas the depth rages from (< 1 – 8) m. Those developed in limestone beds have regular forms, either with circular or elliptical apertures of collapse origin, the diameter of the sinkholes ranges from (< 1 – 20) m, whereas the depth ranges from (< 1 – 15) m. The main reason of the karstification is the high dissolving ability of the gypsum beds, which increases with high static water pressure exerted by the water head in the reservoir. One more karst feature in Mosul Dam foundations are the well-developed brecciated gypsum, which are recognized in these foundations.

2.5.2. Haditha Dam

Haditha Dam site and near surroundings are a well-known karst area in Iraq [19]. A total of 54 sinkholes exist in the dam site and downstream, all are of collapse origin with circular and/ or oval shaped apertures. The diameter of the sinkholes ranges from few meter up to 110 m, whereas the depth ranges from few meters up to 55 m. Majority of the sinkholes are of active type; as indicated by the presence of many fractures of different orientations in their floors [19] and [20]. It was noticed that the main reason for the presence of dense sinkholes is the exposures of the uppermost part of the Anah Formation and the basal conglomerate of the Euphrates Formation. The basal conglomerate acts as water circulation media; both surface and groundwater; consequently, facilitating the solution of the limestone beds of the lowermost part of the Lower Member of the Euphrates Formation. Therefore, no sinkholes are developed in the Upper Member of the Euphrates Formation.

2.5.3. Comparison between Karstification in Mosul and Haditha Dams

Although both Mosul and Haditha dams suffer from karstification, but the process is quite different in both dams, as far as the genesis, size of the sinkholes, the concerned rocks and the karstification depth are concerned.

The authors believe that the karstification process in Mosul Dam is more active than that in Haditha Dam. This is confirmed by the continuous grouting of the foundations in Mosul dam to stop dissolution of the gypsum rocks, but all these attempts are in vain hitherto. The severe and active karstification in Mosul Dam as compared to that at Haditha Dam is attributed to the following reasons: **1)** The main karstified rocks at Mosul Dam are gypsum beds, which belong to the Fatha Formation, whereas at Haditha Dam the karstified rocks are limestone beds, which belong to the Euphrates Formation, **2)** The thickness of the Fatha Formation at Mosul Dam is about 300 m, whereas the thickness of the Euphrates Formation at Haditha Dam is about 50 m, **3)** The karstified gypsum rocks exist through the whole Fatha Formation (Figure 8), whereas the karstified limestone beds exist only in the Lower Member of the Euphrates Formation (Figure 9), **4)** The gypsum beds in the Fatha Formation are overlain by soft marl, which are easily disintegrated and washed out in the developed caverns in gypsum beds; accordingly accelerating the junction of caverns developed in different gypsum beds that occur in different levels (Figure 8). Whereas, in the Euphrates Formation, the karstified limestone beds are either not overlain by rocks; due to the weathering of the Upper Member of the formation or are overlain by thick (not less than 30 m) massive limestone and dolomite beds, **5)** The dissolution ability of anhydrite and gypsum beds is higher than those of limestone and dolomite beds; therefore, the developed cavities and caverns due to solution are larger in size, deeper in extent and more frequent, **6)** The water in the reservoir of Mosul Dam is sulphatic; due to the intensive exposures of the gypsum beds of the Fatha Formation (Figure 6); accordingly, the sulphatic water has more dissolving ability than the carbonate water in the reservoir of Haditha Dam, where the majority of rocks surrounding the reservoir are carbonates (Figure 7). However, the surface water, which flows from the Jazira area towards the reservoir of Haditha Dam is also sulphatic due to the exposures of the gypsum beds of the Fatha Formation in the Jazira area (Figure 7), but still the percentage of the dissolved sulphates in the water of Mosul Dam reservoir is higher than that dissolved in the water of Haditha Dam reservoir, **7)** Although the number of the developed sinkholes at Haditha Dam site and near surroundings is higher than those at Mosul Dam site, but the karstification is more active and intensive; because the whole succession (About 300 m) at Mosul Dam site is karstified, while the karstified succession in Haditha Dam is not more than (25 – 45) m, **8)** The basal conglomerate, which exists between the Anah and Euphrates formations (Figure 9), is the main reason for the karstification. Wherever it is exposed (usually in valleys), then there is a high concentration of sinkholes. This is attributed to the high porosity and permeability of the basal conglomerate; moreover, it is underlain by the cavernous rocks of the Anah Formation; therefore, both units accelerate water circulation; consequently, accelerates and facilitates the solution of the rocks of the Euphrates Formation in Haditha Dam site. In Mosul Dam, the reason of the active karstification is the cyclic nature of the Fatha Formation [3]. Each gypsum bed is underlain by limestone bed and overlain by marl and claystone. Since the marl and claystone beds are impervious~~;~~ but weak; therefore, are easily disintegrated and washed out filling the caverns developed in the dissolved gypsum beds. This is why the karstified gypsum beds appear also as brecciated gypsum.

3 Conclusions

From the reviewed and presented data in this paper, we have the following conclusions:

The geology of the two sites played most important role in the selection of the type and details of foundations' treatments; more successfully in Haditha Dam than in Mosul Dam. While both sites suffer from the presence of karsts; these karsts are of different origins, types, shapes, sizes and depths. In Mosul Dam site, it is of solution type, which was formed as a result of the high dissolution rates of gypsum beds within the foundations.

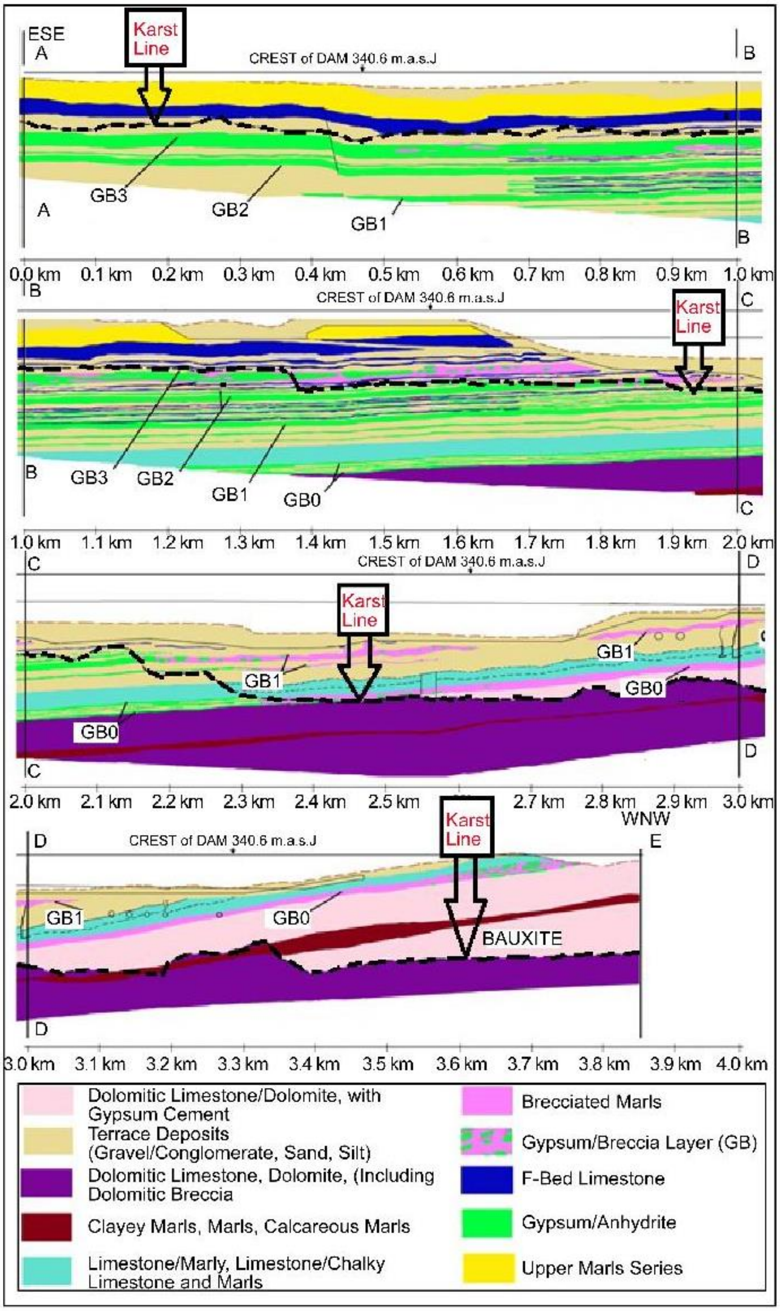

Figure 8: Assumed Karsts line in Mosul Dam foundations (From [1])

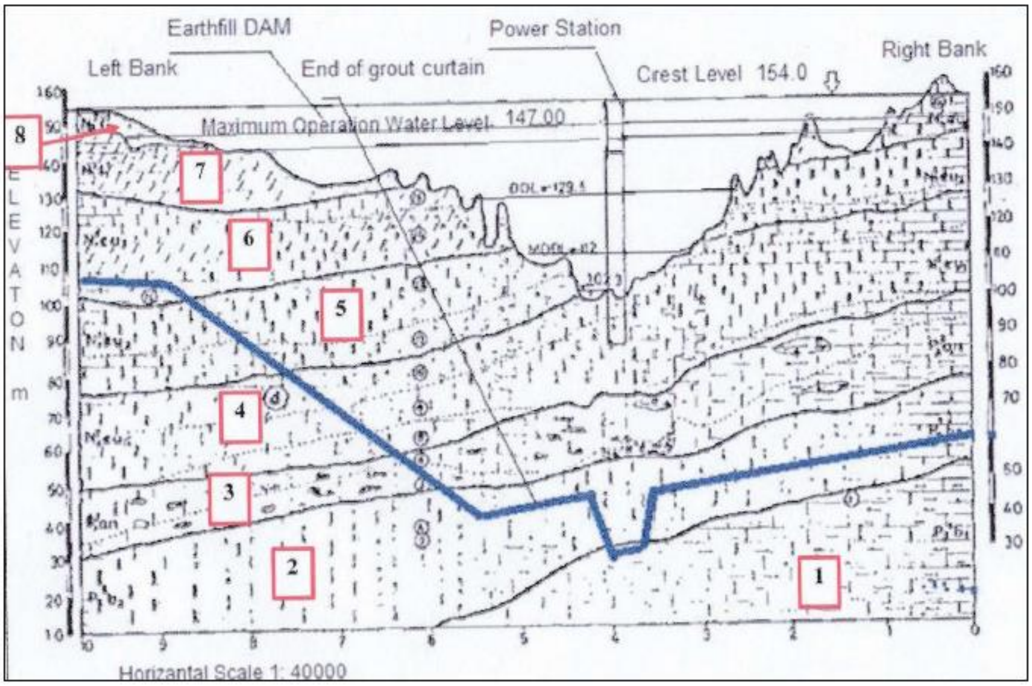

Figure 9: Geological cross section under Haditha Dam, showing the lower limits of the grout curtain. Note that the karstification is developed in the Lower Member of the Euphrates Formation (Units 3, 4 and 5), underlain by the cavernous Anah Formation (Unit 2).

In Haditha Dam site, it occurs in varying degrees in the limestone beds of the Euphrates Formations in the shape of fissures, cracks and nearly isolated sinkholes in the whole rock sequence in the foundations. Sinkholes in Mosul Dam site are of the very active and severely dissolution type, not like those in Haditha Dam site, which are of collapse type and less dangerous due to the fact that limestone is less soluble than gypsum.

The thickness of the karstified rocks in Mosul Dam site is about 300 m, whereas at Haditha Dam site is about 50 m. This large difference in the thickness of the karstified succession of the rocks also played a big role in destabilizing of Mosul Dam.

In Mosul Dam site, the rocks are tilted and deformed due to tectonic activities, which had increased the dissolution ability, whereas in Haditha Dam site, the beds are almost horizontal and not deformed; as they are not affected by tectonic forces.

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Comparative Study of Mosul and Haditha Dams, Iraq: Foundation Treatments in the Two Dams

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Abstract

Mosul and Haditha Dams are built on relatively weak foundations. Both of these foundations suffer from extensive karsts which had demanded intensive foundation treatment works among other design precautions. The karst forms; however, are of different origins, activities, nature and shapes. The foundation treatment in both dams was done mainly by constructing deep grout curtains along with other secondary grouting works. Reducing uplift pressure under the dam and cutting down on seepage losses were the major considerations in these works. An additional important requirement in Mosul Dam was to reduce the permeability of the rock formation in the foundations to such a low limit that it can stop the dissolution of gypsum beds present there. This objective; unfortunately, failed due to the lithological composition of this foundation and the presence of many brecciated gypsum beds, which could not be treated successfully. This had resulted in a comprehensive grouting maintenance program which continuous up to date with the everlasting danger of dam failure. On the other hand, in Haditha dam no such complication occurs as the dam had its foundations mainly in limestone. Proper investigation and good planning and performance of the grouting works in this dam contributed highly to its success. Selecting the deep grout curtain as anti-seepage measure in Mosul Dam was not a very wise decision and constructing a positive cutoff in the form of diaphragm wall could have been the proper choice. Good and deep understanding of all geological data can contribute to the success of a dam design or, otherwise it may lead to unsafe one.

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Keywords: Mosul Dam, Haditha Dam, Karst, Sinkholes, Gypsum, Limestone, Grout curtain. Diaphragm

1 Introduction

Foundation treatment is an essential part in the design and construction of safe dams. Such treatment may take different types, shapes and methods. The objectives are always to reduce seepage through the foundation in order to reduce water losses for one reason; the other more important goals are to enhance the stability of the dam against uplift pressure and/or the washing away of the foundation materials. As all dam designers well know, these measures may vary between a host of possibilities; such as excavating cutoff trenches to reach competent foundation bedrock, execute blanket grouting that aims at creating a homogenous foundation which is less permeable and having higher bearing capacity, perform a deep cutoff which may be a grout curtain or a diaphragm wall. In important dams and in less than good foundation geology combination of some of these measures may be done. Drainage plays also an important role in uplift pressure relief on the downstream base of the dam, which could be in the form of horizontal drainage blankets or vertical relief wells depending on the actual foundation configurations. The geology of the foundation invariably plays the most important factor on deciding the method of treatment and its extent as far as the safety of the dam is concerned. In this paper we try to clarify this by presenting two cases: i.e. Mosul Dam and Haditha Dams foundation treatments. These are the largest two dams in Iraq, which control most of the water resources of the Tigris River, all the water resources of the Euphrates River as they flow into Iraq.

2 The Geological Factors

Mosul and Haditha Dams are both founded on rocks of sedimentary origins. Full description of the geology of the two sites are given in reference [1] which covers geomorphology, tectonics and structural geology, and stratigraphy at the two sites. The same paper concludes that the foundation geology at the two dam sites is quite different, but they share, however, one common phenomenon which prevails in the effective depth of their foundations; this is karstification. The karstification itself is quite different in the two sites in many ways, but at both sites this karstification is a very active process and it is still ongoing. Table (1) summaries and compares the main geological properties and conditions in the two sites.

Given the above geology in the two sites, the following paragraphs detail the foundation treatment in each of the two dams and our comments and conclusions

Table 1: Brief comparison between the main geological properties and conditions at both Mosul and Haditha Dam site [1]

Aspects	**Mosul Dam**	**Haditha Dam**	**Remarks**
Tectonic And Structural Characters	Within the Low Folded Zone of the Outer Platform. The dam is located in the plunge of Butma East anticline.	Within the Inner Platform. The dam is located in an unfolded area; therefore, the beds are almost horizontal.	Both dams are located; tectonically, within the Arabian Plate.
Geomorphological Aspects	Anticlinal ridges, karst forms, flat irons and intensive weathering	Residual soil, Karst forms, moderate to intensive weathering.	The only common feature is the karst forms.
Stratigraphy and Type of the rocks	The dam site is within the Fatha Formation, which consists of cyclic sediments, each cycle includes marl, limestone and gypsum.	The dam site is within the Euphrates Formation, which consists of basal conglomerate, hard dolomite, chalky limestone and undulated limestone.	Both dams are located within sedimentary rocks sequence; almost all rocks are highly karstified.
Karstification	The main karst form is the sinkholes, majority of them are within the gypsum beds. The sinkholes are of solution type The thickness of the karstified sequence is about 300 m.	The main karst form is the sinkholes, majority of them are within the limestone beds. The sinkholes are of collapse type The thickness of the karstified sequence is about 50 m.	The karstification is an active process and still ongoing in both sites.

3 Foundation treatments of the two dams: Details

3.1. General

Foundation treatment in the two dams consisted mainly of deep grout curtain extending into the foundation under the whole length of the dam, and contact or blanket grouting under the core. In Mosul Dam, consolidation grouting was also used locally in the concrete structures foundations where needed to improve rock quality; as far as homogeneity was required, and to stop seepage water circulation in cracks and fissures within the rock mass [2]. In Haditha Dam, local grouting was additionally used for filling localized large cracks penetrating through bench (10) and bench (11) of the Lower Member of the Euphrates Formation between stat. 30+00 and sta. 31+00) [3]. In this dam, the drainage system consists of vertical relief wells installed to reduce excess uplift pressure in the downstream side of the dam base while a horizontal drainage layer was constructed at the downstream of Mosul Dam base. In each of the two dams the deep grout curtain was extended beyond the two ends of the main dam forming secondary curtains of shallower depths, which were meant to cut off any seepage path that may exist due to karstification of the geological formations and stop any underground flow from outflanking the main dam and finds its way back to the downstream river channel.

As indicated in Table (1), karst forms are present in both sites, but they are of different, origin, activities, sizes and shapes. The foundation treatments at the two sites were different in as much as these karst forms and their depths had dictated, whether, in the design of these works or their extent, which is explained hereinafter.

3.2 Mosul Dam: Foundation Treatment

Grouting works in Mosul Dam were comprised of: three rows deep grout curtain under the main dam and its abutments, two rows deep grout curtain under the saddle dam and the grout curtain extensions in the left and right banks. Blanket grouting of twenty grout holes with depth varying between (10-25) meters was added under the clay core of the dam to enhance the properties of the rock mass as far as its bearing capacity is concerned, and to plug all seepage conduits, cracks and reduce its general permeability. Consolidation grouting was also used in the foundation of the concrete structures to improve the general properties of the foundation. The deep grout curtain was designed to: **1)** reduce seepage through the foundations to safe limits, **2)** enhance the dam's stability by reducing uplift, **3)** minimize the dissolution of the gypsum beds present within the Fatha Formation, and **4)** stop the development of sinkholes in future, and to fill the already existent sinkholes and cavities at the depth of foundations. The maximum design depth of the curtain at the deepest point in the river channel was (80 – 100) m. This was based on the assumption that the bottom of the last brecciated gypsum bed (GB0) under the dam which is at this depth represents the deepest limits of the karstification in this foundation. This limit was defined by the designer with what was called "Karst Line" (Figure 1). This assumption proved to be wrong and the dissolution processes continued further down in depth during the operation of the dam as revealed during the maintenance grouting program which has continued from 1987 up to the present date. Figure (1) also shows the brecciated gypsum beds (GB0), (GB1) and (GB2) in their ascending order, the fourth one (GB3) does not appear in the figure as it approach the surface further to the left at the left bank under the chute of the service structure and the flip bucket at its end, and continues further under the saddle dam, which embody the emergency spillway structure. The design criteria of the curtain under the main dam, the saddle dam and in the left and right sides extensions were treated in details in a paper on the foundation treatment of the dam during construction [4] and they are summarised in Table(2)

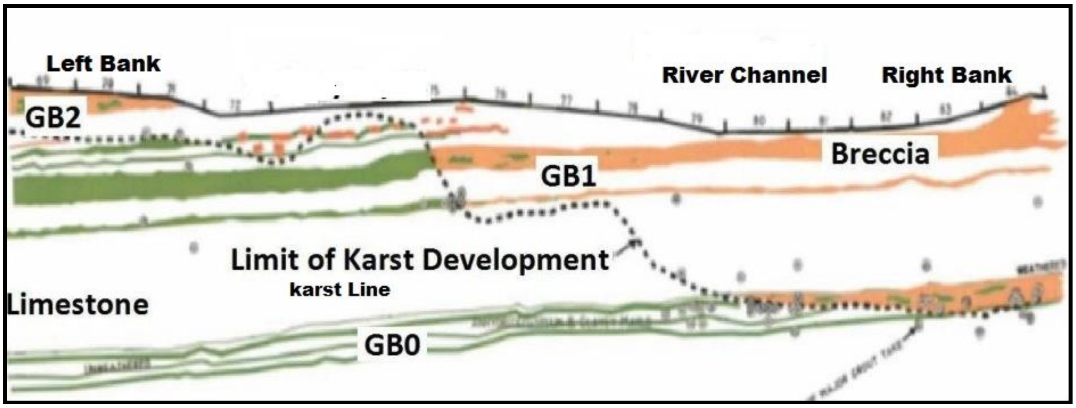


Figure 1: Mosul Dam Designer's visualization of the karst line in dam foundation [Note the existence of GB0 bellow the so called "Karst Line"

The criteria specified by the designer for the deep grout curtain were to aim at getting water tightness of 2 Lugeon at the upper part of the curtain and 5 Lugeon in the lower part of it. This could not be achieved due to the resistance of the brecciated gypsum beds (GB0, GB1, BB2, GB3) to the penetration of grouts and /or not being able to hold these grouts for a long time, in spite of using all possible combinations of grout mixes and grouting methods and procedures. To understand the behaviour of these brecciated gypsum beds one may refer to [5] to see how they start and develop. As dissolution is initiated within a cavity, joint or crack within a gypsum bed by seepage water the gradually increased flow invigorate further dissolution of gypsum and causes the enlargement of the cavities in different shapes and extents. In Mosul Dam, such dissolution in most cases starts within the interface of gypsum with the badly cracked and fissured marl and limestone beds and, furthermore clay filling is washed inside the cavity from the marly layers on top through the cracked and jointed limestone. The resulting breccias are a complex of gypsum fragments, anhydrite and limestone chips and blocks which are locked in fine clay matrix. Such structure did not respond to any type or procedure of grouting and when trials were partially successful, the brecciated gypsum beds could not hold on the grout and dissolution, piping and washing away of the filling material starts all over again (Figure 2). This type of karst may be considered as one of the worst types and should be avoided in hydraulic works if possible, or to avoid grouting it as an anti-seepage measure. Replacement of this material could be done if it is at the surface or at shallow depth, otherwise using positive cut-off such as slurry trenches or concrete diaphragm walls may provide the solution

Table 2: Parts of the deep grout curtain and its characteristics

Part of curtain	No. of Rows	Targeted Formations	Function
Extension of Left Bank From Sec. 215 to Sec.151 Total length 1560m (Sec. Length 24m)	1 Row Done from ground surface	The foundation here up to 20-30m depth is highly pervious especially the F-bed limestone	To limit seepage flow through abutment from Gebel Taira anticline to the end of saddle dam
Saddle Dam and fuse plug From Sec. 16 to Sec. 47 Total length 1152m (Sec. Length 36m)	2 Rows One row was originally designed but a second row was added in 1986 after appearance of springs at spillway bucket area.*	Extends through sand silt gravel deposits then in the upper marl series and finally through the fairly thick pervious F-bed limestone bed	To limit seepage to the area between the end of main dam and in the spillway area and below the fuse plug saddle dam
Main Dam From Sec. 48 to Sec. 114 Total length 2379m (Sec. length 36m)	3 Rows of vertical holes and; 2 Rows of inclined holes done from the sides of the grouting gallery. Length of these holes 25 m.** Drilling and grouting works are carried out from a concrete grouting gallery and grouting tunnel under left abutment.	The vertical holes down to 80-100 meters to penetrate all beds especially the pervious and soluble beds to reach the karsts level.	The vertical curtain to minimize seepage flow to safe limits to stop dissolution and erosion processes in all layers above karst level. The inclined holes to create a tight contact zone between the blanket and top of the curtain
Extension Right Bank From Sec. 123 to Sec. 139 Total Length 408m (Sec. Length 24m)	2 Rows from Sec. 123 to Sec. 132, and 1 Row from Sec. 132 to Sec. 139		Limits seepage flow around right abutment. But It did not extend enough neither laterally nor in depth to reach low pervious rock. The length of holes reached more than 100 m.

*These springs appeared in February 1986 at the filling of the reservoir for the first time and resulted from the seepage under the dam and passing under the spillway foundation and threatened its stability. Therefore it was necessary to strengthen the curtain here.
** The inclined holes were meant to improve contact between the blanket grouting and the top of the grout curtain.

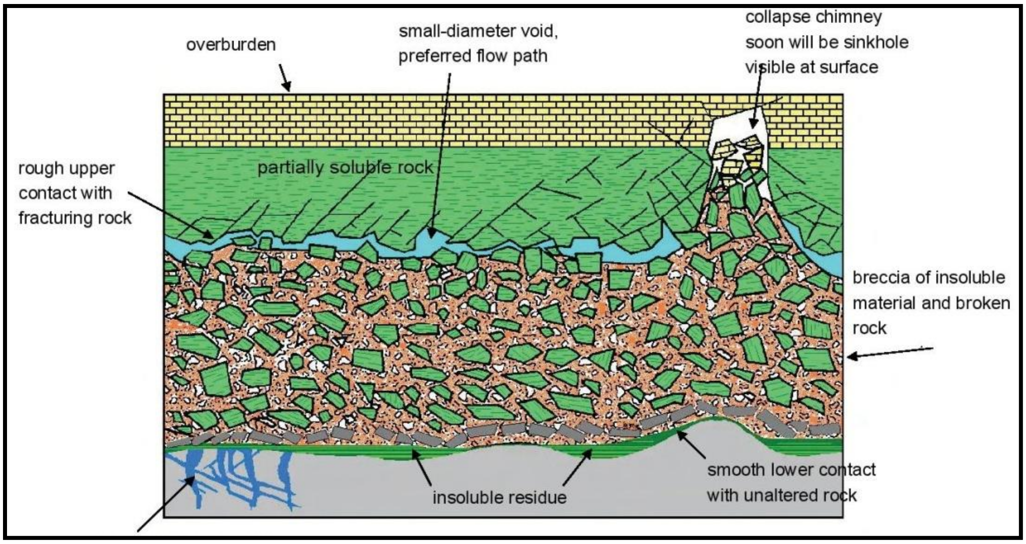


Figure 2: Brecciated gypsum beds' formation processes [5]

It is worth noting that one Lugeon unit is equal to a permeability of 1.3 x 10^{-5} cm/sec. All efforts to get a good curtain failed before impounding the reservoir and there were what was called "open windows" during the impounding and afterwards that resulted in a worsening situation leading to the intensive maintenance grouting program which is continuous up to the present date. During the filling and operation years, many sinkholes developed on the ground surface; first, at the right rim of the reservoir, and then followed by other sinkholes in the right bank, and later on in the left bank (Figure 3), shows the sinkhole at the left bank which appeared on 15th of February 2003.

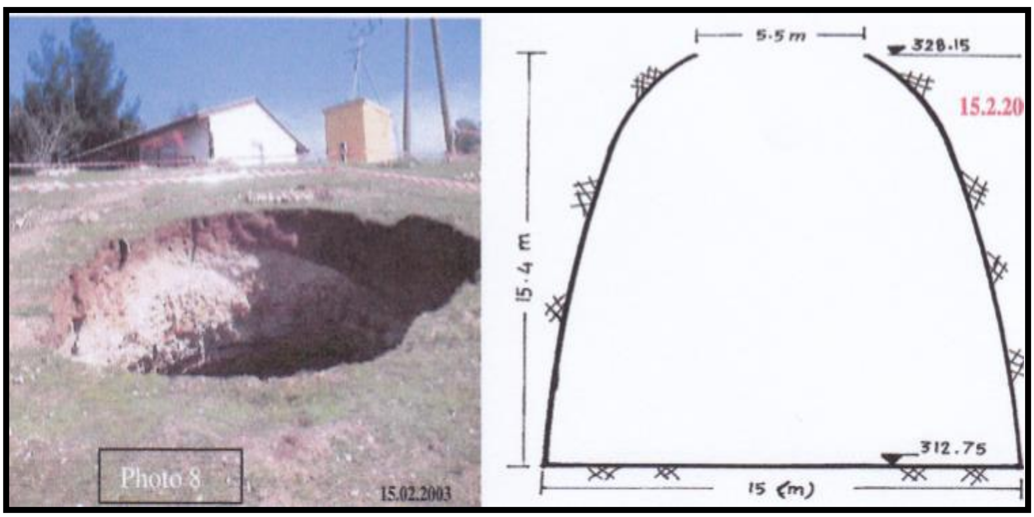


Figure 3: The sinkhole on the left bank close to the downstream of the dam, appeared on 15th February 2015

These sinkholes were all close to the downstream of the main dam. Sinkholes were discovered also afterwards in the floor of the reservoir very close to the dam during a bathymetric survey performed in 2013 [6], which showed the formation of numerous dissolution sinkholes, and indicating direct link between the reservoir and the ground water aquifer extending all around the dam and connecting to the downstream. In 2005, a Panel of Experts postulated in a study on Mosul Dam that this dam could fail due to karsts development in the form of sinkholes with limited or no warning time [7], [8]. In 2006, another Panel of Experts decided that the formation of these sinkholes represent such a hazard to the dam that it threatened it with immediate collapse and recommended in 2007 to reduce the maximum operation water level from design elevation 330.00 m (a.s.l.) to elevation 319.00 m (a.s.l.).

These findings were discussed in details in a recent paper [9] on the subject. The miss-interpretation of the geological data obtained during the investigations has led to misunderstanding of the nature and depth of the karsts phenomena in Mosul Dam foundation, which had caused the adoption of the wrong treatment. This conclusion was clearly spelt out in another paper recently published by the authors [10]. Our opinion is that a positive cut-off in the form of a concrete diaphragm wall should have been used instead of the deep grout curtain. The seepage and gypsum dissolution continues up to date, and in our final appraisal of the present safety condition of the dam we may borrow from the medical literature the term “Malignant” to describe the karst forms and their depths in Mosul Dam foundations in that it is most difficult to treat and cure and threatens the collapse of the dam.

3.3 Haditha Dam: Foundation Treatment

The geological conditions at Haditha Dam site and its surrounding played an important role in the design of the foundation treatment as one would expect. The geological formations here are older than those in Mosul dam, and the karst forms are of different origin. The karst forms, actually occur in the limestone of the Euphrates and Ana formations in Haditha Dam rather than gypsum beds and brecciated gypsum beds in the Fatha Formations and even in the Euphrates Formation below it in Mosul Dam. The foundation treatment in Haditha Dam consisted of a main deep grout curtain under the earth fill dam and power house- spillway combined structure, wing grout curtains at the right bank and left bank, in addition to filling grouting of large voids (fractures, caverns, karst cavities) with area grouting in limited zones of the central part of the dam foundation [3]. Vertical relief wells were installed at the downstream toe of the dam as part of the treatment to prevent building up of uplift pleasure on this side by drainage. The main grout curtain was performed between stations DM.5+75 and DM. 95+14 making its total length 8939 meters. The left bank extension was constructed between DM. 94+80 to DM. 131+ 00 (i.e. 3620 m long), while the right bank extension was done between DM. 0+00 to DM. 97+00 making its total length 9700 meters. The objectives of the main curtain under the dam and the powerhouse- spillway combined structure were to decrease seepage losses and provide seepage stability of the foundation, lower seepage line at the downstream side of the dam foundation and reduce uplift pressure. This was achieved jointly with drainage by using vertical relief wells [11]. There was no question of severe dissolution in Haditha Dam foundations similar to the case in the foundations of Mosul Dam; this is attributed to the fact that the dissolution rate of the limestone is much lower than that of the gypsum prevailing in the Mosul Dam. Scientific literature indicates that solubility of gypsum at 20 C° is two orders of magnitude greater than the solubility of $CaCO_3$, which is the major mineral constituent of the limestone [12]

Under the main dam and power station- spillway structure, the curtain was constructed down to penetrate the Euphrates and Ana formations completely, and to (5 – 10) m deeper into the less karstified and less permeable rocks of the Baba Formation. The values of the coefficients of permabilities of the various formations are given in Table (3) in meters/ day listed from the surface downwards [3]. These values are converted in this paper to centimetres/ sec and shown in the same table. The depth of this curtain reached up to 100 m and generally corresponded to 1.5H (H is the dam height at the point under consideration). Normally, this rule of thumb is used often for small dams and when there are no geological problems within such depth, but generally speaking geological conditions are the governing factor in selecting the curtain depth in the case of difficult or troublesome geology. Figure (4) shows the lower limit of the deep grout curtain and the Formations it penetrates. It must be read in conjunction with Table (4) which gives the legend for these Formations and their description.

Table 3: Values of the Coefficients of Permeability of rock formations in Haditha Dam Foundations from top to bottom

Formation	Permeability Coefficient m/day	Permeability Coefficient cm/sec	Remarks
Alluvial Deposits	**0.5-50**	**$6x10^{-4}$ - $6x10^{-2}$**	**Low to High**
Lower Fars 1	**0.2- 386**	**$2.3x10^{-4}$ – $4.5x\ 10^{-1}$**	**Low to Very High**
Lowe Fars 2	**1.0- 5.0**	**$1.2x10^{-3}$ – $6x10^{-3}$**	**Moderate**
Upper Euphrates	**0.5- 5.0**	**$6x\ 10^{-4}$ – $6x10^{-3}$**	**Low to Moderate**
Midde Euphrates	**0.01- 0.4**	**$1.2x10^{-5}$ - $4.7x\ 10^{-4}$**	**Very Low to Low**
Lower Euphrates	**0.3- 2.0**	**$3.5x10^{-4}$- $2.3x\ 10^{-3}$**	**Low to Moderate**
Ana in the river sec.	**32.5**	**$3.8x10^{-2}$**	**High**
Ana at the abutments	**0.01- 5.0**	**$1.1x10^{-5}$- $6x10^{-3}$**	**Very Low to Moderate**
Lower Baba	**< 0.01**	**< $1.2x10^{-5}$**	**Very low**
Upper Baba	**0.01-1.0**	**$1.1x10^{-5}$- $1.2x10^{-3}$**	**Very Low to Moderate**

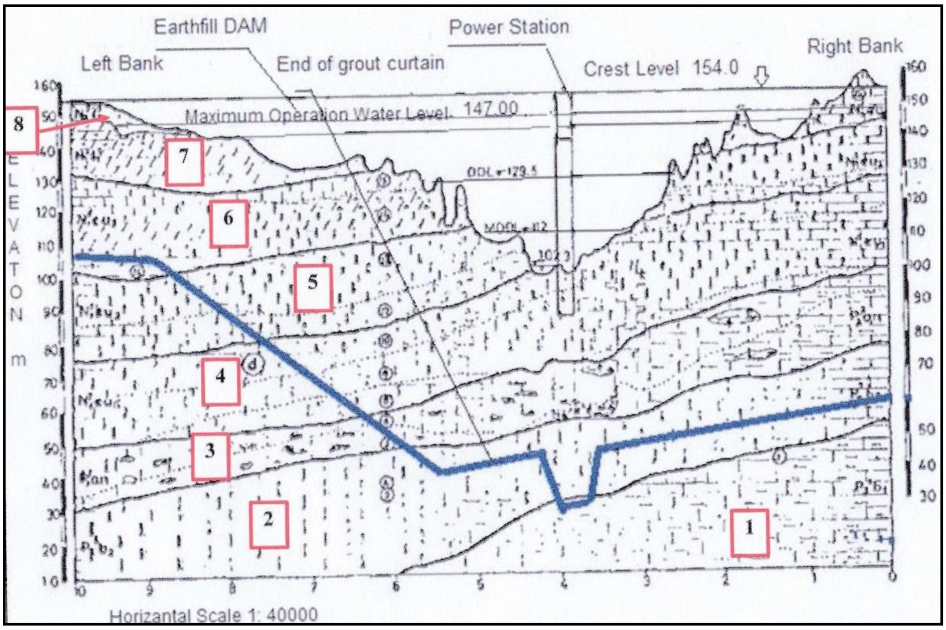


Figure 4: Geological cross section under the dam and Powerhouse- Spillway Structure, showing the lower limits of the grout curtain

Table 4: Simplified lithological column in Haditha Dam site

No	Symbol	Formation	Description
8	**$N^2{}_2f_2$**	**Fatha**	**Alternation of green marl, limestone and gypsum and red claystone appears in the upper half part**
7	**$N^2{}_2f_1$**		**Undulated limestone, very hard, thinly well bedded**
6	**$N^2{}_1eu_3$**		**Brecciated marly and dolomitic limestone, highly deformed and undulated, with lenses of green marl.**
5	**N21eu$_2$**	**Euphrates**	**Chalky dolomitic limestone, massive in the lower part well bedded in the upper part. About 90% of the apertures sinkholes are developed in thus unit, which forms the flat plains in Haqlaniyah, Hadithah, Anah until Al-Qaim**
4	**$N^2{}_1eu_1$**		**Basal conglomerate (The main reason for karstification), overlain by well bedded very hard limestone**
3	**$P^2{}_1an$**	**Ana**	**Massive and cavernous limestone, very hard, silicified and splintery**
2	**$P^1{}_1\ b_2$**	**Baba**	**Massive dolomitic and marly limestone with Lepidocyclina traces fossils.**
1	$P^1{}_1b_1$		

The Soviet geologists considered units Nos.7 and 8 as the Fatha Formation in accordance with the Geological Survey of Iraq (1974), but latter on the Geological

Survey of Iraq merged it with the Euphrates Formation. The main curtain from DM DM 5+ 75 to DM 77+75 was made of two rows of grouting holes with a distance of of 1.5 m between rows and 3 m spacing between holes arranged in staggered fashion. From DM 77+75 to DM 95+14.5 the main grout curtain and the left and right grout curtain extensions were made of single row of grouting holes with 3 m spacing. The top of the main curtain was linked with the base of the dam by means of a surcharge concrete slab (0.7 – 1.0) m thick strengthened by concrete cut-off (3 – – 5) m deep between DM 5+100 to DM 34+60 and DM 45+00 to DM 55+80. The width of the surcharge slab was 12 m in the channel section and floodplain parts of of the dam and (6 – 8) m in its banks extensions. The upper part of the curtain was widened by contact blanket grouting. The number of rows of this grouting in the channel section and flood plain parts varied between (6 – 8) rows but the number was reduced to (2 – 4) rows in the banks extensions and the depth of the blanket varied between (5 – 12) m.

The side extensions of the curtain at the two banks were designed to stop the possible concentrated seepage flows along large fissures and karstic zones in order to reduce seepage losses, and eliminate the possibility of piping and washing away of the fine material filling the karst network of conduits and cavities, which could be caused by the increase of hydrostatic pressure when the reservoir is filled

In both banks, the curtain extensions were made shallower than the main grout curtain; at the end of the right bank curtain it goes down to intersect the zone of the karstified limestone beds in the Ana Formation. The left bank curtain extension stretches down only to intersect the most permeable layer of the limestone in the Euphrates Formation and penetrates (5 – 10) m deeper than the natural ground water level [13], besides, the treatment was below 147 m (a.s.l.), which is the Maximum Operation water level.

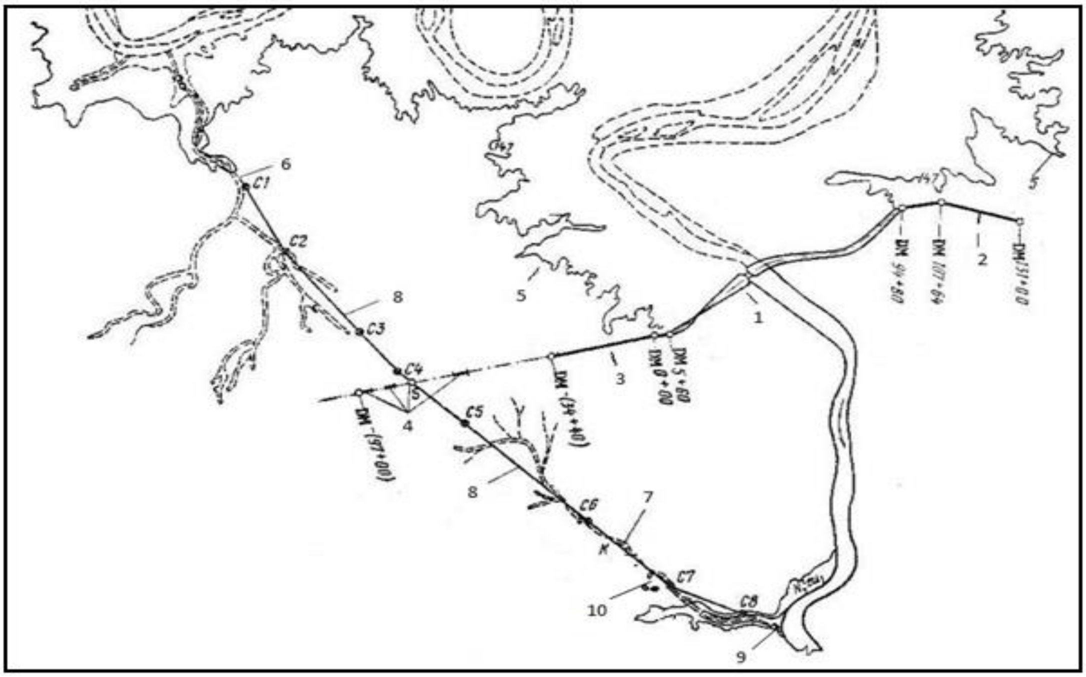
The engineering-geological conditions in the region of the right abutment side curtain are characterized by almost horizontal occurrence of various sedimentary rocks of mainly low permeability. They belong to the Upper and Lower Members of the Euphrates Formation, which overlies on cavernous high permeability limestone of the Ana Formation. Anna Formation; however, in turn overlies the impermeable limestone of the Baba Formation. At this bank it was necessary to seal the Ana Formation which dominated the depth of the curtain, reaching 85 m near the dam and 41 m at the end of the curtain.

The right bank curtain extension itself was completed in two stages. The first stage closest to the dam was only 4000 m and it was completed in 1986. The other 6260 m was completed later on after conducting additional geological investigation due to the observation of the presence of large number of sinkholes and karst cavities at that area. This investigation concentrated on a possible seepage flow between the wadi Al-Akhdar then through Wadi Tanayah, a tributary of Wadi Haglan and ending in wadi Haglan itself; very close to its confluence with the Euphrates River. Figure (5) shows the layout of all parts of the curtain and shows also the investigated line of concentrated karst forms with boreholes' locations.

The longitudinal section along the line of exploration (Fig.6) shows the investigation boreholes' locations and indicates that their depths extend below the expected seepage line between the reservoir water level of 147 m (a.s.l.) to the Euphrates River through wadi Al-Akhdar, wadi Tanayah and wadi Haglan.

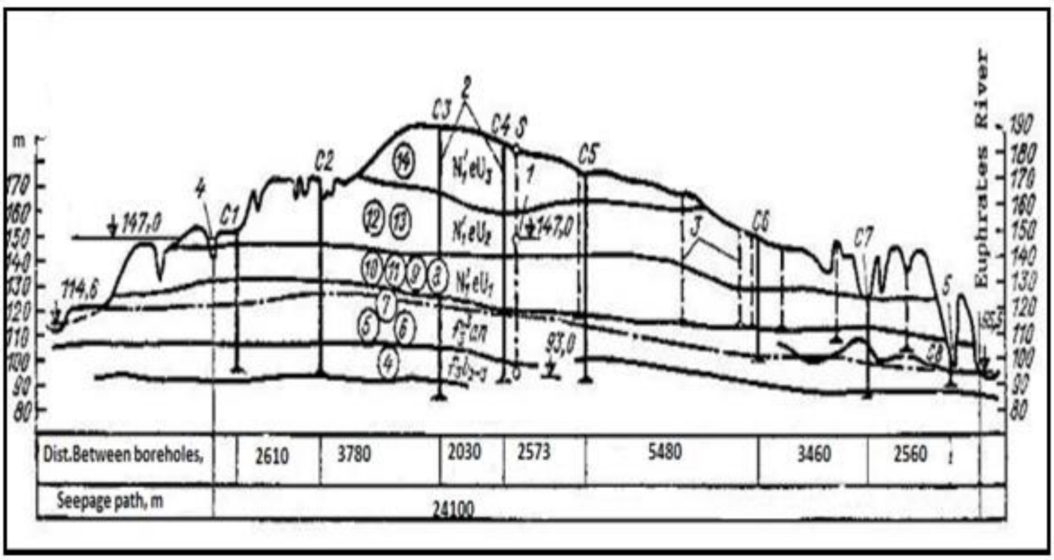
In Haditha Dam site, the geological investigation took very long time to complete, but it was done in a very careful manner; moreover, this work did not have a target time to finish as long as new findings were discovered. This manner allowed the intensification of the work whenever encountering a specific important problem. The designers showed full understanding of the nature of the foundations and put special care on any uncovered anomaly. The investigation was not limited to the site itself; but extended to large area around it. The karst phenomena were also handled with care and understanding whether, in the site itself, or around it. The grouting works took into consideration the results of these investigations in every detail. These endeavours resulted in a good overall design and a stable dam, which has not shown so far any serious defect or miss functioning. In Haditha Dam, there were two aspects; the first dedicated to the curtain grouting under the main dam and the second dedicated to the wing curtain grouting as well.

The control criteria of the completed work were set to satisfy the specified requirement in the design: that is reduction of uplift pressure and seepage quantities under the dam itself, while it aimed at blocking karst cavities and larger fissures in the side curtains. With consideration of the fact that the grouting holes of the planned side curtains intersect the same members of fine-fissured and macro-porous dolomites, so the indicator of the quality of the finished curtain is the absence in the grouted zone of large open fissures and karst cavities. It followed that the grout take per one meter of the grout hole in the side curtains would give a better indication of the grouting quality than would water absorption. Table (5) and Table (6) summarize the criteria under consideration in both the Main dam, Powerhouse -Spillway structure and side curtains on both banks. The water absorption units used by Soviet engineers were given in liter / m.m2 [13]; in this paper, these values are also shown in the same table in permeability units (cm /sec) and in Lugeon units for illustration and comparison with Mosul Dam grouting criteria.



Legend: 1) Grout Curtain in Dam Foundations; 2) Left-bank Curtain Extension; 3) Part 1 of Right- bank Extension; 4) Part 2 of Right- bank Extension; 5) Water Line of Reservoir at Elevation 147 m (a.s.l.); 6) Wadi Akhdar; 7) Wadi Tanayah; 8) Line of Exploratory boreholes; 9) Springs in Wadi Haglan; 10) Sinkholes [13].

Figure 5: Plan showing the Grout Curtain Extensions



Legend: 1) Grouted fragment of right-bank extension in part 2; 2) exploratory boreholes (C1, C2, C8); 3) Sinkholes; 4) Wadi Al-Akhdar; and 5) Wadi Tanayah [13].

Figure 6: longitudinal section along line of exploratory boreholes along the right-bank

Table 5: Control Criteria for Grouting work under Haditha Dam the Main Dam and the Left Side Extension adjacent to the Dam only

Part	Criteria				Remarks
Main Dam	Water Absorption				
	Formation	L/ (min.m^2)	Permeability cm/se	Lugeon Units	
2Row Curtain	Euphrates	0.16	$2.7x\ 10^{-5}$	2	
	Ana	0.20	$3.4x\ 10^{-5}$	3	
	Baba	0.40	$6.8x\ 10^{-5}$	5	
1Row Curtain	Euphrates	0.25	$4.2x\ 10^{-5}$	3	
	Ana	0.30	$5.1x10^{-5}$	4	
	Ana	0.20	$3.4x\ 10^{-5}$	3	
	Baba	0.40	$6.8x\ 10^{-5}$	5	
1 Row Curtain	Euphrates	0.25	$4.2x\ 10^{-5}$	3	
	Ana	0.30	$5.1x10^{-5}$	4	
Powerhouse-Spillway Structure	This work was performed by a different Contractor				
				5	In addition: maximum grout take is 50 kg/m
Side Extensions					
Left Bank 2 Row Extension	Fatha	0.16	$2.7\ x\ 10^{-5}$	2	Adjacent part to the dam only
	Euphrates	0.2	$3.4\ x\ 10^{-5}$	3	Euphrates

The right bank extension and the remaining part of the left side extension are checked according to the following values in Table (6), as can be seen, these are given in terms of grout take in kilograms per meter of the grouted interval.

Table 6: Control Criteria for Grouting Works in Grout Curtain Side Extensions

Part	Criteria: Grout take (kg/m)	Remarks
Left Bank Extension		
Remaining Part of 1 Row Curtain	**200**	**Criteria for the first part 2 Row Extension is given in previous table**
Right Bank Extension		
Stretch 1	**200**	
Stretch 2	**250**	

3.4 Summarized Comparison

In summary and comparison; the foundation treatment in each of Mosul and Haditha Dams consisted mainly of deep grout curtain extending into the foundation under the whole length of the dam, and contact blanket grouting under the core. In Mosul Dam, consolidation grouting was also used locally in the concrete structures foundations where needed to improve rock quality; as far as homogeneity was required, and to stop seepage water circulation in cracks and fissures within the rock mass. In Haditha Dam, apart from the deep grout curtain blanket; grouting was also performed at the top of the deep grout curtain, which consisted of variable number of rows and depths depending on the particular location along the dam. Local grouting was additionally used for filling localized large karstified cracks penetrating through bench (10) and bench (11) of the Lower Member of the Euphrates Formation between station DM 30+00 and station DM 31+00 [3]. In this dam, drainage system of vertical relief wells was also installed to reduce excess uplift pressure in the downstream side of the dam base. In installing these relief wells there was no fear of any dissolution of foundation material as these were mainly of limestone. Such an arrangement cannot be made in Mosul Dam; as more drainage means increased dissolution of the gypsum present there. The deep grout curtain in Mosul Dam was not successful in reducing the seepage to the limits necessary to stop the dissolution of the gypsum present in the foundations.

In each of the two dams, the deep grout curtain was extended beyond the two ends of the main dam forming secondary curtains of shallower depths.

These were required to cut off any seepage path that may exists due to the karstification of the geological formations and stop any underground flow from outflanking the main dam and finds its way back to the river channel.

In Mosul Dam, the left side extension has not been successful in sealing the foundation to the required level in spite of additional works that consisted of performing a second row of grouting holes to the original single row and also deepening the whole curtain. Seepage and dissolution of the gypsum beds continues up to now. It is a proven fact now that this seepage had contributed to the formation of the two sinkholes, which appeared at this bank close to the dam. More of such sinkholes are expected and this was one of the reasons to lower the maximum operation water level of the reservoir from 330 m (a.s.l.) to 319 m (a.s.l.) in 2006.

4 Conclusions

4.1. The foundation geology of any dam plays the most important role in the selection of the type and details of foundations' treatments. While both Mosul and Haditha Dams sites suffered from the presence of karsts; these karsts were of different origins, types, shapes, sizes and depths. In Mosul Dam site, it was of dissolution type, which was formed as a result of the high dissolution rates of gypsum beds within the foundations. In Haditha Dam site, it occurred in varying degrees in the limestone beds of the Euphrates and Ana formations in the shape of fissures, cracks and nearly isolated collapsed sinkholes. Sinkholes in Mosul Dam site are of the dangerous dissolution type which could develop quickly and appear suddenly without enough prior notice but, sinkholes in Haditha Dam site are not the same as they are of the collapse and stable closed type and they take very long time to develop which make them less dangerous. This is attributed to the fact that limestone is generally less soluble than gypsum. In both cases, deep grout curtain was implemented, but with different degrees of success. The deep grout curtain in Mosul Dam was not able to lower the permeability and reduce seepage quantities to the specified amounts compatible with the dissolution properties of gypsum rock and anhydrites, in addition the specific nature of the brecciated gypsum beds present there made such work extremely difficult and not fruitful in most cases. These beds dominated four levels of the foundations and they played a very negative role due to their peculiar nature of not being able to hold permanently the grouting materials. The end result was an inefficient curtain, which has led to the intensive maintenance grouting program that continues up to date with the constant hazard of dam failure and collapse.

In Haditha Dam, the curtain was required to seal the cracks and fissures and fill the sinkholes to get a reasonably tight foundation to reduce seepage seepage losses to lesser quantities, and to reduce uplift pressure on the downstream downstream side of the dam base, the depth and width and intensity of grouting holes were all tailored to the specific needs of all the finite reaches along the dam foundation. This was only possible as a result from the intensive and careful geological investigation works which were carried out ahead of the grouting and were repeated whenever there was doubt or an anomaly. Drainage of the under layers of the foundation was made by installing relief wells, which were drilled at the downstream toe of the dam. Generally speaking, the whole treatment was correctly designed and properly constructed and accomplished its required objectives.

4.2. The thickness of the karstified rocks in Mosul Dam site is about 300 m, whereas at Haditha Dam site is about 50 m. This large difference in the thickness of the karstified succession of rocks played also a big role in causing more difficulties in the grouting process in Mosul Dam. Moreover, in Mosul Dam site, the rocks are tilted and deformed due tectonic activities, which had increased the dissolution ability, whereas in Haditha Dam site, the beds are almost horizontal and not deformed; as they are not affected appreciably by tectonic forces.

4.3. In reflecting on the design decisions taken during planning and design stage and final performance of the foundation treatments in both dams, it can be seen how human errors of judgment can play a significant role in the success or failure of Engineering Works. Failing to understand the nature of the foundation geology and misinterpreting the investigation data led to the adoption of the wrong anti-seepage method in Mosul Dam. One alternative to the grout curtain could have been the construction of a positive cut-off in the form of a diaphragm wall. At the time of Mosul Dam construction technological possibilities were available to construct such a diaphragm from the top surface of the foundation which would have been of much shorter depth than if it is attempted as would today from the dam crest, but it would have meant extending the completion period by another year. We are sure that such extension of time would have been acceptable by everyone including the owner, have they known the consequences of failing to take such a decision at that time. In Haditha Dam, although the nature of the foundation was simpler, very comprehensive geological investigations were still needed and were done with precision and utmost care; moreover, the understanding and interpretation of these data were correct and successful. This had led to the proper foundation treatment and getting a stable dam in the end and stable dam.

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Comparative Study of Mosul and Haditha Dams in Iraq: Different Construction Materials Contribute to Different designs

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Abstract

Mosul and Haditha Dams are the two largest dams of Iraq. They were constructed in localities having completely different materials for use in the core and rip-rap. While clay for the core was abundant in Mosul Dam site it was completely missing in the other dam site. Where solid and sound limestone for the rip-rap was available in large quantities in Mosul dam only dolomitic limestone of inferior quality was there in Haditha Dam site. In Haditha Dam, the use of the only available material for the core was mealy dolomite and it was used successfully, but the addition of an asphaltic concrete diaphragm was necessary to improve impermeability of this core. The use of this material for the first time in the world was a challenging task to the engineers, who could not have done this without carrying out first comprehensive field and laboratory research. Even sand and gravel materials were available in the two sites in ways that borrowing and using them required completely different techniques in the two sites. In the shells of Mosul Dam, they were placed and compacted after minimum treatment, filter material; however, had to be sorted out and mixed in screening plants. In Haditha Dam site dredging of the materials from the river channel resulted in adopting a hydraulic filling procedure in building the shells and eliminating the filter zones. Good quality limestone was used in Mosul Dam rip-rap but the missing of such rock quality in Haditha Dam dictated the use of concrete facing protection placed by mechanical means. The different construction materials used in the two dams resulted in producing two contrasting designs which had also required different

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methods of construction and to some extent different machinery. In Mosul Dam, everything followed the standard and classical methods and specifications. In Haditha Dam new specifications were necessary for many items of the work. In both cases, the engineers were successful in producing good designs which were safe and functional.

Keywords: Mosul Dam, Haditha Dam, Clay, Mealy Dolomite, Diaphragm, Hydraulic Fill

1 Introduction

In this paper, two examples are given depicting two different dam designs. The difference is attributed to the basically different available construction materials at the two sites. Moreover, the use of these materials required; the use of completely different technologies, different completion time was needed, and to be sure resulted in a different unit cost per cubic meters of stored water. The two dams are the Mosul Dam on the Tigris River and Haditha Dam on the Euphrates River, both in Iraq.

In Mosul Dam, there were abundant quantities of clayey materials from nearby borrow areas and plenty of sandy gravel which could be easily quarried from the floodplain deposits or conglomerate from the terraces at the river banks very close to the site. This was useful in adopting a conventional design of the cross section with all that was required for a very low permeability core and more permeable sandy gravely shells in addition to the required filter materials for the transition zones at the upstream and downstream faces of the core, and the horizontal drainage blanket at the downstream side. Good quality limestone from the Euphrates Formation outcropping at very close proximity lent itself for good use in the upstream rip-rap and downstream slope protection. Construction procedures were standard and specifications of the earthworks were very similar to those used in similar large and important earth fill dams. No new research work was needed to investigate the characteristics of the materials and only standard laboratory tests were used to identify the materials and to carry out quality control during construction.

In Haditha Dam, the case was completely different. No clays were available available at the site or at any reasonable distance from it. Sandy gravel materials were available in large quantities at the river channel and the banks of the river but at some distance at the upstream. Dolomitic limestone was available from the Euphrates Formation but the quality was questionable and could not be used for upstream rip-rap, although it was sufficient for use in the protection of the downstream slope of the dam. The extraction of these materials, transporting and placing them in the dam body required different technologies than those utilized in Mosul Dam. Mealy dolomite derived from the Euphrates Formation which was used in the core was a completely new material in dam construction. No previous experience of using it as a major construction material in dams was known worldwide, only a small portion of few meters' height was constructed in the upper upper level of Tabqa Dam in Syria [1] Tabqa Dam was designed also by Soviet engineers the same as Haditha Dam. Even with its proved other qualities, dolomite dolomite by itself could not give the required level of low permeability and an asphaltic concrete diaphragm had to be used in conjunction with it to satisfy the anti-seepage criteria required for the core.

This paper aims at comparing the two dams from these perspectives and highlights the innovative use of dolomite. Before doing this however, an overview of the two dams must be given for illustration and to lay the ground for further discussion.

2 Mosul Dam: an overview

2.1 General

The construction of Mosul Dam was started on the 25th January 1981 and completed on 24th July 1986. Studies and investigation works were carried out by different consultants who had selected different sites and prepared different designs from 1951 until 1978. The present selected Mosul Dam site was the subject of the last investigation campaign, and the contract for preparing the planning report, the final design and tender document were awarded late in 1978 and these works were completed in 1980 only to start construction immediately afterwards. The Mosul Dam scheme, in fact, comprises three associated works which augment each other aiming at the best utilization of the water and power resources. The main earthfill dam is the main element in the scheme, the low earthfill reregulating dam at 8 kilometers downstream of the main dam was planned and constructed to reregulate the flows from the main dam power station to satisfy daily irrigation demands downstream and generate base power at the same time.

The Pump Storage power station, which is the third element in the scheme, is to generate peaking power and it was located at the core of Butma South anticline at the right abutment of the main dam; it drew its water supply from an intake in the reregulating reservoir just 2 kilometers downstream of the main dam. At the start of the planning stage borrow areas for possible construction materials were investigated. Sources for clayey materials, sand and gravel and limestone were located and this investigation showed the availability of these materials in good quantities; which lead to define the design features of the project. The designs of both the main dam and the re-regulating dam followed conventional procedures and used the accumulated experience worldwide on this type of dams. Only the main dam however, is discussed here being a large dam according to the International Commission of Large Dams (ICOLD) and comparable to Haditha Dam.

2.2 Design Features

The site of the Mosul Dam was selected as the most suitable location to serve the three Jazira irrigation projects. It also offered the largest reservoir volume from topographic considerations. The geological conditions of the site did not seem to have received enough considerations [2]. All the alternative sites that were investigated before, including the present one, suffered from the presence of soluble gypsum rock, but all consultants had thought that grouting could solve the seepage problem in the foundations and stop dissolution. The designed earthfill dam consists of two parts. The first part is the main high dam closing the Tigris river channel together with its right and left abutments. While the right abutment was located on the plunging part of Butma South anticline, the left abutment extended on the left bank till the right abutment of the spillway head structure. The second part of the dam is the low saddle dam extending from the left abutment of the spillway head structure following E-W direction toward Jebel Terra anticline. The Total length of the dam, spillway head structure and the saddle dam is about 3600 meters out of which 100 meters is the width of the spillway head structure. The emergency spillway structure is located within the saddle dam on the left bank and has a width of 400 meters. The powerhouse is constructed on the right bank downstream from the main dam. Four steel-lined tunnels deliver the water to the powerhouse below the earthfill dam. Similarly, on the same bank, two steel-lined tunnels were constructed to be integrated parts of the bottom outlet structure. This structure was intended for emptying the reservoir in emergencies and for carrying repair works on the dam. These tunnels were also used for river diversion during construction; (Figure, 1) illustrates the general layout of the Mosul Dam.

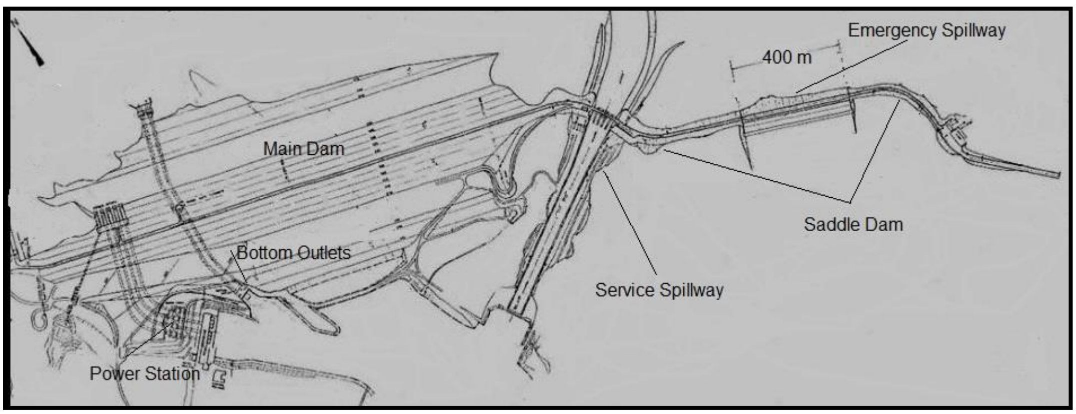


Figure1: General Layout of Mosul dam

The maximum height of the dam is 113 meters from the deepest point in the river channel; this height was obtained based on the topographical and hydrological consideration to get the maximum storage of the reservoir. Accordingly, the crest level was fixed at 341.00 meters above sea level m (a.s.l.).

To cope with future settlement, the crest was super elevated by up to 2.0 meters, depending on the height of the dam at the location of super- elevation. The maximum crest elevation at the end of construction was thus 343.20 m (a.s.l) [3], hydrological conditions at the dam site, and design water levels of the reservoir are detailed in Table (1):

Table 1: Hydrological Parameters and Reservoir Water levels of Mosul Dam

<table>
<tr><th colspan="4">Hydrological Conditions at the Dam Site</th></tr>
<tr><th colspan="2">Description</th><th colspan="2">Remarks</th></tr>
<tr><td>Catchment Area</td><td>54400 km^2</td><td colspan="2" rowspan="5">Mosul Dam is the 2nd largest storage dam on the Tigris. The other dam is Ilisu dam in Turkey. Other smaller dams are built on the river tributaries in Turkey also. These figures are expected to decrease considerably after the Ilisu Dam operation and the full development of the (GAP) irrigation project in Turkey</td></tr>
<tr><td>Total Annual Runoff</td><td>Billion m^3</td></tr>
<tr><td>Maximum</td><td>43.400</td></tr>
<tr><td>Mean</td><td>21.100</td></tr>
<tr><td>Minimum</td><td>11.700</td></tr>
<tr><td>Mean Annual Discharge</td><td>569 m^3/sec</td><td colspan="2">Reference [4]</td></tr>
<tr><td>Maximum Design Discharges</td><td>m^3/sec</td><td colspan="2" rowspan="4">Reference [3]</td></tr>
<tr><td>PMF</td><td>27000 m^3 /sec</td></tr>
<tr><td>P = 0.01%</td><td>15000 m^3 /sec</td></tr>
<tr><td>P = 0.1%</td><td>12000 m^3 /sec</td></tr>
<tr><th colspan="4">Storage and Operation Water Levels</th></tr>
<tr><th>Description</th><th>Water level m (a.s.l.)</th><th>Storage m^3</th><th>Remarks</th></tr>
<tr><td>Normal Operation Water level</td><td>330</td><td>11.11×10^9</td><td>This level was reduced in 2006 to 319 in order to reduce gypsum dissolution and formation of sinkholes downstream of the dam [5]</td></tr>
<tr><td>Maximum Operation Water</td><td>335</td><td>13.13×10^9 Capacity for flood routing between level 330 m (a.s.l.) and 335 m (a.s.l.) is 2.03×10^9</td><td>This level is reached in routing the 0.1% design flood.</td></tr>
<tr><td>Maximum Flood Water Level</td><td>338</td><td></td><td>At this level, the earthfill part of the Emergency Spillway collapses and its operation will be initiated.</td></tr>
<tr><td>Lowest Operation Water Level</td><td>300</td><td>2.95×10^9</td><td>This is the minimum water level required for Power Generation. A lower level of 270 m (a.s.l.) can still be attained by using the bottom outlets. This level is the top level for sediments accumulation.</td></tr>
</table>

The design and construction of the earthfill dam followed classical methods and specifications based on the current worldwide practices. The dam profile is traditional; provided with central core supported by massive shells. On both the upstream and downstream sides wide berms were placed to provide additional stability to the profile, due to the presence of very thin and weak clay layers in the foundation rock. The core is separated from the downstream shell by two filter layers, one is a coarse filter zone and the second is fine filter zone, and a drainage layer. Their purpose is to prevent erosion from the core and safely drain off any seepage quantities passing through it. As a horizontal blanket, the drain extends at the base to the downstream shell and underneath the toe weight to the downstream in order to prevent pore pressure build-up in the downstream shell. Also on the upstream side, the core is separated from the shell by a filter layer. In the case of cracks potentially forming in the core, materials from this filter will be transported into such cracks, initiating thereby self-healing processes. Because the toe weights consist of a material of low permeability fill of random nature, they have therefore a a horizontal drainage blanket at the base. The upper part of the upstream shell located above the toe weight is protected by a layer of rip-rap against wave action. The downstream face of the dam and the downstream slope of the toe weight are covered by a layer of slope protection material of crushed stone in order to prevent erosion by rainwater.

The crest of the dam is covered by a thick cap consisting of large boulders of various sizes and zoning (1 to 10 tons) from elevation 330.00 m. (a.s.l) upward to protect from airstrikes and this crest has a width of 10 meters. This protection was called the "Blasting Cover". The design of this blasting cover followed the outlines of such designs in Norway which is a unique feature in earthfill dams, and it was added due to the threats of the Iran-Iraq war at that time. The outer slopes of the shell were 1: 2.5 below elevation 330.00 m. (a.s.l) and 1: 1:73 above this level, which gave a maximum width of dam base of 650 meters in the river section. A typical cross-section of the dam at the river channel is shown in (Figure 2).

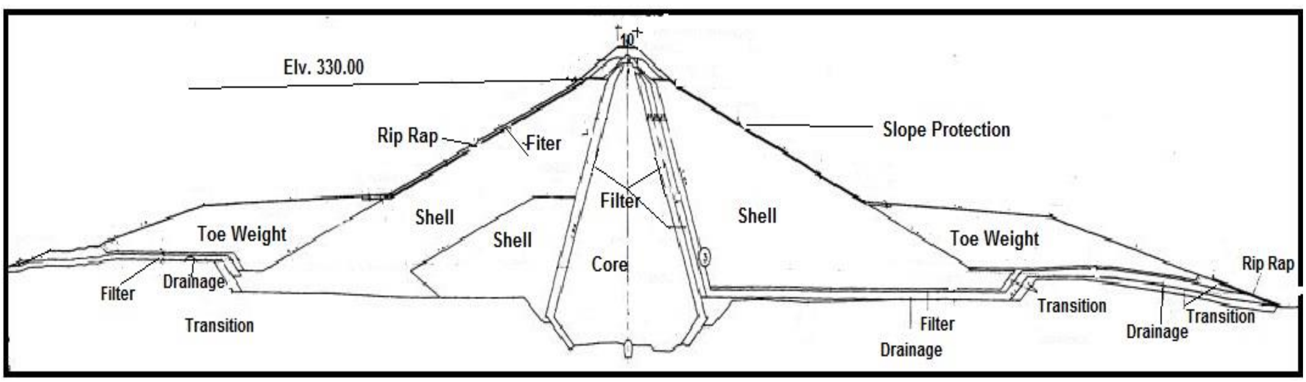


Figure 2: Typical Cross Section of the Main Dam at the River Channel (St. 2+400).

The maximum width of dam base is 650 meters and the maximum height of earthfill is 113 meters, Figure (2) does not reflect the actual dimensions of the dam as vertical and horizontal scales used are not the same, but it shows the actual disposition of materials in the cross section .The large toe berms showed in Figure (2) have their top level at elevation 290 m (a.s.l.) and were not part of the original design but they were added later on during the detailed design stage required for construction. During the foundation excavation of the grouting gallery, the intake structure for the power tunnels and the PowerStation itself, very thin clay layers of (10 -20) cm thickness were recognized in these excavations in four horizons. These layers extend over long distances and they are parallel to the other rock layers indicating their sedimentary origin, it is clear that they were the product of successive cycles of sedimentation [3]. Moreover, they showed marked signs of slickenside especially in the right bank which indicated the occurrence of displacement along them as a consequence of faulting or past seismic activities. The excavations in the foundations were deepened to remove some of them but could not discover or remove other potential ones. A new set of stability calculation for the dam was made recognizing the presence of these layers and using the sliding block analysis and Sarma method for the stability analysis of embankments and slopes [6]. The calculation indicated critical sliding conditions under seismic loading, which required the addition of the mentioned toe berms as additional weights to ensure stability. No special specification was required for the quality of the materials in these toe weights whether on limits of compaction or permeability, as the main objective of using them was to get the extra weight. Random fill materials were mainly of surplus excavated foundation materials and other waste materials.

2.3 Construction Materials and Methods

The total volume of the used earthfill materials was 37.70 million m^3, which included 6.01 million m^3 of clay for the core, 19.88 million m^3 gravels and sands for the u/s and d/s shells, 6.37 million m^3 for the random fill in the toe weights at the upstream and downstream of the section. Another 4.45 million m^3 of graded sand and gravel filters were also used in the filter zones and drainage layers. Additionally, limestone was used for the slope protections and riprap with a total quantity totaling 0.97 million m^3. The detailed properties of the materials were as follows:

<u>Core material</u>

The core material is sandy silt, which was borrowed from flood plain deposits along the river. It was placed at optimum moisture content in layers of 25 cm and compacted by sheep foot rollers to give at least 95% of the maximum dry density. The geotechnical properties of the clay core material are shown in Table (2):

Table 2: The Geotechnical Properties of Clay Core Material.

Property	Value
Classification	CL
Liquid Limit (LL)	38.6 - 43.6 %
Plastic Limit (PL)	21.1 - 21.5 %
Plasticity Index (PI)	17.1 - 22.5 %
Maximum Dry Density (γ_{d})	17.0 kN/m^3 (average)
Moisture Content, as placed	19.7 % (average)
Permeability coefficient (k)	1.8 x 10^{-6} cm/sec
Cohesion (C)	50-60 Kpa [7]

Shell Materials

For the shells, river alluvium and processed conglomerate from river terraces were used. The river alluvium was processed to remove excessive fines before it was used. The other material was used without treatment even with the presence of sulphate as bonding material to the matrix [2]. The materials were placed in layers of 50 cm thickness and compacted in 4 passes with vibratory smooth steel rollers. The properties of these materials are shown in Table (3):

Table 3: The Geotechnical Properties of shells Material of Mosul Dam

Material	Property	Remarks
Material from River Alluvium		
Percentages of fines after treatment	**< 0.88 mm=2.5 % (average)**	**Treatment was done by washing excessively fine material**
Coefficient of Permeability	**1.5 x 10^{-2} – 3 x 10^{-1} cm/sec**	**Using in situ tests**
Effective Angle of Internal Friction	**40°- 43°**	**Using large-scale triaxial tests**
Materials from Conglomerate		
Natural State	**Cemented to various degrees**	**Obtained by common excavation and ripping with occasional blasting**
Coefficient of Permeability	**4.5 x 10^{-2} – 2 x 10^{-1}**	**Using in situ tests**
Effective Angle of Internal Friction	**40°- 45°**	**Using large-scale triaxial tests**
Other Materials		
Waste Rock From Rip Rap Production		**Used in some parts instead of Alluvium and Conglomerates**

Filters and Drainage Materials

These materials were obtained by processing of alluvial gravely sand. The main filters of the dam downstream of the core were constructed as double filter, consisting of a fine filter and a coarse filter zones. The first one adjacent to the core core was of sand and fine gravel of the size fraction (0 – 7) mm, while the next one one was a mixture of sand together with fine and medium gravel. It was a blend of 20% of the size fraction (0-7mm) and 80% of the fraction size (7 – 25) mm. The drainage material represented a medium to coarse gravel blended from 20% of the size fraction (7 – 25) mm and 80% of the size fraction (25 – 150) mm.

Toe weights, Riprap and Slope Protection

The materials placed in the toe weights were random material. Only uniform sand was excluded from being used. Most of the material used was either from excavated marl from the Fatha Formation or from waste rock from blasting operations. The riprap consisted of limestone blocks of up to 1000 kg in weight. Above elevation 300.00 m (a.s.l) the riprap was coarser than below this elevation because normal reservoir fluctuates between 300.00 m (a.s.l) and 330.00 m (a.s.l). The bigger blocks were used on the dam crest in the so-called “Blasting Cover” and they were in the range of 0.5 to 10 tons. On the downstream side the slope protection materials were the same as the rip-rap, but of smaller blocks largely in the weight range of (5- 60) kg.

3 Haditha Dam: an overview

3.1 General

The Construction of Haditha Dam was begun in 1977 and it was completed in 1988. Investigation works and preparation of the general design and specifications were made by Soviet organizations in contracts with the Iraqi Government under the Treaty of Technical and Economic Cooperation between the two governments. The All-Union Institute” Hydroprojekt” of Moscow took up the guidance of the investigations, preparation of final design, detailed design and the preparation of the detailed specification of the earth fill dam. The construction works of the earthfill dam were done by the Iraqi State Organization for Dams (SOD) with technical Soviet support. The detailed design and construction of the powerhouse were awarded by (SOD) to Energoprojekt – Hydrogradnja from the previous Yugoslavia. The preliminary design of the powerhouse was done by Hydroprojekt Institute- Moscow, excavation of the powerhouse pit by (SOD) and Soviet support. The long period of investigation and construction was in lieu of procedures of similar works carried out in the Soviet Union. The usage of mealy dolomite as a core material in this dam for the first time in the world required extensive laboratory and site testing of this material to prove its suitability. The usage of the asphaltic concrete diaphragm in conjunction with the dolomitic core required conducting additional testing. These and the performance of grouting tests meant that the detailed specification could only be issued gradually according to the progress of the works. The long period of construction was also in part due to the volume of research work and testing programs that were necessary.

3.2 Design Features

The selected site of Haditha Dam is located in a narrow part of the Euphrates River few kilometers upstream from Haditha city. This selection was determined by the topographic and geological conditions and mode of occurrence of karstified rocks in the abutments of the dam in addition to the presence of local construction materials and the suitable conditions of performing the works. The total length of the dam is 9064 meters, which includes 8875 meters of the earthfill part and 189 meters of the hydropower station and spillway combined structure which is located at the river channel. The earthfill part is divided into 3310 meters in the right bank, 4985 meters in the left bank, and another 580 meters in the river channel. In Figure (3) the general layout of the dam is given.

The maximum height of the dam is 57 meters from the deepest point at the river channel, which was dictated by topographical and hydrological factors. The dam crest level, according to these considerations was fixed at 154.00 m (a.s.l.), and the width of crest was 20 m.

The Hydrological conditions at the dam site and design water levels of the reservoir are detailed in Table (4).

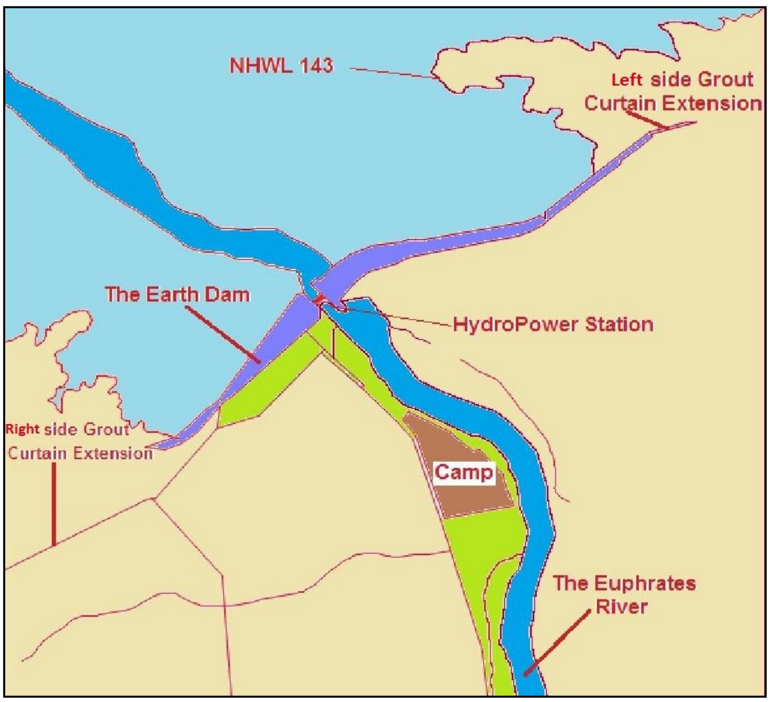


Figure 3; Haditha Dam Layout.

3.3 Materials and Methods of Construction

The design of the earth fill dam and the methods of construction used in Haditha Dam were governed by the availability of local materials at the site or close to it. The total volume of materials required for the construction of the dam was 30 million m^3. Clay for the dam core was virtually nonexistent at any reasonable hauling distance from the site, which is a marked difference from Mosul Dam site. Instead, 77 million m^3 of mealy dolomite was available in addition to about 36 million m^3 of sandy gravel materials in the river banks, and 8.8 million m^3 dolomitic limestone and dolomite rock were also available [8]. Suitable conventional type core materials were not located in sufficient quantities during preliminary stages of investigations, which lead to looking for alternative solution. The presence of large quantities of dolomite drew the attention of the engineers, who were involved in this project to this material as a possible construction material. It is believed that dolomite had never been used before in major dams as the main construction material for a vital section. In Tabqa dam in Syria; however, a portion of the dam body only of few meters high was constructed of similar material. Previous knowledge regarding the properties and behavior under different loading conditions did not exist. A challenging task was facing the engineers throughout the preparation of the planning report to determine the various properties of this new material in order to adopt it in this field of engineering, and this required the performance of extensive programs of field and laboratory investigations.

Table 4: Hydrological Conditions at Haditha Dam Site and operation parameters of the reservoir.

<table>
<tr><th colspan="5">Hydrological Conditions at Haditha Dam Site</th></tr>
<tr><th colspan="2">Description</th><th colspan="3">Remarks</th></tr>
<tr><td>Catchment Area</td><td>235000 km²</td><td colspan="3" rowspan="4">Haditha Dam is the last storage dam on the Euphrates River in a cascade of dams, i.e. Keban and Karakaya dams in Turkey and Tabqa and Tishrin Dams in Syria</td></tr>
<tr><td>Total Annual Runoff</td><td>30 Billion m³</td></tr>
<tr><td>Mean Annual Discharge</td><td>950 m³/sec</td></tr>
<tr><td>Maximum Design Discharge (P = 0. 01%)</td><td>13000 m³/sec</td></tr>
<tr><th colspan="5">Storage and Operation Water Levels</th></tr>
<tr><th colspan="2">Description</th><th>Water level m (a.s.l.)</th><th>Corresponding Storage (Billion m³)</th><th>Remarks</th></tr>
<tr><td colspan="2">Normal Operation Water level</td><td>143</td><td>6.4</td><td>Out of this storage 0.2 Billion m³ is dead Storage, and 6.2 Billion m³ is live</td></tr>
</table>

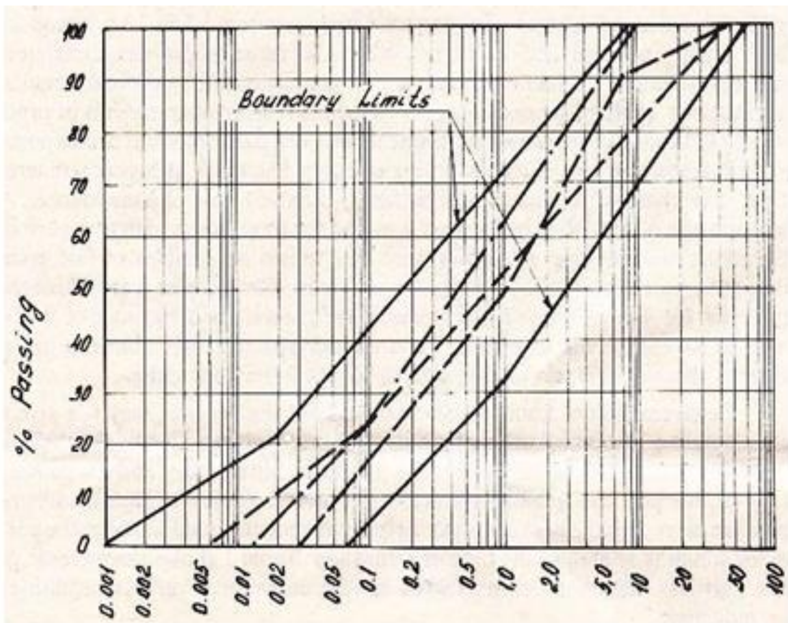
			Storage
Maximum Operation Water	147	**8.2**	**This is only realized in wet years**
Maximum Flood Water Level	152.2		**The volume between levels 147 m (a.s.l.) and 152.2 m (a.s.l.) is required to route floods up to the Maximum Design discharge of 13000 m^3/se (P = 0.01%)**
Annual firm water yield of Haditha and Habbainya reservoirs (P = 90 %)		**10.7**	

The selected dolomite material for the core is called "mealy dolomite" or what is equal of saying "powder dolomite"; the reason is due to the fact that this material is reduced to sandy powder state after excavation and treatment by mechanical means. After excavation, the material may be produced into lumps or powder. The big lumps can be then broken by mechanical means depending on the size and moisture content. Details of the mealy dolomites' properties and the tests performed at Haditha Dam site are explained in details in a paper which was presented to the ICOLD Congress in Lausanne in 1985 by one of the Iraqi research engineers at the dam site laboratory [1].

Full description of the dominant geological formations at Haditha Dam area and their details were given by a recent paper by Sissakian et al. (2018) [9]. The source of the dolomite utilized in construction was the Euphrates Formation, which is one of the dominant formations at the site and which outcrops mainly at the right and left bank of the river. This formation has varying thickness between (13 – 26 m) [1] and it was formed in four benches. The dolomite material excavated from these benches by blasting and the use of excavators had a powder form with characteristics varied between yellowish grey chalky clayey and mealy to yellowish grey and light grey detrital and mealy[10]. Detritus is defined as small loose pieces of rock that have worn or broken off, or any debris or disintegrated material.
Read more on http://www.yourdictionary.com/detritus#8UIDtxWjp68qs1f7.99.
In natural state the moisture content of the used dolomite varied between (3.5% - 12.5 %) and its bulk density between (1.55 – 2.11) tones /m^3. When excavated, completely vertical walls stayed in stable conditions that were excavated by ordinary bucket type excavators. In the laboratory it was found that the best temperature to dry up dolomite test samples taken from the construction site was 150 C° and drying period did not exceed three hours which helped in the fast progress in construction.

Shrinkage and swelling characteristics were investigated on fine-grained dolomite with particle size diameter less than 1 mm. The samples which were saturated in water for 9 days showed a swelling of 0.3% and no shrinkage was observed. Tests on larger diameter samples showed no indication of either swelling or shrinkage.

Determination of grain size distribution was not possible using mechanical action of the shakers which caused continuous increasing trend of the finer fraction due to the reduction of the bond between the particles. So, wash screening of saturated samples was used as it gave more reliable results. It was found that the increase of fine particles (less than 0.1 mm) was 5.8% when sieving dry dolomites. Wash sieving of saturated dolomite after 24 hours gave an increase to 26.9% and an increase to 32.1% in wash sieving of saturated dolomite after 48 hours. An average gradation curves for dolomite samples from the main quarry on the right bank of the river are given in Figure (4) which also shows the design envelope curves required for the construction of the dam. From this Figure it may be seen that the average percentage of fine particles which is less than 0.2 millimeters is about t 30% of the total material.



Grian size (mm)

Figure 4: Average Curves of Grain Size Distribution of Dolomite material in comparison with design envelope (Boundary) curves.

Much research work was done in the field and in the laboratory to investigate the permeability and filtration characteristics of dolomite under different conditions. Special attention was also paid to study its stability against piping. Standard laboratory experiments showed that the permeability could vary between (1.1×10^{-3} and 3.1×10^{-5} cm/sec) depending on the dolomite bench where the samples came from and the corresponding bulk densities which varied between 1.67 ton/m^3 to 1.81 ton/m^3. Different hydraulic heads where used for samples coming from different benches showing different porosity characteristics. The hydraulic heads gradients corresponding to the above range of permabilities varied between (4.00 – 1.63). Field tests were then conducted on test embankments which were constructed with controlled laid layers in order to reveal possible anisotropy. Water was poured in pits which had been dug in these test embankment to a depth not less than 3 layers. Polyethylene sheets were used to prevent water flow through the bottom of the pit. Results indicated the permeability varied between (4.3×10^{-4} – 2.1×10^{-5} cm/ sec) and the corresponding hydraulic gradients used varied between (0.58 – 0.64). Other set of tests were done to check seepage conditions at the contact of smooth concrete surface with dolomite, and also in the presence of existing seepage paths. Both sets of experiments showed that washing of dolomite particles occurred during the first 24 hours and with increasing head only, after that the water was clean. It was concluded that whatever seepage paths were there, they tend to be filled by dolomite particles due to its compaction when subjected to greater pressure in addition to the tendency of the fine washed particles to agglomerate closing these seepage paths.

In order to investigate the strength properties of the filled dolomite, standard shear tests were performed for various types of samples taken from different benches. A standard small shear ring and another larger shear ring with a diameter 305 mm and effective area 730 cm^2 were used for testing of fine and coarse fractions with samples up to 60 mm in diameter. Other samples from field test embankments were also tested in the same way. The results showed that the strength of this material was provided by internal friction. Its cohesion was very small and could be neglected; it ranged between (0.13 kg/cm^2 - 0.8 kg/cm^2). Final adopted design values were: tan $\varphi = 0.6$ and $C = 0$, $E = 10$ MPa and $KP = A.10^{-4}$ cm/sec and density of $\gamma d = 1.75$ [1, 8].

Compaction of dolomite muck in the laboratory with various moisture contents were done by the standard Proctor test procedure. Relative density tests provided practically the same results for majority of dolomite benches making it evident that the required dry density γd should be equal to or more than 1.8 ton/m^3 and the relative density should be equal to or more than 0.90. Relative density of more than 0.97 was also attained in all cases with the exception of one bench which had a maximum dry density of 1.73 $tons/m^3$.

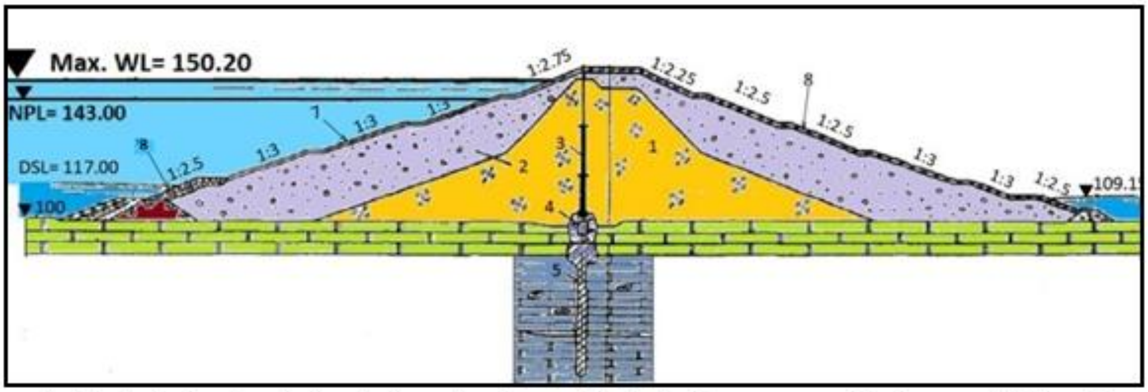
Dolomite preparation in the quarry involved the loosening by pre-splitting blasting using explosive charges. To raise the moisture content of the dolomite to its optimum value of (15% - 18 %) the surface of the blasted material was arranged into blocks for water saturation. The quantity of water and period of saturation was estimated according to the volume of material and the season. The color of the moistened dolomite would turn yellowish brown when it was wet but as it dried its color would become powdery white. Bucket excavators would then excavate the material from almost vertical faces in the quarry mixing together the material from different benches before loading. Another method was also tried by filling water into the drill holes and without blasting, but in such case the excavation became harder and big lumps should be broken down during filling by heavy machinery. Filling operations were carried out using layers of 25 cm thick and then compacted by 35 ton loaded dumpers making (8 -10) passes. The control of compaction was based on the determination of the dry density which would be judged in accordance with the above established criteria. Vibratory rollers were used later on (plain and sheep foot) which enabled the increase of layer thickness to 40 cm achieving the same values of density but with slightly higher optimum moisture content (16% - 19%).

Although testing showed that dolomite fill was stable against piping, the relatively high permeability coefficient of the dolomitic core warranted the use of asphaltic concrete diaphragm in conjunction with this core. The diaphragm was constructed as the filling progressed upwards and its centerline was located at 10 meters upstream of the centerline of the dam. It extended down to the foundation surface where it was rested on a concrete slab at the top of a short cut-off wall that formed also the grout curtain cap. The thickness of the diaphragm was 0.8 meter in the lower part, 0.6 meter in the middle part and 0.4 meters in the uppermost part. The mix design of the asphaltic concrete was obtained after a series of tests and dolomite powder was used as mineral filler. Such diaphragms were used in many dam sites in the previous USSR and much experience had been accumulated at the time of Haditha Dam planning and construction. The reader is referred for detailed information on this matter to a paper written on this subject and given as reference [11] in which Haditha Dam was cited.

A typical cross-section of the dam is shown in Figure (5). This figure indicates the details of the dolomite and asphaltic concrete diaphragm core arrangement. It shows also the upstream and downstream shells, which were constructed from the sandy gravelly materials obtained from the river banks and channel upstream of the dam by using dredgers. The material was transported by pumping using steel pipelines that were laid on the ground surface to final destination at the dam site.

The shells of the dam were constructed mainly by using hydraulic filling method, only a small portion in the left bank was constructed by placing the sand-gravel mix in dry conditions. A hydraulic fill dam is one in which the material is transported in suspension in water to the embankment where it gets placed by sedimentation and then excess water would be sluiced out by special outlet pipe. In a semi- hydraulic fill dam, the material is transported by hauling units and dumped at the edge of the embankment. It is then washed to its final position by water jets. The sorting out effect of flowing water is utilized in creating a fine-grained zone at the center of the embankment with the coarser fractions being placed at further out positions on the sides. In Haditha Dam the materials were normally deposited into blocks around the outlet pipe which sluices the water down to the collection channel after its load of material settles down. In the hydraulic filling of Haditha dam, the finer material was deposited adjacent to the dolomite core which in effect eliminated the need for the graded filter zones upstream and downstream of the core which was required in the case of Mosul

Dam.



1) Mealy Dolomite; 2) Sand- Gravel mixture; 3) Asphaltic concrete diaphragm; 4) Grouting gallery; 5) Grout curtain; 6) Stone revetment; 7) Reinforced concrete slabs protection on porous concrete drainage layer; 8) Rock mass revetment

Figure 5: Typical Cross Section of the fill dam (All levels are in m a.s.l.).

The sand-gravel materials of Haditha Dam shells were dredged from the river channel and they were characterized by considerable non uniformity. The average particle diameter varied between 0.24 to 16.7 millimeters, coefficient of uniformity ranged between 4 to 300 and higher, and the permeability coefficients of the natural mixture in the quarries were between Ax 10^{-3} to Ax 10^{+1} cm/sec. Examination of the particles size fractions in the natural quarries was necessary in order to ensure the required particle size distribution in the placed fill in the dam body using the hydraulic filling method. Required strength design parameters of the hydraulic fill of the shells were adopted and these were: tan $\varphi = 0.55$ an C=0. The dry density of the hydraulic fill was specified to be 1.85 g/cm^3 (tons/m^3) with 60% of the content being of fraction larger than 1 mm, the permeability coefficient of the fill should not be less in this case than Ax 10^{-3} cm/sec. When stability analysis of the dam was performed, these design parameters provided good slope stability under conditions of the phenomenon “Liquefaction” under the dynamic effects from earthquakes and occurrence of excess pore pressure. The accepted parameters of strength of the sand-gravel soils which were being placed in dry conditions in the dam were: tan $\varphi = 0.55$ an C=0, permeability coefficient greater or equal than Ax 10^{-3} cm/se, with the dry density of the sand -gravel mixture with 90% probability is not less than 1, 80 gm/cm^3 (tons/m^3) with an average value of 1, 90 gm/cm3 (tons/m^3) [8].

In Haditha Dam site, good quality rock for the use of the riprap layer in the upstream face of the dam was lacking. The available rock of dolomitic limestone that was found in the Euphrates Formation did not have enough strength and abrasion resistance which was a marked difference from Mosul Dam site. These factors lead the designers to adopt the use of reinforced concrete slabs as a replacement except for a small part of the upstream at the right bank which had to be protected by riprap after rigorous selection of the required rock.

The thickness of the slabs was 40 cm. Casting of these slabs was done in panels by lining machine which was specially manufactured in Germany and it was tailored to the required dimensions of the dam face. The required filter layer under this concrete facing was replaced by a 20 cm thick layer of specially manufactured porous concrete which could be cast in place taking advantage of the same lining machine prior to the placement of the concrete facing slab itself. The mix design of this porous concrete had to take into consideration the required porosity to allow the relief of seepage water during the drawdown of the reservoir at a reasonable rate. It also considered the possibility of clogging due to the migration of fine sand particles from the shell under it. Many trial mixes were investigated and tested before selecting the final approved mix suitable for such use and gap-graded aggregate was used to arrive at the required results.

In summary, the use of dolomite in the core of Haditha Dam was only possible after long and careful research work to discover all its properties and to prove its suitability for use in such an important work. Nevertheless, an asphaltic diaphragm had to be incorporated in conjunction with the dolomite in the dam core, which came to compensate for the relatively high permeability of dolomite itself. Generally speaking, the design and construction of the dam may be considered as unconventional with the use of this new material, and also due to the use of hydraulic filling dictated by the location of the borrow areas at the river channel and banks at some distance upstream.

4 Discussion and Conclusions

From the above proceeding, one point was made very clear; that is, the use of different construction materials may result in a completely different design of an earthfill dam and may require adding the use of different construction procedures. Local materials available at the site at an economical cost is one of the major elements in shaping design decisions, although it may not be the only element as seen from the case of adding huge toe weights in Mosul Dam. The examples of Mosul Dam and Haditha Dam however, are very good examples of the importance of local materials available in shaping the final design. In Mosul Dam site; good quality clay, sand and gravel were present at the site in abundant quantities, together with the availability of high-quality limestone. These materials were put to good use in producing a fine, classical and functional design of the cross section. In Haditha Dam site, the case was exactly the reverse. With the exception of sandy gravely materials at the banks and river channel, no clay was to be found anywhere at a reasonable distance from the site. Even the exposed rocks at the site were not competent enough for any sort of rip-rap works. The engineers faced the possibility of using of what was available of local materials, which were dolomite or not to build the dam at all, at a time when Rolled

Compacted Concrete (RCC) dams were not developed to the standards we know of today. Such a dam could have been built as an RCC dam after thorough treatment of the foundation with consolidation grouting to the required necessary depth under the whole base of the dam. It took however, a lot of engineering ingenuity and long and patient research to use the available dolomite as the main material for the core of this dam and to finish with a good and stable design.

The available dolomite at site was therefore studied in all respects relevant to hydraulic structures such as large storage dam. Its suitability was proven, but the relatively high permeability of its fill required the engineers to take a further step by augmenting the dolomite core with the asphaltic concrete diaphragm. Standard control tests of the compacted dolomite materials were found to apply in this case and were used. Strength parameters were studied and taken into consideration in the design. The availability of sandy-gravely deposits in the upstream river channel required the adoption of hydraulic filling procedures which eliminated the need to have graded filter zones to stop possible piping of the dolomite particles which had shown very low tendency for dispersion and to such piping.

As a final conclusion, it can be said that the designers of both dams, even with their use of different construction materials, were equally successful in producing good and stable designs as far as the embankment cross section and appurtenant structures are concerned. The design of foundation treatment however was not equally successful in the two dams. Good understanding of the geology at Haditha Dam resulted in successful treatment, but unfortunately misunderstanding the geological data for Mosul Dam foundation contributed to its current safety problems and its collapsing hazards.

In Haditha Dam, much research work was needed in order to use dolomite as core material which contributed to the long period of construction, but this has paid off in the increased knowledge of dolomite as a potential material to be used in dams. In Mosul Dam, the ample dimensions of the various elements of the designed cross-section contribute to the better stability of the dam cross section even with the known problems in its foundation due to the possibility of forming sinkholes at depth. The dam can by its present design take much more settlement, and the thick layers of filters can have very favorable effects in sealing cracks in the dam body even in the case of appreciable settlement.

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