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Geological and Geotechnical Study of Badush Dam, Iraq

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Abstract

Badush Dam is a combined earthfill and concrete buttress dam; uncompleted, it is planned to be a protection dam downstream of Mosul Dam, which impounds the Tigris River. Mosul Dam is also an earthfill dam; it is the largest dam in Iraq. The safety of Mosul Dam is a matter of debate since its commissioning in 1986. This is attributed to the geological conditions at the dam site are not suitable due to thick exposures of karstified gypsum rocks, which extend, deep down, into the foundations. Therefore, Badush Dam was planned and designed to protect the population and present infrastructures downstream of Mosul Dam, if the latter would collapse. The geological conditions at Badush Dam site are similar to those at Mosul Dam site, which means; the foundations of the dam, are located on karstified gypsum beds also. Grouting works were planned and designed, and they were partly performed simultaneously with the beginning of the construction of Badush Dam in 1988 and continued until the suspension of the construction in 1991. The constructed parts attained about (30 – 40)% of the work items. The design of the Badush Dam indicates clearly the temporary nature of its use, which is reflected in the thin inclined clay core and other embankment details. The basic design considerations of the dam were to have a dam, which is high enough to contain the full volume of Mosul Dam wave of 10 X 10^9 m^3 when routed through its reservoir, and to limit at the same time the released discharge within the capacity across the downstream reach of the river without causing flooding. In this study, we have presented and discussed the geological and engineering geological conditions; whether Badush Dam can function as a protection dam or can it be remodeled to become a normal storage dam to replace Mosul Dam.

Keywords: Collapse of Dam, Grouting, Karstification.

Introduction

Karstification is one of the main geological hazards, which endangers safety of dams when are constructed in karst areas covered by karstified gypsum and/ or limestone beds; even if the karstified rocks are in the subsurface. This will increase the problem; since the true depth of the karstified rocks will not be easily detected. This is the case in Mosul Dam, which exists upstream from Badush Dam; the former suffers from serious dissolution problems in its foundations and is prone to collapse. Another main problem in treatments of the foundations of dams constructed in karst areas may be the grouting, which is performed to protect the foundations from the dissolution of the karstified rocks (Thuro et al., 2000; Johnson, 2008; Bonaci et al., 2009; Milanović, 2011; Bonaci and Bonaci, 2013; U.S. Army Corps of Engineers, 2017).

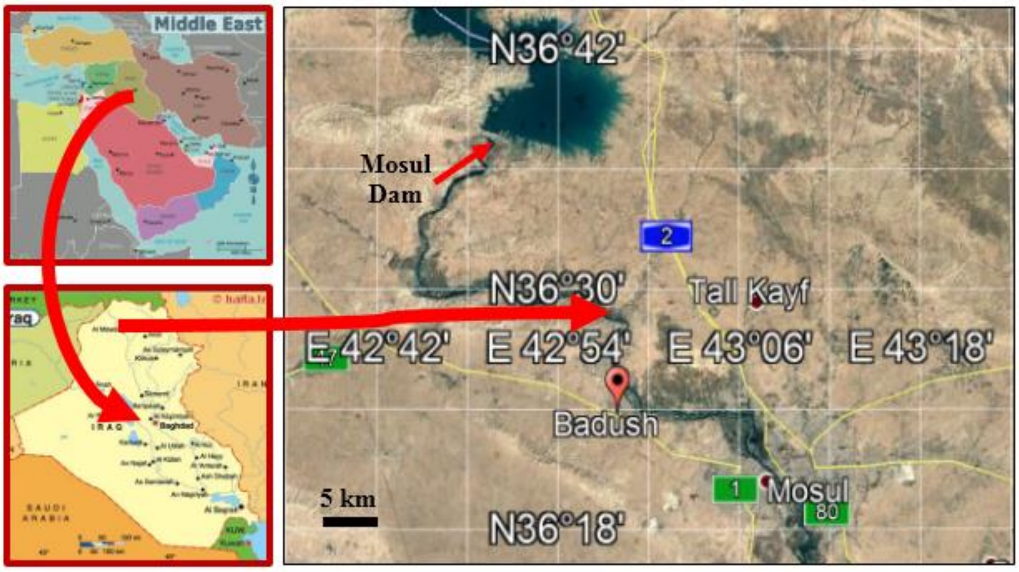
Karst areas are considered problematic sites for construction of large hydroprojects, including dams and reservoirs due to their hydrogeological complexity (Dreybrodt, 2002). Nevertheless, a large number of dams have been constructed successfully worldwide in karst areas. Although the concept of construction large dams; worldwide is benefited from the experience acquired from failure of many dams (Milanović, 2011), but Mosul Dam is apart from this concept. The dam suffers from severe leakage problems; and is considered as the most dangerous dam in the world (Al-Ansari et al., 2015a).

Filling of a reservoir causes a change of the boundary conditions within the karst aquifer (Dreybrodt, 2002). This is the case in Mosul Dam where large hydraulic gradients are created, and new pathways of flow were activated; as it was noticed from the grouting boreholes cores, which were found to be free from the grouting materials (Adamo et al., 2015). This assumption is confirmed by Dreybrodt (2002); he mentioned that the new conditions change the pattern of karstification, which is a highly dynamic process, and is likely to be accelerated under the extremely high hydraulic gradients. Consequently, even if water loss is low after first filling of the reservoir, it may increase in time.

Hiller et al. (2011), studied dams constructed in karst areas and have mentioned that "The reason for this leakage is the high hydraulic gradient imposed by the reservoir that drives aggressive water through the fracture and fissure system of the bedrock and this aggressive water dissolves the rock and increases permeability fairly fast. Thus, on the one hand water losses through enlarged fractures can become a problem for the reservoir; on the other hand, the void space itself can be a risk for the dam structure above". These conditions coincide with the existing conditions at Mosul Dam, which suffers from severe karstification problems. It would be the same case in Badush Dam.

Badush Dam is located 40 km downstream from Mosul Dam and 16 km NW of Mosul city; northwest of Iraq; constructed to impound the Tigris River flood wave (Figure 1).

Figure 1. *Location Map of Badush Dam as shown its Location in Iraq*



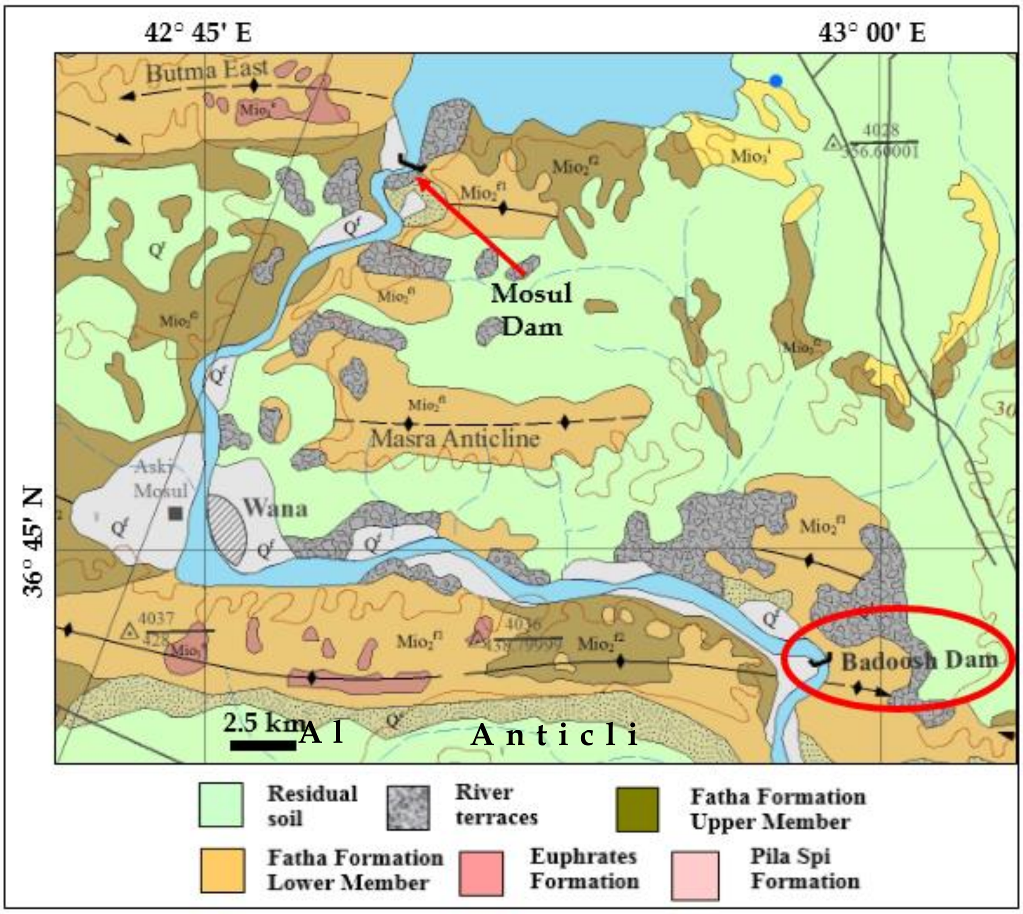
Aim of the Study

The main aim of this study is to present the geological and engineering geological conditions of Badush Dam, which is located in an active karst area. Moreover, to indicate the influence of the karstification on the foundations of the dam, which are located on karstified gypsum beds of the Fatha Formation. Besides, indicating if the dam can function as a protection dam only; as it is designed, planned and located, or can be functioning as a normal storage dam to replace Mosul Dam.

Geological Setting of Badush Dam Site

The geological setting of Badush Dam site and surroundings is briefed hereinafter, using the best available data, including: Geomorphology, Tectonics and Structural Geology, and Stratigraphy (Hagopian and Valupec, 1977; Muhi Adeen et al., 1977; Sissakian 1995; Fouad et al. 2003; Yacoub et al., 2011; Fouad, 2012; Sissakian et al., 2013). The geologic map of the dam site is presented in Figure 2. Moreover, ENERJOPROJECT (1989a and b) performed geological investigation accompanied by drilling with 83 deep drill holes; some of which exceeded 100 m in depth; totaling to 5732 m with full core recovery, testing and analyzing the properties of the recovered rock samples. However, the authors prefer to use the data acquired from the studies carried out by Hagopian and Valupec (1977), Muhi Adeen et al. (1977), Sissakian (1995), Fouad et al. (2003), Yacoub et al. (2012), Fouad (2012) and Sissakian et al. (2013). This is attributed to the fact that the latter groups are more experienced with the regional geology of Iraq and well experienced in dealing with karst forms geology and their consequences.

Figure 2. *Geological Map of Badush and Mosul Dams' Sites (After Sissakian et al., 2013)*



Geomorphology

The main geomorphological units with their enclosures are briefly mentioned hereinafter.

Units of Alluvial Origin

Flood plain and river terraces are well developed at the dam site and along both banks of the Tigris River. The sediments of both units are used in the construction of the dam.

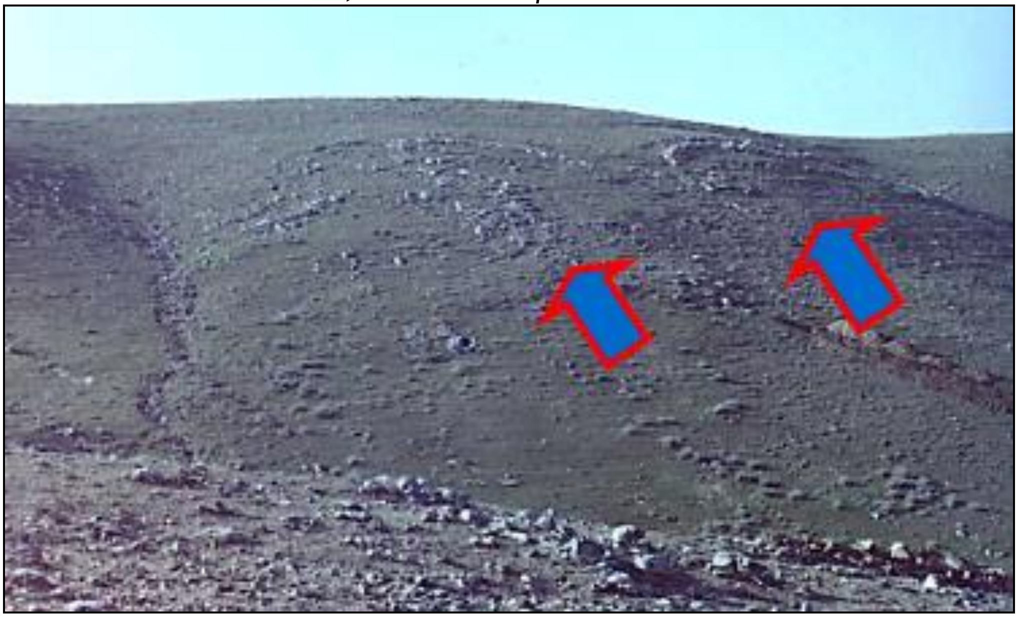
Units of Structural – Denotational Origin

The depositional and erosional glacis are rich in gypsiferous cement. Also anticlinal ridges and flat irons are well developed in the Fatha Formation.

Solution Units

Sinkholes of different shapes, sizes and activities are well developed in both the Euphrates and Fatha formations. Due to very active karstification, which has dissolved the gypsum beds, 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 (Figure 3).

Figure 3. *Limestone Beds Showing False Dipping towards Subsurface Karsts within the Fatha Formation, 15 km South of Badush Dam*



Tectonics and Structural Geology

Badush Dam is located on Alan anticline; it is 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 (Fouad, 2012). Alan anticline is a double plunging anticline with almost E – W trend; the southern limb is steeper, and the eastern plunge is east of the Tigris River, i.e. east of Badush Dam (Figure 2).

Stratigraphy

The exposed geological formations and main Quaternary sediments are briefed hereinafter and presented in Figure 2.

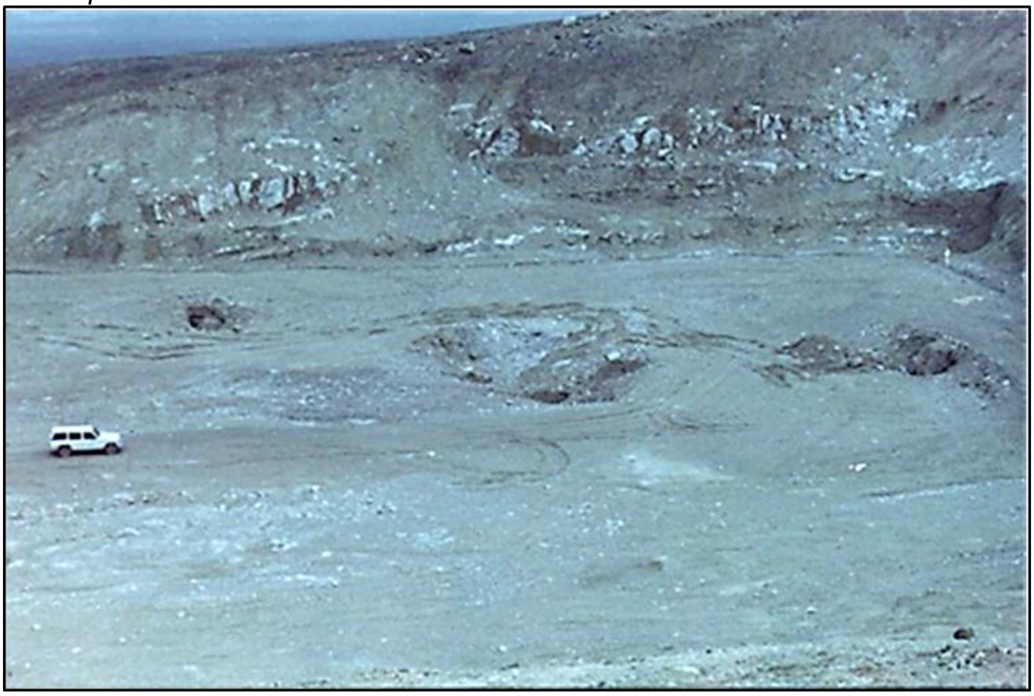
Euphrates Formation (Lower Miocene)

The formation is exposed at 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.

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. In the Upper Member; however, reddish brown claystone appears in the cycles. The gypsum and limestone beds are highly karstified (Figure 4). The thickness of the formation ranges from 117 m at the left bank to 300 m at the right bank.

Figure 4. *Karstified Gypsum Beds, in an Industrial Site South of Badush Dam Site, about 15 Km. Note the Karstified Gypsum Beds (in White Color) Along the Rims of the Site and the Sinkholes in the Floor*



River Terraces (Early Pleistocene)

The terraces are accumulated in different parts, along 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. The thickness ranges between (5-8) m.

Residual Soil (Holocene)

The residual soil covers large parts of the surroundings of Badush Dam (Figure 3). It is reddish brown clayey soil with rock fragments. In areas covered by the Fatha Formation, the residual soil is gypsiferous.

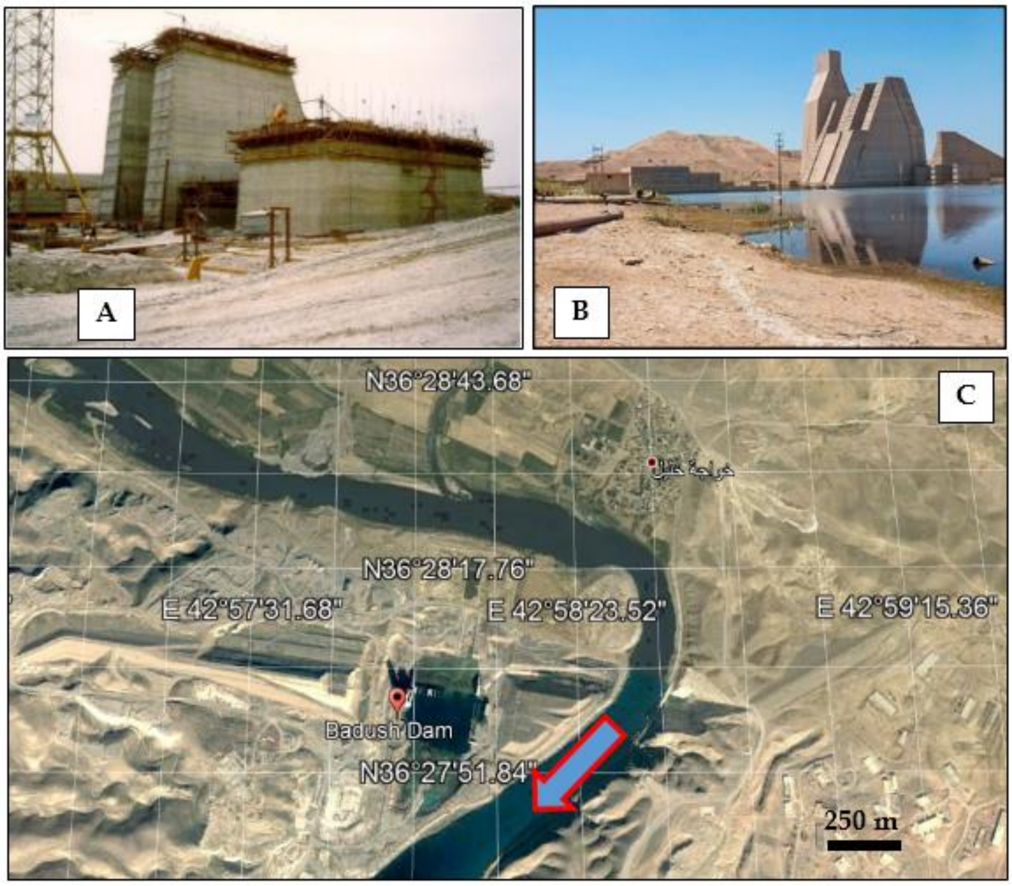
Flood Plain Sediments (Holocene)

The flood plain sediments are developed along both banks of the Tigris River; locally in two levels. The sediments consist of sand, silt and clay, locally are gypsiferous. Large quantities of the flood plain sediments were used as construction material (aggregate) in different parts of Badush Dam.

Engineering Characteristics of Badush Dam

Badush Dam is a combined earth fill and concrete buttress gravity dam; not finished yet (Figure 5); constructed on the Tigris River. The dam's designed main purpose is to provide protection from the failure of the Mosul Dam, which is located 40 km upstream and suffers from severe karstification problems in its foundations.

Figure 5. *Badush Dam* a) *The Concrete Part during Construction* b) *Abandoned Concrete Part of the Dam* c) *Google Earth Image Showing the Constructed Parts of the Dam*



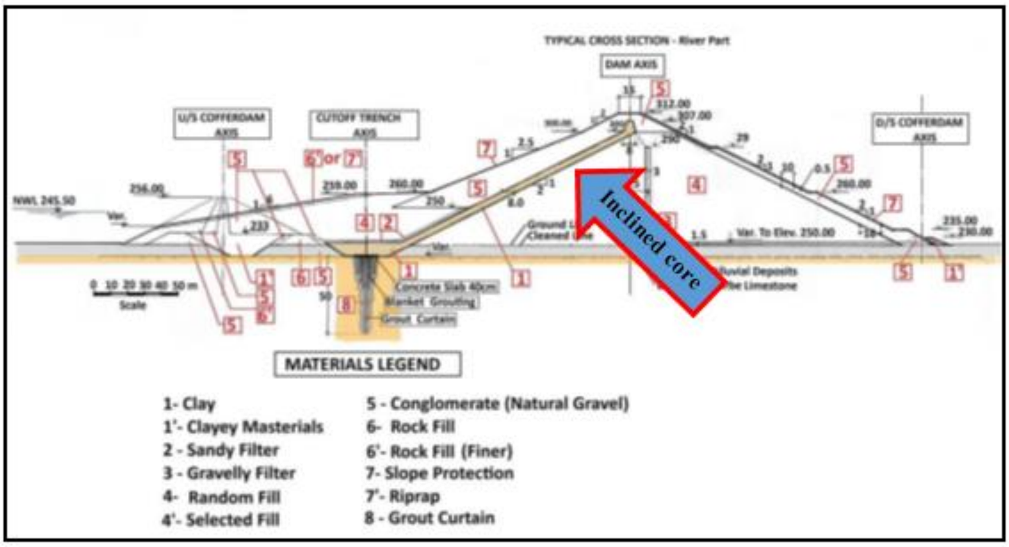
In addition, the hydroelectric power station would have an installed capacity of 170 MW and the dam would further regulate tail water from Mosul Dam (Al-Ansari et al., 2015a and b).

The dam's height is 103 m; length is 3730 m; volume is 6 X 10^6 m^3; bottom gated spillway capacity is 4000 m^3/ sec; reservoir capacity is 10 X 10^9 m^3. The reservoir capacity is designed to contain the whole volume of water, which is stored in Mosul Dam's reservoir. This is attributed to the fact that Mosul Dam is unstable and prone to collapse; due to intense karstification within the gypsum rocks of the Fatha Formation upon which its foundation is constructed.

Badush Dam is designed as a protection dam by ENERGOPROJEKT. The normal reservoir water level is 245.5 m (a.s.l.) and the maximum water level is 307 m (a.s.l.). The crest level is at a level 312 m (a.s.l.) allowing 61.5 m between the normal and maximum water levels is for flood protection from a probable collapse of Mosul Dam as a free board. At its maximum level, Badush reservoir can hold 10 X 10 ^{9} m^3, enough to absorb and route the Mosul Dam flood wave, according to a flood wave study (Al-Ansari et al., 2015a).

The design of the Badush 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 (Figure 6).

Figure 6. *Cross Section of Badush Dam at the River Channel (ENERGPROJECT, 1988b)*



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. This was based upon 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.

Problems of Badush Dam

As Badush Dam is located within an area covered by karstified gypsum and limestone bearing formations; therefore, the foundations of the dam suffer from karstification, which is the same case of Mosul Dam. The problems of Mosul Dam are well studied and presented in many published papers and a book (Al-Ansari et al., 2015a and b; Sissakian et al., 2014, 2015 and 2016; Adamo et al., 2015a). The existing problems at Mosul Dam site are the same problems which will be existing in the site of Badush Dam if the construction of the dam will be restarted. This is attributed to the fact that the exposed geological formations and even in subsurface are the same at both dam sites (Figure 2). The problems will appear in Badush Dam unless the suggestions given by Sissakian et al. (2017) are considered. The main problems, which will appear in the dam site, are briefed hereinafter.

Lithological Succession

The thickness of the Fatha Formation in the left side of Badush Dam is about 100 m (Hagopian and Valyuobec, 1977); whereas, in the right side is about 300 m (Mohi Al-Deen et al., 1977). These thicknesses should be considered during the design of the grouting boreholes in order to reach the lowermost karstified gypsum beds. Moreover; the Fatha Formation is underlain by the Euphrates Formation, which includes karstified limestone beds. Therefore, to design a relevant and accurate grouting program or a diaphragm, whichever is constructed, it is very necessary to know the true lithological succession in the dam site.

A good example is Mosul Dam, where the grouting program is performed since the beginning with the construction in 1983, until now; but without any significant important impact, since the dissolution of the gypsum beds is continuous with water leakage (Al-Ansari et al., 2015a and b; Adamo et al., 2015a and b, 2017). The same problem will arise at Badush Dam site if the construction is restarted with the same design and the same grouting technique, materials and depths of grouting boreholes.

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 (Figures 3, 4 and 7) (Sissakian and Salih, 1999; Sissakian and Ibrahim, 2004; Sissakian and Abdul Jab'abar, 2005; Sissakian and Al-Mousawi, 2007; Sissakian et al., 2014, 2015, 2016, 2017; Al-Ansari et al., 2015b). The karstified subsurface rocks exhibit strange forms in the overlying rocks on the surface (Figures 3 and 7). The exposed folded rocks did not obey the structural rules; hindering their true dips direction and amount. Moreover, they may form collapse form on the surface (Figure 7) covering part of the rocks in the succession, accordingly, misleading the true lithological succession. The karstified rocks also may give a pseudo lithological succession upon drilling, (Figure 8), especially if the site geologist is not well experienced in the geology of karst areas. This is one of the most significant reasons in miss interpretation of the geological subsurface data and its consequences; as it had happened in Mosul Dam (Sissakian et al., 2017), and will be repeated in Badush Dam too if the construction is continued. Moreover, circular forms also can occur due to filling of the karst by the overlying rocks (Figure 9). All these forms are excellent indications for the presence of subsurface karst (Sissakian and Abdul Jab'bar, 2005).

Figure 7. *Folded Limestone Bed Showing False Dip Direction and Amount due to the Presence of Subsurface Karst below them, 15 km South of Badush Dam*

Figure 8. *A Large Subsurface Karst (Limited by Red Line) Appeared after Excavation of the Bedded Rocks of the Fatha Formation at an Industrial Site, 15 km South of Badush Dam. Note the Circular form at the Upper Left Corner, which Indicates a Subsurface Karst. Also, Note the Pseudo Lithological Succession in a Suggested Borehole Location (the Black Line); accordingly, no Gypsum Rocks will be encountered in the Extracted Core (white Dashed Line)*

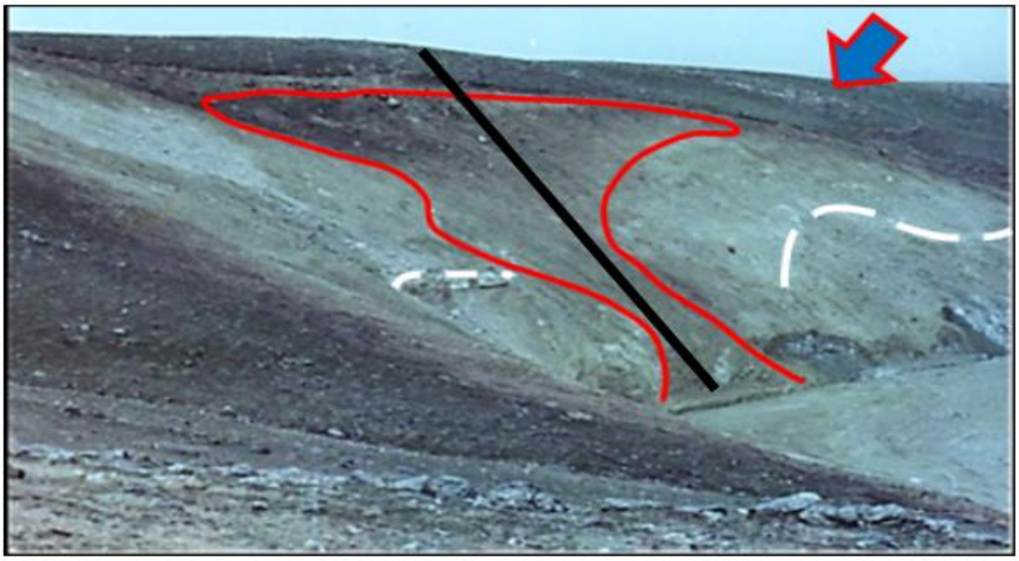
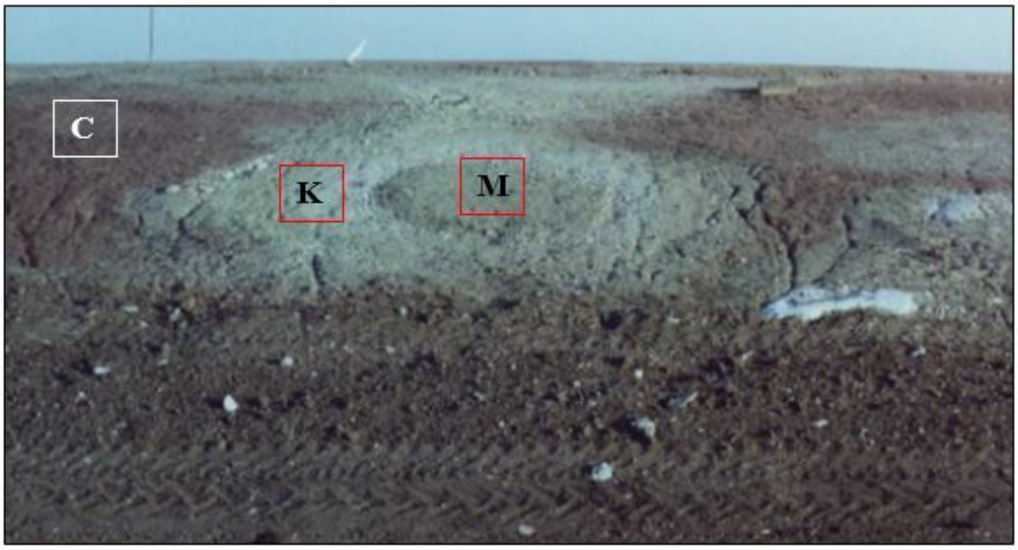


Figure 9. *Cross Section in a Circular Form Indicating a Subsurface Karst, 12 km South of Badush Dam. M= Green Marl, K= Karst Filling Materials, C= Reddish Brown Claystone. Note the Absence of Gypsum (Small White Pieces) and Limestone Beds due to Karstification*



Grouting Program

Grouting is one of the significant actions taken to overcome the karstification problems in engineering sites (Thuro et al., 2000; U.S. Army Corps of Engineers, 2017). Negative effects of grouting; however, on the engineering structures are also common (Milanović, 2001; Bonacci et al., 2009; Bonacci and Bonacci, 2013).

Grouting programs in Mosul Dam were implemented in different parts at different depths; following different grouting techniques and using different materials (Al-Ansari et al., 2015 and Adamo et al., 2015 A and B, and 2017). The implemented grouting in Mosul Dam; however, is not successful; hitherto, although extremely large quantities of different types of grouting mixes and techniques were used (Al-Ansari et al., 2015; Adamo et al., 2015a and b and 2017). This is attributed; mainly to the miss-interpretation of the true karst line depth (Sissakian et al., 2017). It is worth mentioning that the same grouting materials and techniques were used in both Mosul Dam and Badush Dam. Accordingly, the same negative results will occur at Badush Dam site if the construction continues with the present design of the dam, especially after filling of the reservoir and in the same way as it happened at Mosul Dam.

When grouting program and/ or grout curtains are implemented, then the hydrostatic pressure gradients on the curtain are increased with higher levels than ever. Therefore, the high hydraulic gradients accelerate the dissolution expansion of fractures and bedding planes beneath the dam by several orders of magnitudes. Accordingly, intolerable leakage of karstic reservoirs can occur over the lifetime of a dam site (Bonacci et al., 2009).

Discussion

Large engineering structures, including hydrological projects, which are constructed in karts areas suffer from severe problems endangering their stability; mainly due to leakage and deterioration of the foundations (Milanović, 2001; Dreybrodt et al., 2002; Bonacci et al., 2009; Bonacci and Bonacci, 2013; Al-Ansari et al., 2015; Adamo et al., 2015a and b). 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 (Adamo et al., 2015a). The same will be the case for Badush Dam; if the construction is continued with the same design.

Badush Dam is constructed in gypsum prevailing formation (Figure 2). The dissolution of gypsum in the subsurface had caused different and abnormal morphological forms, which did not follow the usual structural rules (Figures 3, 7, 8 and 9) indicating the presence of subsurface caverns of different sizes and shapes, and at different depth (Jassim et al., 1988; Sissakian and Abdul Jab'bar, 2005).

Badush Dam is designed by ENERGPROJECTS (1988a and b) to be a protection dam as it is clear from its thin and inclined core (Figure 6). The engineering specifications of the dam do not allow the dam to function as normal storage dam impounding the Tigris River flood wave with a reservoir capacity of about 10 X 10^9 m^3 of water. This storage capacity is designed to contain the full volume of Mosul Dam wave of 10 X 10^9 m^3 when routed through its reservoir. The available head between the Mosul regulating dam power station and the

Badush site would be utilized to produce electric power before and after the failure of Mosul Dam (ENERGPROJECTS 1988a and b). Afterwards, to route the stored water gradually without endangering the population living downstream of Mosul Dam and the existing infrastructure.

In the case of being a protection dam only, Badush Dam with its present design can function normally providing the foundations should be well grouted and the true depth of the deepest gypsum beds should be accurately known, and accordingly the grouting boreholes should be designed to fulfill the true depth. The difference in the head, which increases the solubility of the gypsum; in Badush Dam, will be about 15 m; as the downstream water level elevation is 230 m (a.s.l.) and the normal operation level for the normal case is 245.5 m (a.s.l.) (Figure 2). This head difference when compared with that of Mosul Dam (about 100 m) will cause less dissolution for the gypsum beds.

In the case of being a storage dam; however, Badush Dam will not be able to function as a normal dam, according to the present design, this is attributed to: **1)** The thin and inclined core of the dam. **2)** The head difference will be very much higher than in the normal case. This head will increase the dissolution of the gypsum beds in the foundations of the dam. **3)** The average designed depth in the grouting works in the already constructed parts of the dam is about 100 m, whereas the deepest gypsum beds under the foundations is at a depth not less than (150-200) m, since the thickness of the Fatha Formation in the left side of the dam is about 300 m (Muhi Al-Deen et al., 1977). This means the grouting will not stop the dissolution of the gypsum beds; as it is the case in Mosul Dam. **4)** The whole design of the dam and other related earthfill works should be amended to be able in bearing the exerted stress from the stored water into the reservoir.

Conclusions

From the current study, we can conclude the following: If Badush Dam performs as a protection dam only, then, the present design is relevant; providing that there will be a suitably revised grouting program. If the decision is taken to resume works in Badush Dam as a storage dam replacing Mosul Dam; as it has been suggested lately by Mosul Dam Workshop (2016). 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 at the dam site and near surroundings is accurately known. 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 300 m, especially in the right side of the Tigris River. 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 by dense karstic conditions. The rocks beneath the 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 Badush Dam. In the case that, the required depths of grouting boreholes are excessively deep, then the designers may think of adding a clay blanket at the upstream to limit this depth and reduce the seepage path length accordingly. Additionally, the design of the earth fill part of the dam must be radically revised to take care of the extra hydraulic head created in such a case.

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