

Defects in Foundation Design Due to Miss-Interpretation of the Geological Data: A Case Study of Mosul Dam

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Abstract

Existing engineering problems in Mosul Dam and their background are discussed in this paper. A thorough review of the available geological reports was made. These reports covered many decades of investigations from 1953 up to the investigations performed during the construction of the dam. A large volume of geological information was accumulated during these investigations, but it is unfortunate to see that some of the basic facts were not interpreted correctly. This applies to the incorrect correlation of the encountered beds in the exploration boreholes and miss-understanding of the actual stratigraphic succession at the dam site. This misinterpretation contributed to misleading results regarding the true karst zones and the type of rocks and their thicknesses in the foundation zone and surrounding area. As a result, the dam was placed on problematic foundations consisting of brecciated and highly karstified gypsum/anhydrite rocks and/or conglomerates in which gypsum forms the main constituent as cementing materials. Karstified beds were not recognized in some depths and were described as normal marl and/or breccias. This also added to the use of improper method of foundation treatment by adopting a deep grout curtain as the main anti-seepage measure instead of using a more positive measure by constructing a diaphragm wall. The mentioned misinterpretations are discussed here in details together with their consequences, and a more accurate picture of the geology is presented.

Keywords

Karstification, Gypsum, Karstified Rocks, Karst Filled Sediments, Mosul Dam

1. Introduction

Mosul Dam (previously known as Saddam Dam) was constructed during

1981-1986 on the Tigris River about 60 Km NW of Mosul City, Iraq (**Figure 1**). It is a multipurpose earth fill dam for irrigation, flood control, water supply, and hydropower. It is 3.4 km long, 113 m high with crest width of 12 meters and a base width of about 600 meters at the river section. Its storage capacity is 11.11 km³, and the dam is built on highly karstified gypsum and limestone beds [1].

The project was planned since 1952 by the Iraqi Development Board. The location of the dam was changed many times upstream and downstream from its present location depending on the submitted reports by the various consultants to the Ministry of Irrigation (Water Resources). Although the geological conditions in the present dam site and for few tens of kilometres up-stream and/or down-stream are the same, the geological conditions were not the essential parameters in the site selection. The deciding factors were to get maximum storage of water and to have control of the irrigation projects planned at the north of Iraq. The exposed rocks at the dam site belong to the Fatha (ex-Lower Fars) Formation and it consists of cyclic deposited sediments. Each cycle consists of green marl, limestone and gypsum [2].

Many reports were written on the problems in the foundations of Mosul Dam by different authors and agencies. Al-Ansari *et al.* [3] published a book, which can be considered as the most comprehensive to cover the whole aspect. Another significant geological report is that presented by [4].

The main aims of this study are to shed light on the ambiguous geological conditions, which were miss-interpreted and to describe the consequences of this interpretation, which include the continuous grouting that has been carried

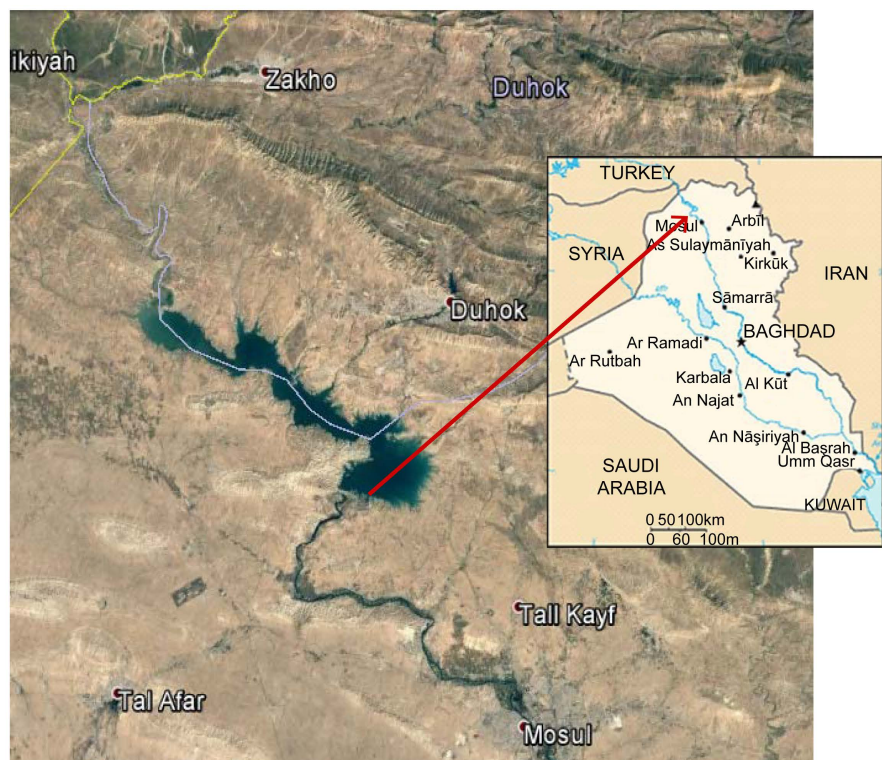


Figure 1. Google Earth image showing the location of Mosul Dam.

out and continues till now. The logical geological information in the dam site and in its foundations is presented here.

In order to fulfil the aims of this study, tens of reports on Mosul Dam were reviewed with special emphasis on those dealing with the geological investigations and foundations treatments. Moreover, many other reports and maps concerning regional geology and detailed studies, which were carried out by the Iraq Geological Survey were also consulted.

2. Geological Setting

In the following, a brief description of the dam site geology is presented. The adopted nomenclature for identifying the various structures and formations is what is commonly used in Iraq. It is different from what is given in the Swiss Consultants Consortium reports (1989). The nomenclature is based on the names of similar local structures found elsewhere in Iraq. The used data are taken from sources like [3] [5] [6] [7] [8].

2.1. Stratigraphy

The exposed rocks in the dam site and near surroundings belong to the Miocene Period within the following formations (**Figure 2**):



Figure 2. Geological Map of Mosul Dam site and near surroundings. Formations: 1 = Euphrates and Jeribe, 2 = Fatha Formation, Lower Member, 3 = Fatha Formation, Upper Member, 4 = Injana Formation.

a) Euphrates Formation (Lower Miocene): The formation consists of limestone and dolostone all being well bedded and highly karstified. The thickness of the formation ranges 20 - 45 m. It is not exposed in the dam site apart from restricted outcrops in the core of Butmah East anticline.

b) Jeribe Formation (Middle Miocene): The formation consists of well bedded limestone, marl and marly limestone. The thickness of the formation ranges between 15 to 40 m. No karstification is reported in this formation elsewhere in Iraq. Due to the fact that Euphrates Formation is composed of limestone also [9] [10] [11] [12] and sometimes it directly underlies Jeribe Formation, it is very difficult to differentiate the Euphrates and the Jeribe formation in the field unless microfossils are found. The Jeribe Formation overlies the Euphrates Formation directly when there is no Dhiban Anhydrite in between; therefore, the differentiation between the Euphrates and Jeribe Formations in the field becomes very difficult. The formation is not exposed in the dam site according to the regional geological mapping.

c) Fatha (ex-Lower Fars) Formation (Middle Miocene): The formation consists of cyclic sediments and each normal cycle consists of green marl, limestone and gypsum. However, in some cycles one of the three main constituents may be absent. The Fatha Formation in the dam site and near surroundings is divided into the following informal units:

Unit A: Consists mainly of limestone and marl with subordinate gypsum beds. The thickness of this unit is about 70 m.

Unit B: This unit consists mainly of thick gypsum beds with subordinate marl and limestone. The thickness of this unit is about 20 - 30 m.

Unit C: This unit consists mainly of limestone with subordinate marl beds and it was used as a marker horizon to divide the formation into two members, lower and upper. The top of the unit is the contact between the two members (lower and upper). The thickness of this unit is 8 - 12 m.

Unit D: This unit consists of proper cycles, green marl, reddish brown claystone, limestone and gypsum. The reddish brown claystone appears only in the Upper Member. The thickness of this unit is 50 - 70 m.

Units E and F: These units consist of proper cycles, green marl, reddish brown claystone, limestone and gypsum. However, in the upper cycles; reddish brown fine sandstone beds appear in the units. The thickness of both units is 80 - 120 m.

d) Injana (ex-Upper Fars) Formation (Upper Miocene): The formation consists of cyclic fluvial sediments. Each cycle consists of sandstone, siltstone and clay stone. All are reddish brown in colour. The thickness of the formation ranges 80 - 120 m.

e) Quaternary Sediments: These include river terraces and flood plain sediments, the former occur in different levels. The pebbles are cemented by gypsiferous and sandy materials, whereas the other includes high percentage of gypsiferous material within the silt, clay and fine sand.

The geology of the dam site is also characterized by the presence of four dis-

tinct layers of brecciated gypsum within the Fatha formation. These layers have thicknesses which range of 8 - 18 m and they are designated in the Swiss Consultants Consortium reports [13] [14] [15] [16] as the GB-layers. The GB0 is at a depth of 80 m from the ground surface in the river section, while GB3 was uncovered in the excavation of foundations of the ski jump structure at the end of the spillway chute.

The importance of these gypsum layers stems from their resistance to take grout materials during the construction of the deep grout curtain under the dam. In addition, they could not keep the grout material when subjected to the rising hydrostatic pressure due to the impounding of the reservoir. The correct behaviour of these GB layers was not fully grasped in spite of the long discussions on this subject, which had taken place during the many meetings with the Mosul Dam International Board of Experts (IBOE), which was assigned by the owner to oversee the design and construction of the dam [17]-[25] and Mosul Dam IBOE report to the minister of Irrigation 1984 [26]. These meetings had taken place during the construction of the dam and extended even through the maintenance period. The failing to find proper solutions for the continuous seepage seemed to originate from the miss-interpretation of the basic geological facts, and miss-judgement of gypsum rock behaviour in this environment and its dissolution phenomenon, in addition to the peculiar nature of the brecciated gypsum in not accepting grouting materials. This has led to the current maintenance work on the grout curtain which continued from 1985 until today.

The red clay stone beds were described by the Swiss Consultants Consortium below the so-called Jeribe Formation and were called “Bauxite” [14]. Their thickness range is 1 - 25 meters and they are most probably “Terra Rossa”. This Indicates the erosion phase between the Lower Miocene (Euphrates Formation) and Middle Miocene (Fatha Formation). Such claystone beds include high percentage of kaolinite; a clay mineral with extremely high ability of expansion after being saturated [27] and they are good indication for the presence of karsts caves.

2.2. Tectonics and Structural Geology

Mosul Dam site and the near surroundings are located within the Low Folded Zone of the Outer Platform, which belongs to the Arabian Plate. The whole area belongs to the Zagros Fold - Thrust Belt [28]. The Low Folded Zone is characterized by long and narrow anticlines separated by shallow and wide synclines. The right abutment of Mosul Dam is located in Butmah East anticline whereas; the left abutment is located in Taira anticline. Both anticlines trend in E-W direction with steeper northern limb.

3. Results

The recognized ambiguities in the geological conditions; as far as the dam safety is concerned, are discussed in the following:

The dam site was chosen for reasons other than geologic merits as it offered

very large volume of storage and the location served the irrigation purposes of supplying water to the Jazera irrigation project nearby. From a geologic standpoint, the foundation is very poor, and the site geology is the principal cause of continuing intense concern about the safety of the structure. Specifically, the dam was constructed on alternating and highly variable units of gypsum, anhydrite, marl, and limestone, each of which, apart from the marl is soluble in water under all conditions [1]. The presence of the brecciated gypsum layers designated in the Mosul Dam literature as GB layers, adds to the complexity of the already complicated geological situation. After thorough and careful reviewing of the existing geological reports and those, which deal with the foundation's treatments, the following miss-understandings of the geological conditions by the designers of the dam and also by the site supervisory staff may be observed. These misunderstandings have caused problems to the dam as a whole and to its foundations in particular.

3.1. Stratigraphic Succession

According to the authors the true stratigraphic succession is the one given in this study, which is different from what is mentioned by the [4] [13]. The age of the formations is not an important aspect in the geotechnical applications; however, the true stratigraphic succession should be known to be able to predict the type of rocks in the subsurface sections.

The correct stratigraphic rock column (see **Figure 3**) is one of the main issues and it was not defined correctly during the interpretation of the geological data,

Epoch	Period	Formation	Member	Thick. (m)	Lithology
	Holocene	Fluvial Sediments		5 - 25	Clastics, highly gypsiferous
	Pleistocene	Bai Hassan (ex-Upper Bakhtiari)		100 - 350	Cyclic deposits of coarse conglomerate and claystone with rare sandstone
	Pliocene	Mukdadiya (ex-Lower Bakhtiari)		300 - 550	Cyclic deposits of coarse sandstone, siltstone and claystone, some of the sand stone beds are pebbly
Tertiary	Upper	Injana (ex-Upper Fars)		33 - 420	Cyclic deposits of reddish brown sandstone, siltstone and claystone,
			Upper	150 - 180	Cyclic deposits of green marl, reddish brown claystone, limestone and gypsum. Occasionally sandstone and claystone may occur in the uppermost parts
			Lower	200 - 220	Cyclic deposits of green marl, limestone and gypsum. The gypsum and limestone beds are highly karstified. In the lowermost part, thick alternation of green marl and limestone occur
	Middle	Fatha (ex-Lower Fars)		20 - 30	Well bedded marly limestone
				35 - 50	Well bedded and highly karstified limestone and dolomitic limestone
	Lower	Euphrates			
	Eocene	Upper	PilaSpi	100 - 130	Well bedded limestone and dolomitic limestone Occasionally karstified

Figure 3. Stratigraphic column of Mosul Area (after [8]).

especially the drilled boreholes data. Previous work and geological maps indicates that the foundation of the dam is entirely located on the Fatha Formation and not on the Jeribe and/or Euphrates Formation as mentioned in the consultants reports. This means that there is still karstified gypsum beds below the deepest encountered limestone and marl beds, which were considered as the Jeribe Formation in the same references. Those limestone and marl beds belong to informal unit designated as A1 unit of the Fatha Formation, which are exposed west of the dam site [6].

The assumption of the Swiss Consultants Consortium [13] that the highly impermeable Jeribe Formation underlies the lowermost Brecciated Gypsum layer (GB0) was also not correct. Later evidence from the grouting maintenance program points out to this. The following may be cited from [29] which states:

“The following Maintenance grouting of the foundation has been conducted continuously as a 24 hour per day, six days per week activity by the Ministry’s Staff since 1988. During this time the lowermost anhydrite/gypsum transition zone (GB0) has been the most troubling for grouting. Grout teams have returned to the same area many times to re-grout the gallery three-line curtain. It has been reported that in some instances the same holes have been re-drilled after several months and continued to accept grout. Currently, the target depth for grouting is to terminate the grout curtain 20 m below the karstic line at the Jeribe limestone in the right side of the dam and at the marl beds in the middle and left side of the dam. The assumption is that the Jeribe Formation is relatively impervious; however, the Panel has not seen evidence to support that conclusion. Hole depths from the gallery through the GB0 stratum into the Jeribe Formation are in the order of 100 m. Evidence from the grouting program over the years suggests that the karstic front in the GB0 stratum is migrating down dip, to the east”.

3.2. Units

- Use

This may be explained by that the Jeribe Formation was in fact no more than Unit A1 of the Fatha Formation as explained above. The red clay stone beds described by the Swiss Consultants Consortium below the so-called Jeribe Formation which were called “Bauxite” [13] and which had a thickness of 1 - 25 m are most probably “Terra Rossa”. Terra Rossa is silty clay to clayey soil that has red colour and is mostly associated with limestone [30] [31] [32] [33]. It is usually the residual product of limestone dissolution by groundwater, typical of karst weathering. Terra Rossa is probably in part a residue from limestone dissolution and sometimes associated with the detritus material. The presence of Terra Rossa indicates the erosion phase between the Lower Miocene (Euphrates Formation) and Middle Miocene (Fatha Formation). Such clay stone beds may include high percentage of kaolinite a clay mineral with extremely high ability of expansion after being saturated [27] and it is a good indication for the presence of karst caves [30] [31] [32] [33].

3.3. Karst Zone and/or Line

The constructed cross sections (**Figure 4**) show the karst line running in varying depths along the axis of the dam. The karst line was indicated on a long section of the dam axis by the Mosul Dam Supervisory staff [34]. The supervisory staff

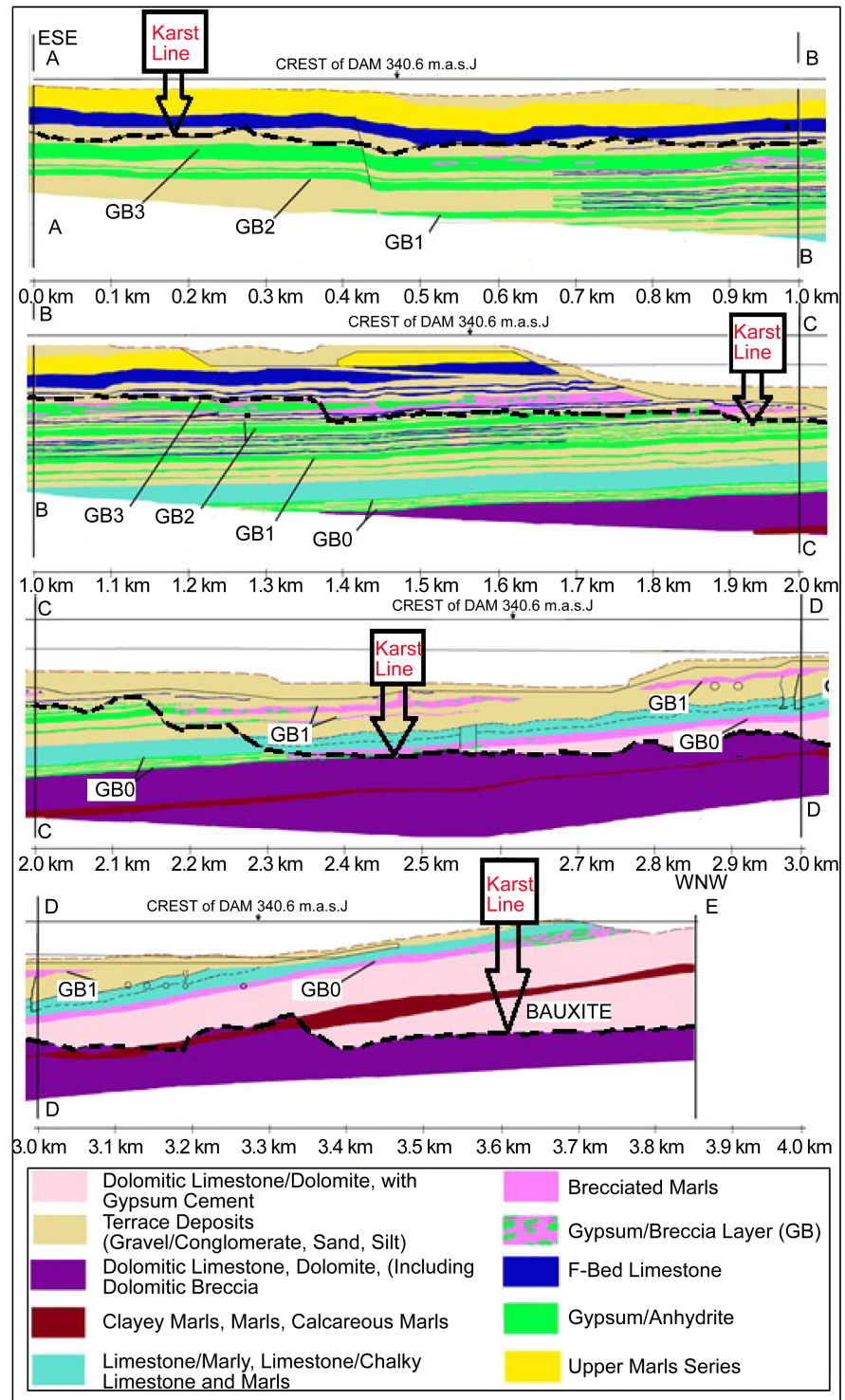


Figure 4. Lithological cross sections showing the karstification line; (the thick dashed lines). After [34]. Note that the karst lines cross the Lithological bed.

was formed by a joint venture from the Swiss Consultants Consortium and Energoprojekt of Belgrade to conduct daily supervision of the works. As it is presented, the karst line doesn't follow certain bed or the regional dip, which is not possible from a geological point of view. Normally the karstification is related to certain bed(s) and therefore, it should follow the regional dip and not cross it (**Figure 4**). Moreover, the karst line as shown rises upwards against the dip, which means the karstification, is not related to a certain bed and/ or depth.

The plotted karst line was used in the design as an indication of the lower boundary of all Gypsum and other karstified beds. It was considered to define the required depth of the deep grout curtain under the dam; the curtain was even taken 20 meters below these karsts as a precautionary measure [35]. But, the continued dissolution in the foundation below this depth during the maintenance grouting showed that the actual karst line is much deeper than the defined one. This supports the opinion set out previously, that the interpretation of the foundation stratigraphy by the dam geologists was not the correct and they did not correlate with recognized stratigraphy of other similar locations in Iraq like the wax plant which is 20 km away.

3.4. Some Remarks on the Foundations Treatment

The construction procedures described in the [16] shows that the foundation surface preparations for placing the fill materials of the dam were not adequate or not correct in some places when compared to common international experience. One example of this is how the clay core was placed directly on the gypsum beds in the cut-off trench in the left side of the river section. Here it was not possible to remove the gypsum beds due to their thickness. It was assumed that the anti-seepage measures (Blanket Grouting and the grout curtain) were able to stop the seepage flow at the (core-foundation) interface completely. Such an assumption cannot be guaranteed since any grouting works can never achieve a value of 100% efficiency. In a research work by [36] it is stated that even a permeability as low as 10^{-8} ms^{-1} under 20 m water head can allow leakage of 20 000 m^3 per day. In the same reference, the following conclusion was reached: "Seepage through the foundations and abutments of dams containing soluble rock may produce settlement and redistribution of pore pressures which could threaten stability". This Seepage will undoubtedly lead to dissolution of gypsum and corresponding settlement of the core in the long time perspective. This is true also for all the gypsum beds present in the Fatha formation, even those at large depths.

In the preparation of foundations of the upstream and downstream shells of the dam at the left side of the river channel, excavation of unsuitable materials was restricted to fluvial top soil, sand and silt of the flood plain sediment and so the shells were placed on the conglomerates of the river terraces [16]. The cementing materials of these conglomerates were soluble secondary gypsum, which on dissolving by water may result in very porous mass that can settle considerably due to the weight of the shells and may cause them to crack severely. In

a paper by [37], conglomerates cemented by gypsum in foundation of hydraulic structures are described as “particularly hazardous”.

In preparing the foundation of some of the concrete structures, the procedure used was to remove all doubtful materials and replace them by rollcrete. No objection can be raised against the removal, but in some places this was not followed consistently. An example can be seen in the foundation preparation of the earth-fill part of the emergency spillway (fuse plug) in front of the concrete weir. Here, the left half of the core was located on the existing marly impermeable layer but the right half was located on conglomerates. The surface of the conglomerates was only cleaned and a horizontal clay blanket was placed on top of it in front of the clay core to cover its surface and, some drainage arrangement was added at the back in order to drain the water seeping through the conglomerate layer. The same remark on the behaviour of conglomerate that was stated before applies here. The dissolution of the secondary gypsum binding material can result in excessive settlement in the clay fill and undermine the integrity of the core. In one more instance, the foundation of the ski jump structure at the end of spillway chute was placed on 31 meter thick rollcrete mass overlying a thick bed of gypsum. If the gypsum bed would start to erode by dissolution, then a big question mark is left with regards to the safety of this huge structure. Rollcrete was used in huge quantities to replace much of the existing foundation materials under almost all of the concrete structures. This work was not anticipated in such quantities at the investigation phase or during the design stage and it added significantly to the total cost.

3.5. Laboratory Test and Analyses

From the review of the available data of the laboratory tests and analyses, it is clear that the used materials in constructing the various parts of the dam were subjected to geotechnical tests only [16]. No data regarding the chemical properties of the construction materials were found in order to support the suitability of the material to be used in the dam body. This is especially important for the river terrace conglomerates, which were processed and used for the construction of the upstream and downstream shells of the dam and also for the filters. It is already explained that these conglomerates contain secondary gypsum as cementing material and the presence of such gypsum in the filling materials is not considered as a safe practice. Processing of these materials for the gravel filters was performed by crushing and sorting out the various fractions according to the recommended zones stipulated in the technical specifications. No washing was considered in the process, which means that there existed the possibility of contamination of this filter with gypsum exists. If such material contaminated with gypsum is used as filter, then such use would be detrimental to the safety of the dam.

3.6. Experience of the Consultants and Contractors

The companies forming the design consortium were considered as the best con-

sultants for dams worldwide at the time of Mosul Dam construction as were the companies forming the contractor's joint venture (GIMOD). Nevertheless they were not highly experienced in karstification problems induced by the dissolution of gypsum beds and their consequences. Moreover, they did not anticipate the peculiar behaviour of the gypsum breccias layers, which do not accept permanently all tried types of grouting materials [38].

From the IBOE reports collection it got obvious that the field geologists did not have good and clear picture of the geological conditions prevailing at the site during the investigations and design phase. One of the major gaps was the lack of knowledge on the extend of karsts in depth and the ground water movement regime contributing to its development before construction. Therefore they could not, visualize how the situation could become worse after impounding of the reservoir and applying the additional full head of hydrostatic pressure. The addition of this hydrostatic head caused accelerated dissolution of the gypsum beds and forming new cavities of various sizes. This accelerate he deterioration of the deep grout curtain by opening up the grouted gypsum breccias crossing it and leaving open seepage conduits and pipes. Sinkholes and dissolution tunnels formation activity around and very close to the dam body was also observed clearly after impounding.

A back analysis of the design, of the anti-seepage measures under the dam, prevails that using the deep grout curtain was not a correct or wise choice. A better solution would have been using a diaphragm wall going down in the foundation even deeper than the present depth of the curtain which was fixed according to the erroneous karsts line depth. Such diaphragm wall should also extend along the dam axis beyond the dam body in both the left and right banks to much longer distances than the present grout curtain extensions in those two banks. Such a diaphragm wall could have stopped all seepages in the left bank, at the river section and the right bank, and could have reduced the dissolution potential of the gypsum almost to a zero value. Blanketing the upstream of the dam by clay blankets for certain calculated distance at both banks close to the abutments would have also enhanced the dissolution situation here and would have hindered the formation of sinkholes and dissolution tunnels very close to these abutments [39]. This blanketing should have already been considered by the designers in (1984) when the above described phenomena appeared for the first time.

4. Discussion

Gypsum induced hazards are well known in Iraq, especially in areas where the Fatha Formation (ex-Lower Fars) is exposed. Documenting this was done over the previous decades in studies, which were written by many researchers; among them are: [7] [40] [41] [42] [43]. All these studies and many more deal with the induced problems to engineering structures constructed in areas built on gypsum rocks.

Gypsum beds are highly karstified not only in Mosul Dam site area, but in the

whole surroundings. Good example is the wax plant site, which is located 25 kilometres south of Mosul dam. There, the gypsum beds are highly karstified and characterized by large caverns filled by clay and marl (**Figure 5** and **Figure 6**). The dissolved gypsum beds had left large cavities filled with weathered clayey and marly materials as well as some limestone and gypsum fragments (**Figure 7**). Therefore, when a borehole is drilled in such location gypsum may be missed. The site geologist, especially when he is not familiar with such cases will most probably consider the next encountered gypsum bed in the borehole as the first one; and consequently will miss the true serial number of the gypsum beds.

The misleading configuration of the karsts line projected at the Mosul dam (**Figure 4**) by site geologists made the geological picture of the foundation even



Figure 5. Karstified gypsum beds in Wax plant site. Note the absence of the gypsum in the left side.

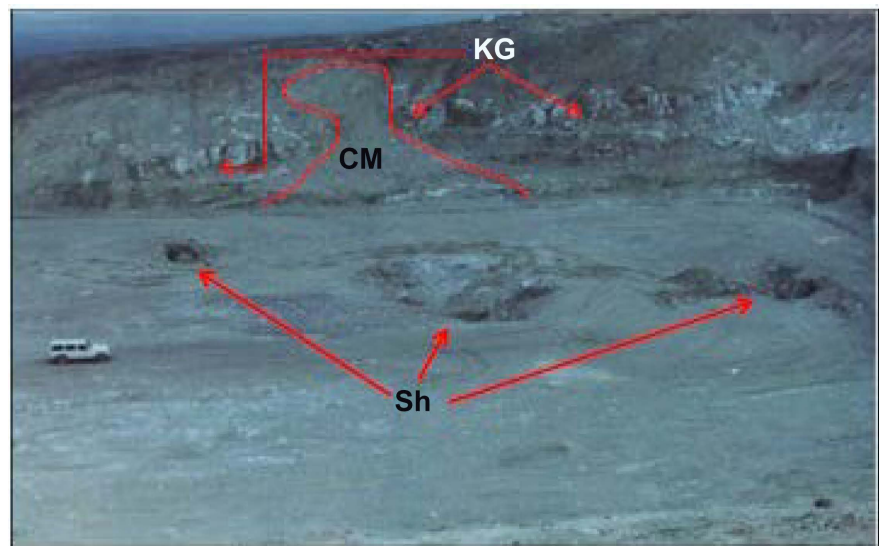


Figure 6. Karstified gypsum beds in Wax plant site. Note the karstified (**KG**) and/or absence of the gypsum in different sides of the site, presence of many sinkholes (**Sh**) in the floor, and the filled cavern by clayey and marly materials (**CM**).

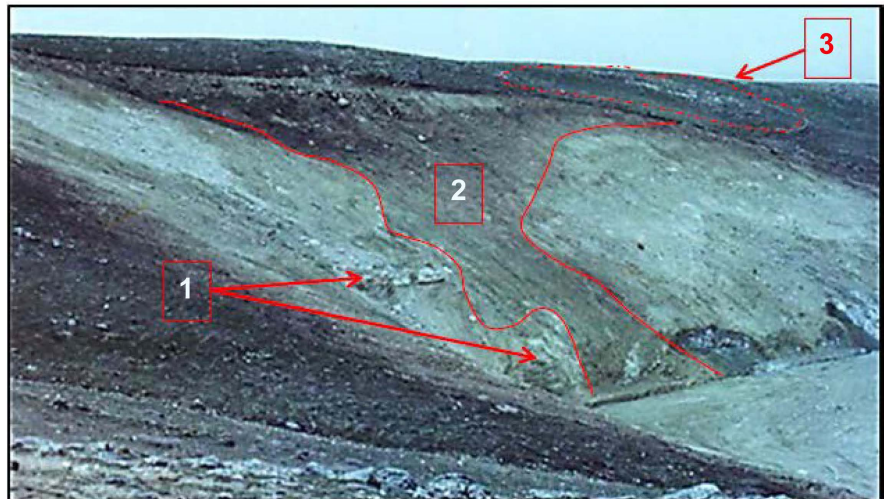


Figure 7. Karstified gypsum bed in the wax plant site (1). Note the large existing formed cavern (2) that is filled by clayey and marly materials. A circular form (3) indicating the presence of a karsts form below the surface.

more disfigured, as the karst line cannot extend upwards in the geological beds against the dip as shown in the Mosul Dam geological literature. Thus the assumed karst line should have been questioned before construction.

It may be said with certainty that this misinterpretation is one of the main reasons for the failure of the grouting programs over the years in different locations and the inability of this curtain to achieve its intended function in spite of the different procedures and different grouting mixes and materials used. Adding to this, the understanding of the gypsum karsts and the gypsum breccias beds behaviour was limited. This explains the failed attempts to achieve the specified design criteria in the deep grout curtain and such design criteria which were fixed by the designers themselves. This is well documented in the study of [4].

The recognized red claystone, which was so called “Bauxite” by [13] is actually of “Terra Rossa”; sediments which indicate karst depression [27]. It is very strange that this was not considered when defining the karst on the geological cross section (Figure 4). Such sediments are well developed in the contact of Upper Oligocene and Lower Miocene rocks in the vicinity of Anah in the west of Iraq [44]. Failing to recognise the true nature of these sediments had led to further misunderstanding of the geology even though it is one of the most significant indications for the presence of karst in any geological setting. Sections: B - C, C - D and D - E (Figure 4) do not suggest the presence of Terra Rosa in the definition of the karst line. This adds another reason for the unsuccessful grouting and re-grouting works and explains why the maintenance of the grouting curtain has lasted for many decades and still needs to continue.

In reviewing the many reports, such as [4] it is seen that the only solution, which has been considered to stop the seepage and in consequence to stop dissolution of the gypsum was the construction of the grouting curtain. In those reports and studies it has not been recognized that such curtain needs to show a

100% efficiency to achieve this. The curtain was designed (depth and extension wise) based on the drawn karst line shown in the cross sections of (Figure 4). Accordingly, the curtain was not deep enough to stop seepage and dissolution of gypsum under the dam even if grouting itself would have been a successful solution.

For every engineering site and especially for sites of this extent the true succession of the stratigraphic (lithological) column should be known accurately. This includes the spatial extension (vertical and horizontal) and depth of individual beds under the surface of the ground should be well known prior to any design work. There for the decision of the proper depth of boreholes for geologic investigations is very important. Moreover the proper interpretation of the obtained information is equally important information in deciding the limits of any foundation treatment work including grouting operations. This matter was overlooked in Mosul Dam site; which is clear from the constructed cross sections and the designed depth of the grout curtain.

The thickness of the Fatha Formation in Butmah anticline is 392 m [7]. In reviewing the geological map of Mosul Dam site (Figure 2), it is clear that the dam abutments are located within the Upper Member of the Fatha Formation. This means that the thickness of the subsurface section in the dam site is not less than (250 - 300) m, whereas the majority of the drilled boreholes didn't reach such depths. Consequently these boreholes did not reach the lowermost gypsum beds in the Fatha Formation. It is believed that the thick succession of the encountered marl and dolomite beds in some of the drilled boreholes belong to the Fatha Formation Unit A1 [6] and not to the Jeribe Formation that never shows karstification indications anywhere else in Iraq [45]. Consequently, the majority of the grouting drill holes did not reach the lowermost karstified horizons. It is worth mentioning that the Fatha Formation is underlain by the Jeribe Formation (20 - 50 m) thick as average in Mosul Dam site), and the Jeribe Formation is underlain by the Euphrates Formation (25 - 45 m) thick in Butmah anticline [7]. The latter is known to be highly karstified everywhere; therefore, the karstification zone extends in the foundations of Mosul Dam site down to (300 - 375) m. This depth has never been considered and/ or reached by the drilling and/or in planning for construction of the grout curtain.

Recently compiled reports by different authorities, companies, authors [4] [29] [35] [46]-[51] to the evaluate the safety of Mosul Dam have shown many ambiguities in the presented data. Thus, it is most probable that these reports do not furnish accurate information on the geology. A good example is the report prepared by [29] [35] [46] in which they reiterated the opinion and belief of the Panel of Experts [38] which was contracted by them which stated: "The Panel concludes that the safety of the Mosul Dam cannot be assured because of the unpredictable and unique foundation conditions. The presence of layers of gypsum, anhydrite, and karstic limestone throughout the foundation provides materials susceptible to solution and erosion over the short and long term". This statement indicates a clear confirmation that the true geological conditions in

the dam site were not fully understood at the time of construction and afterwards. Moreover, both reports showed that the authors were not sure of the quality and reliability of the available data, which is declared in the following statement “In producing this report, [29] [35] [46] information provided by others. The completeness or accuracy of this information is not guaranteed by WI/BV JV”. Such information and data, nevertheless, were used by the designers of Mosul Dam and, therefore, it is not surprising that the karstification problem in the dam foundation remained unsolved, grouting works continued through the following decades without reaching a final and conclusive end.

Another testimony to the inaccuracy of the available geological data may be taken from the report of the Engineer and Development Research Centre (ERDC), which belongs to the United States Army Corp of Engineers [47]. This report furnishes the geological data after digitization of all available maps, cross sections, figures and other information and establishes a data base using GIS for the conceptual geological modelling. But it states, however, that: “None of the information such as descriptive logs from geological borings was accompanied by numerical location information. This lack of exportable or positional data greatly complicated the process of generating a GIS and a 3-D conceptual model, both of which are essential to site-specific interpretation and communication of engineering significance”.

The report adds: “The primary source of information for the ERDC project was a 13-volume compilation of data and information on Mosul Dam spanning its construction and 20 years of operation, known as the Mosul Dam Library of Documents (LOD) [29] [35] [46]. Based on information provided, the ERDC team expected the LOD to include most of the geologic data necessary to form the basis of the conceptual model. Because the LOD was provided to the ERDC on CDs, the team anticipated that there would be some exportable data sets with adequate positional accuracy to be incorporated into a GIS”. So, it is believed strongly that many locations of the drilled boreholes and/or constructed cross sections; alongside the karst line were not accurately located during the compilation of this report and/or establishing of the data bank for GIS usage. It follows that this report also cannot be used to present a real visualization of the foundation conditions and that the 3-D conceptual model obtained by this study is not reliable.

The real conditions of Mosul Dam remains as an open question until further intensive geological investigation are done. This investigation needs to be done incorporating deep insight of the overall geology of the region and better understanding of the historical karsts conditions prevailing with special emphasis on gypsum karsts.

To overcome the ambiguities raised from miss-understanding and/or miss-interpretation of the geological data, and because Karstification of gypsum and limestone beds are the main cause; therefore, we highly recommend performing the following steps:

- 1) Drilling at least 10 boreholes to depths not less than 400 meters; each. The

recommended locations are as near as possible to the foundations of the dam and the most problematic locations.

- 2) The coordinates of the boreholes should be recorded very precisely.
- 3) The boreholes should be drilled with well experienced drillers being well experienced in drilling through karstified rocks.
- 4) The core recovery should be not less than 85% to assure the drilled core will represent the true status of the penetrated sections.
- 5) The description of the extracted cores should be performed with well experienced geologist being well acquainted in description of karstified rocks
- 6) Full colored photography should be applied to the extracted core.
- 7) The lowermost part of the cores, when are free of gypsum beds, should be studied by well experienced paleontologist to decide whether the penetrated rocks are within the Fatha (ex-Lower Fars), the Euphrates Formation or Oligocene rocks. To assure the depth of the karstified rocks.
- 8) Storing of the core in relevant core boxes providing that the boxes will be numbered properly and kept in safe stores; assuring their usage in future; if needed.
- 9) Performing many geophysical traverses by well experienced geophysicists using macro gravimeter and ground penetration radar methods in the locations of the drilled boreholes and near surroundings.
- 10) The acquired geophysical data should be corrected using the drilling data, and vice versa.
- 11) According to the acquired data, the constructed karst lines, which are super imposed over the constructed geological cross sections should be corrected by a well experienced structural geologist and/ or field geologist.
- 12) Accordingly, all previously designed grouting programs and construction of the grout curtain should be redesigned.

5. Conclusions

The main general conclusions and recommendations that may be derived from the above are the followings:

- 1) It is very clear that there was a lack of misunderstanding and misinterpretation of the geological investigations carried out for selecting the proper site for building such a large dam as the Mosul dam by all the previous consultants. Although these investigations and studies were carried out by various consulting firms, the final word on the suitability of the site rested with the last Consultants and Designers. *i.e.* the Swiss Consultant Consortium. Unfortunately, this Consultant showed also a very high level of misunderstanding and misinterpretation of the huge amount of geological data obtained during the previous investigations and the ones performed in the design and construction phases which lead to a series of errors and bad decisions.
- 2) This misinterpretation was evident in not defining the correct Lithological profile under the dam; the proper definition of the extent of karsts and the location of the karsts line and even in missing the true identities of some of the geo-

logical formations; mixing for example between the Jeribe formation and the Euphrates formation and also between Terra Rossa and Bauxite. Such misunderstanding contributed to the faulty design of the grout curtain.

3) One more evident failure in the design of Mosul Dam was the adoption of the deep grout curtain as the anti-seepage measure. Adopting such a solution would indicate underestimation of the behavior of gypsum which is highly soluble rock in aqueous solutions. Grout curtains cannot be constructed to 100% efficiency in any imaginable way and the smallest amount of seepage can be detrimental to the safety of any dam built on such geology, which is a common knowledge to dam designers all over the world. In Mosul dam, which is characterized by a very high hydrostatic head, this could be catastrophic. The conclusion is; the Consultant had shown either groundless optimism or complete lack of knowledge.

4) The geological investigations showed the presence not only of gypsum beds but indicated also the presence of four brecciated gypsum layers at various depths within the range of the grouted zone. The Consultants and the foundation treatment Sub-contractors could not understand the nature and structure of these layers even by examining the cores of these layers. These layers proved to be most resistant to all types of grout mixes and materials and procedures. When such layers were grouted, this was only temporary and soon they were eroded leaving gaps in the curtain. This is the reason that the grouting has been repeated time and again over the years and the dissolution process continuing with no hope of stopping. It is very unfortunate that had the Consultants understood the geological problems correctly at the beginning and, had they known more about gypsum and brecciated gypsum behaviour, they would have used a positive cutoff diaphragm rather than using this doubtful grout curtain. Constructing such diaphragm could have been done at that time with the available technologies at much more saving and with much better results.

5) One of the solutions that have been suggested during the previous years to protect from the possible failure of Mosul Dam was the construction of Badush Dam at about 40 kilometers south from Mosul Dam site. Basically, this is a sound proposal, but certain precautions have to be taken. First, the site of Badush Dam is located in the same Fatha Formation as Mosul Dam. The fact that gypsum was not observed in the geological boring does not mean it does not exist and it may exist at deeper depth. Second, the site is very close to the Wax Plant site at the right side of the river Tigris. Boreholes could miss gypsum in Badush Dam site the same way as the case was in the Wax plant; which was shown previously in this paper. It is therefore, strongly recommended to have much more drilling at this site and to go much deeper in depth than what was previously done. One important aspect of the design should be the use of diaphragm wall and not to put faith on any grout curtain here.

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