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ORIGINAL PAPER

The Role of Geological Investigations for Dam Siting: Mosul Dam a Case Study

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Abstract Dams are engineering structures constructed for different purposes. They are of different sizes, shapes and types. In all cases, many essential studies should be carried out before deciding the location, type and size of the dam. Among those studies is the geological investigations which should be carried out to deduce the geological conditions in the most relevant site, depth of the foundations and their types, cut-off depth, type of the available construction materials, and type of the expected geological hazards. Without proper geological investigations, the siting of a dam will cause serious hazards during construction and during commissioning of the dam. In this study, Mosul Dam case is considered as the consequences of inadequate geological investigations which were carried out by the contractor and supervised by Swiss Consultant. The location of the dam site and its foundations are built over a highly karstified area, where gypsum and limestone beds are exposed and exist deep under the ground surface, and even deeper than the foundations. Accordingly, grouting treatment was carried out and still on going, but all the attempts to have a safe and relevant dam were in vain. In this study we have provided the essential studies which should be included during the geological investigation to have a safe and sound dam.

Keywords Mosul Dam · Geological investigations · Karstification · Grouting · Gypsum

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1 Introduction

Geological investigation for selecting and locating dam sites is one of the most significant studies which should be carried out in different scales and stages before deciding the best location for a dam. Therefore, an adequate assessment of site geologic and geotechnical conditions is one of the most significant aspects of a dam safety evaluation. Evaluation of the safety of a new dam requires, among other things, that its site, abutments, foundation and reservoir have been adequately examined, explored, and investigated so that the geological conditions are fully understood as much as possible.

The geological investigations should include four main topics; these are (Woodward 2005):

1. The geology of the dam site including the foundation for the dam itself and the sites for other structures such as spillway, diversion tunnel and outlet works. To check whether the dam foundation has sufficient strength and durability to support the type of dam proposed, whether the foundation is watertight, especially, when karstified rocks occur in the site and in deeper horizons bellow the foundations.
2. The geology of the area to be occupied by the reservoir once the dam is completed. Whether the storage area is watertight or are there areas of cavernous limestone and/or gypsum which might lead to the dam not retaining water.
3. Stability of the slopes in the dam site and reservoir area whether landslides into the reservoir are possible which might cause a wave of water to be pushed over the top of the dam.
4. Finding sources of the construction materials which will be needed to build the dam in nearby areas of the dam site including all required types like: aggregates of different types and sizes, filling materials in the core and both surfaces (if the dam is of earth-fill type).

The main aim of this article is to shed light on the role of the geological investigations in dam siting and to elucidate the consequences when the investigations are inadequate and/or the acquired data is miss-interpreted, which means the interpretation of the acquired data was not relevantly performed. Accordingly, wrong conclusions may be achieved. Mosul Dam (Fig. 1) case is presented as a good and unique example for inadequate geological investigation in dam siting and the consequences which were the reason for calling the dam as “the most dangerous dam in the world” (Al-Ansari et al. 2015a, b, 2017).

1.1 Previous Studies

Studies concerning the role of the geological investigation in dam siting are enormous. Moreover, many guidelines, instruction booklets, safety codes are also available at different sources. Among the mentioned sources, but not limited to; are: Swiss Consultants Consortium (1984), Woodward (2005), Kocbay and Kilic (2006), Kelly et al. (2007), Fraser (2001), Nezhad et al. (2012), Bell (2013), Al-Ansari et al. (2015a, b), Sissakian et al. (2015), Adamo et al. (2017), Jayanath et al. (2017), Kanik and Ersoy (2019) and Poorbehzadi et al. (2019). All the mentioned publications either deal with a certain dam with its problematic geological conditions and/or mention the necessary steps which were considered during the geological investigation for dam siting to have a safe dam site during constructions and after commissioning of the dam.

However, we have specified some of the studies mentioning their main subjects. Cetin et al. (2000) explained how the settlements in Ataturk Dam in Turkey were solved. Dreybrodt et al. (2002) and Hiller et al. (2011) discussed the problems exerted by karst forms below dam foundations. Bonacci (2008) described how the water losses were treated in Boljuncia reservoir in Croatia. Hiller et al. (2012) discussed the karstification problems in Birs Weir at Basel in Switzerland. Milanovic (2011) discussed the karstification problems in gypsum karstification in dam sites. Andreo et al. (2015) explained the process of environmental investigation in karst systems. Mozafari and Raeisi (2016) discussed the karstification problems in the foundations of Salman Farsi Dam in Iran. Milanovic (2018) discussed the engineering problems caused by karstification in dam sites.

2 Materials and Methods

To fulfil the aims of the current study, tens relevant published articles were reviewed in order to present the most necessary steps which should be followed during performing geological investigation to select a compatible and safe dam site. Moreover, Mosul Dam case is presented as a typical example of performing inadequate geological investigation and wrong interpretation of the acquired data from these geological investigation (Al-Ansari et al. 2015a, b; Sissakian et al. 2015, 2017).

3 Necessary Steps in Geological Investigation

The necessary steps which should be followed during performing geological investigation for dam siting are briefly mentioned hereinafter. However, it is strongly recommended to perform the geological mapping within the investigation by the national geological survey office with contribution of university and other concerned specialists. Because the geologists in a national geological office have more regional data which can be used in the interpretation of the acquired data, especially the subsurface data. This is attributed to the need for required necessary regional geological data in the dam site and reservoir area.

1. *Geological Maps* Studying available geological maps for the selected dam sit; if the dam site is already selected. Otherwise, many alternative sites should be recommended depending on the geological data acquired from the geological maps and then should be ranked using other necessary data which are concerned with dam siting.
2. *Geological Mapping* Geological mapping at a scale of 1: 5000 should be performed by well experienced geologists having excellent engineering geological background. The geological maps should present;
   (a) Type of the exposed rocks and their thicknesses in the dam site.
   (b) Mechanical and geotechnical properties of the exposed rocks in the dam site and deeper than the foundations (more than cut-off depth).
   (c) To elucidate if there are karstified rocks (gypsum and limestone) and/or expansive clays.

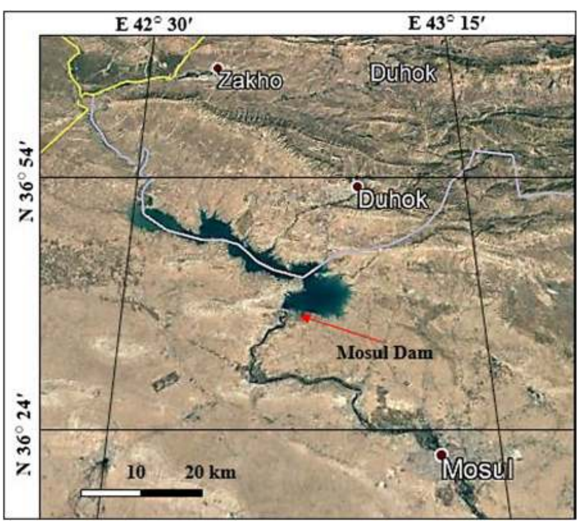

Fig. 1 Satellite image showing the location of Mosul Dam

   (d) Presenting all existing faults and other structural elements which shed light on the existence of active faults.
   (e) Presenting all Neotectonic evidences.
3. *Drilling Operations* Boreholes should be drilled in the dam site and reservoir area. The number, depth and spacing of the boreholes depend on:
   (a) Type of the dam.
   (b) Height of the dam.
   (c) Geological complexity of the dam site and reservoir area.

However, the following aspects should be considered:

(i) All boreholes should be drilled by full core recovery type.
(ii) The core recovery should not be less than 85%.
(iii) RQD should be calculated.
(iv) Depth of the boreholes should not be less than the deepest karstified bedrocks, expansive clays, fractured and/or sheared zones, active faults (if any); otherwise deeper than the cut-off depth of the foundations. In such case the depth should be at least 1.5 H, where (H) is the maximum hydraulic head acting on the foundation as a rule of thumb.
(v) The site geologists should be well experienced in core description, especially karstified rocks and/or karst filling materials.
(vi) Systematic sampling of the extracted core in order to apply required geotechnical tests which will provide the mechanical properties of the penetrated rocks.
(vii) Applying chemical analyses for the cored rocks and unconsolidated materials, especially those which will be used in construction of different parts of the dam. +
(viii) Applying colored photography of the extracted core before sampling but after being cleaned from the drilling mud and/or fluids. The colored photos may be used during the construction of the dam or

even during commissioning when needed for certain use.

(xi) Applying geophysical logging for the all drilled boreholes to indicate:

- To correct the drilling depths of the penetrated rocks.
- To indicated the mechanical properties of the penetrated rocks.
- To indicate cavities, voids, fractured and/or sheared zones in the borehole.

(x) Full scale Lugeon field permeability tests may be necessary in important cases when permeability is questionable

4. *Karstification* Karstification is one of the main significant processes which should be studied to indicate whether the dam site and reservoir area suffer from karstification or otherwise. Karstification can be of two main types:

(a) *Surface Karst* When karstification is on surface, then its indications can be seen and recognized by experienced geologists, among those indications are:

(i) Presence of karst forms such as sinkholes (of all types and sizes, including active and inactive forms).

(ii) Presence of circular and/or crescent-shaped cracks on surface which may indicate the presence of shallow karst forms (Fig. 2).

(iii) Presence of blind valleys.

(b) *Subsurface Karst* This type is more dangerous than the surface karst, because it may not be detected in the dam site, foundation area, reservoir area and other structures of the dam by the site geologist. Accordingly, significant problems will arise during construction and commissioning of the dam (Jassim et al. 1987, Fig. 3). The presence of subsurface karst forms can be detected by:

(i) Interpretation of high resolution satellite images, where different indications can be recognized by well experienced geologist, among them are (Sissakian and Abdul-Jabbar 2005):

- Presence of false dipping towards certain side.
- Presence of abnormal valleys.
- Crossing of rock beds to the valleys without obeying the V-rule of dipping beds (Figs. 4 and 5).

(ii) Falling of the drilling pipes during continuous core drilling operation.

(iii) Loss of the drilling water and/or muds during continuous core drilling operation.

(iv) Loss of the core.

(v) Presence of Terra Rosa (red soil, karst filling material) is indication for karstification. Such clayey soil was interpreted as “bauxite” in Mosul Dam by Swiss Consultants Consortium (1989) and Wakeley et al. (2007) and interpreted as Terra Rosa by Sissakian et al. (2017).

(vi) Interpretation of the logging data to indicate karst cavities or otherwise.

5. *Slope Stability Analysis* All slopes (natural and man-made) in the dam site and reservoir area should be studied and analyzed to recognize their activity and all other slope stability problems. All existing types should be carefully mapped (Fig. 2) and analyzed, and to indicate if they are active or inactive forms. Moreover, all prone areas for mass movements should be clearly indicated and treated relevantly.

6. *Hydrogeological Studies* The groundwater in the dam site and reservoir area should be studied and mapped including:

(a) Depth of the groundwater.
(b) Type of the groundwater.
(c) Type of the aquifer(s).
(d) Corrosiveness of the groundwater and salts contents.

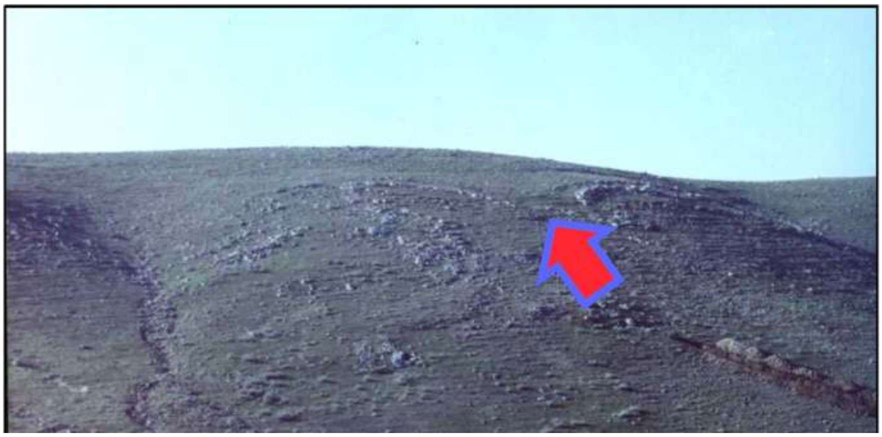

Fig. 2 False dipping and crossing of valleys by the dipping rocks without obeying the V-rule

Fig. 3 Subsurface karst forms (red arrows) appeared after excavation of an industrial site within the rocks of the Fatha Formation in Shiekh Ibrahim anticline 45 km south of Mosul Dam. Note the crossing of valleys by the dipping rocks without obeying the V-rule (Blue arrow)

(e) Seepages of the groundwater; their locations and quantity.
(f) Checking for new seepages during constructions and commissioning, and the difference in the yield quantities of existing seepages.

7. *Geophysical Studies* Different types of geophysical studies should be performed in the dam site and reservoir area to indicate the following data:

(a) To indicate groundwater level by means of Electrical Method.
(b) To indicate subsurface caverns (Karst forms) by means of Micro-gravity Method, or even by using geo-radar investigations in important cases.
(c) To indicate the mechanical properties of the rocks and the depth of the weathering zone by means of seismic refraction and gravity Methods.

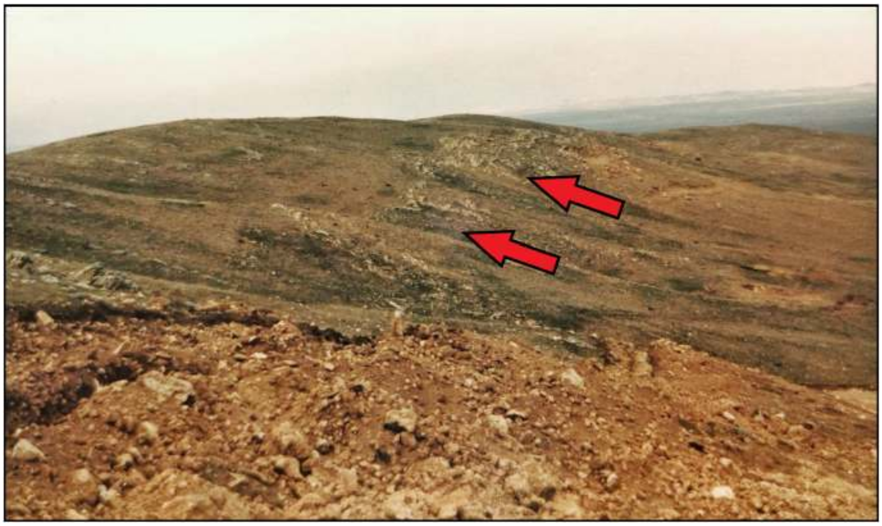

Fig. 4 Crossing of valleys by the dipping rocks without obeying the V-rule

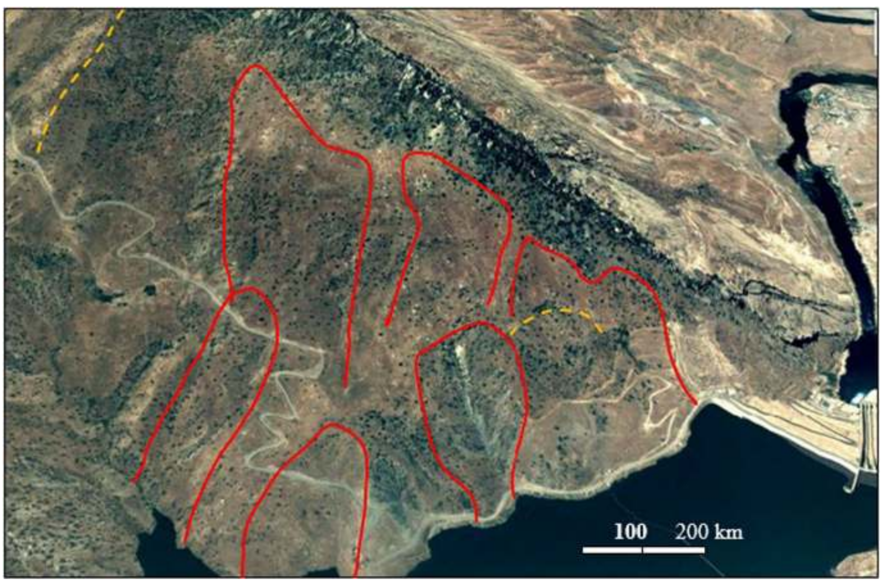

Fig. 5 Interpreted satellite image near Derbendikhan Dam showing unstable slopes in red lines and dashed orange lines shows cliffs (after Sissakian et al. 2019)

8. *Seismicity Study* Seismic zonation map should be consulted during the site investigation. In seismically active area, it is necessary to assess the degree of earthquake tremors and design must include provisions for the added loading and increased stresses. Historical seismicity studies are also required in case of important dams to have a complete file of the seismic events that might hit the site.

9. *Burrow Areas* Construction of a dam requires large quantity of construction materials like soil, rock, concrete and aggregates. The most economical type of dam will often be the one for which materials are to be found in sufficient quantity at a reasonable distance from the site. So availability of such materials nearby the proposed site should be assessed during the geological investigation. Different laboratory and in-situe tests should be applied to elucidate the characteristics of the

materials found in burrow areas and which will be used in the dam's construction.

4 Mosul Dam: A Case Study

4.1 History of Mosul Dam Project

The investigations for building Mosul Dam project started in 1950 and it was referred to as Aski Mosul Dam. The location of the dam was suggested in 1953 to be at a village called "Dhaw Al-Qamar", which is located 12 km north of Aski Mosul village. The dam was designed so that its capacity reaches 8.7 km^3 at 320 m (a.s.l.) while the maximum elevation of the dam reaches 324 m (a.s.l.). In 1956, the Iraqi Government asked Harza Company to perform a new site survey and design for the dam. In 1960, Harza Company suggested two sites for the dam; different from those suggested earlier by other companies, because the dam will be built on highly soluble gypsum and very thin clay beds. The first suggested site was to build a dam with a storage capacity of 7.8 km^3 and the other site was with a storage capacity of 13.5 km^3. In 1962, the Iraqi Government asked Techno-prom Export (Soviet company) to perform another investigation for the site of Mosul Dam. The company suggested a new site that is 600 m south of the site suggested by Harza Company. The dam was designed with a storage capacity of 7.7 km^3 (Al-Ansari et al. 2015a, b).

All the above companies suggested that the dam should be of an earthfill type with compressed clay core, but there were different views about the exact location of the dam. Grouting was suggested to be performed under the dam, spillway and the electricity generation station as foundation treatment. In addition, they suggested that detailed geological investigation should be performed before any construction activities should begin. In view of these reports, the Iraqi Government asked a Finish company "AmitranVoima" in 1965 to carry out new investigations. The company suggested a site, which is located 60 km northwest of Mosul city and they pointed out that the geology of the area is very complex and required further investigations, therefore a Yugoslavian company (Geotechinka) worked on further geological investigations at the suggested site in 1972. AmitranVoima then again carried out more investigation in 1973. All the reports were then studied by the International Board of Dams Experts which was appointed by the Government in 1974 and recommended extra geological investigations. In a further step the Iraqi Directorate General for Dams asked a French company (Soletanch) to perform more geological investigation on the suggested site. This was done during 1974–1978). Later on in 1978, the Swiss Consultants Consortium was asked to be the consultants for Mosul Dam project and a consortium of German and Italian companies (GIMOD) was asked to execute the civil and steel works of the project in 1980. The work started on 25th January, 1981 and finished 24th July, 1986 (Al-Ansari et al. 2015a, b).

4.2 Details of Mosul Dam

Mosul Dam is one of the most important strategic projects in Iraq for the management of its water resources. The dam was constructed on the Tigris River (Fig. 1), it is located 60 km northwest of Mosul city. The dam is 113 m high, 3650 m long including the spillway, has a 10 m top width and the crest level is 341 m (a.s.l.). The dam is faced with rock and has an earth fill with a clay core. The dam was designed to impound 11.11 km^3 of water at normal operation level of 330 m (a.s.l.), including 8.16 km^3 and 2.95 km^3 of live storage and dead storage, respectively. The dam has a concrete spillway located on the left abutment.

4.3 Geology of the Mosul Dam Site

The oldest exposed rocks in Mosul Dam site belong to the Fatha Formation of Middle Miocene age; however, in the reservoir area, the oldest exposed rocks belong to the Pila Spi Formation of Late Eocene age (Fig. 6). The exposed formations in the dam site and reservoir area are described briefly hereinafter (Sissakian and Al-Jiburi 2014).

- *Pila Spi Formation* (Late Eocene): small outcrops of the Pila Spi Formation are exposed in the extreme northwestern side of the reservoir (Fig. 6). The formation consists of well bedded, dolomite, dolomitic limestone, limestone and rare marl. The exposed thickness of the formation is few meters only.

- *Euphrates Formation* (Early Miocene): the Euphrates Formation is exposed in the core of some anticlines in the reservoir area (Fig. 6), as well in the foundations of the dam. The formation consists of well bedded, hard limestone, marly limestone and dolomitic limestone. Some of the limestone beds are karstified as indicated by the presence of sinkholes. The thickness of the formation in nearby areas ranges from (15–50) m.
- *Jeribe Formation* (Middle Miocene): the Jeribe Formation is not recorded to be exposed in the dam site and reservoir area. However, the formation is recorded in the foundations of the dam (Sissakian et al. 2014). The formation consists of well bedded, hard limestone. The thickness in near surroundings is about 60 m.
- *Fatha Formation* (Middle Miocene): the Fatha Formation is widely exposed in the dam site and reservoir area (Fig. 6). The formation is characterized by cyclic sediments, the thickness of the formation is variable; in Butmah is 392 m, in Ain Zala 325. The formation consists of two members; these are:

  Lower Member the Lower Member consists of cyclic sediments, each cycle consists of green marl, limestone and gypsum. The abutments of the dam are located within this member. The rocks of this member are highly karstified, not only in the dam site and the reservoir area, but else-where in Iraq.

  Upper Member the Upper Member consists of cyclic sediments, each cycle consists of green marl, red claystone limestone and gypsum; in the uppermost part reddish brown sandstone is present. This member covers majority of the reservoir area.

- *Injana Formation* (Late Miocene): the Injana Formation is exposed in the eastern, northeastern and some parts of the northern banks of the reservoir (Fig. 6). The formation consists of fining upwards cyclic sediments of reddish brown sandstone, siltstone and claystone. The thickness of the formation is variable ranges from (200–330) m.
- *Mukdadiya Formation* (Late Miocene–Pliocene): the Mukdadiya Formation is exposed in the eastern bank of the reservoir (Fig. 6). The formation consists of fining upwards cyclic sediments of grey sandstone, siltstone and claystone; some of the sandstone beds are pebbly. The thickness of the formation is variable ranges from (100–230) m.

Mosul Dam site and reservoir area are located within the Low Folded Zone; within the Outer

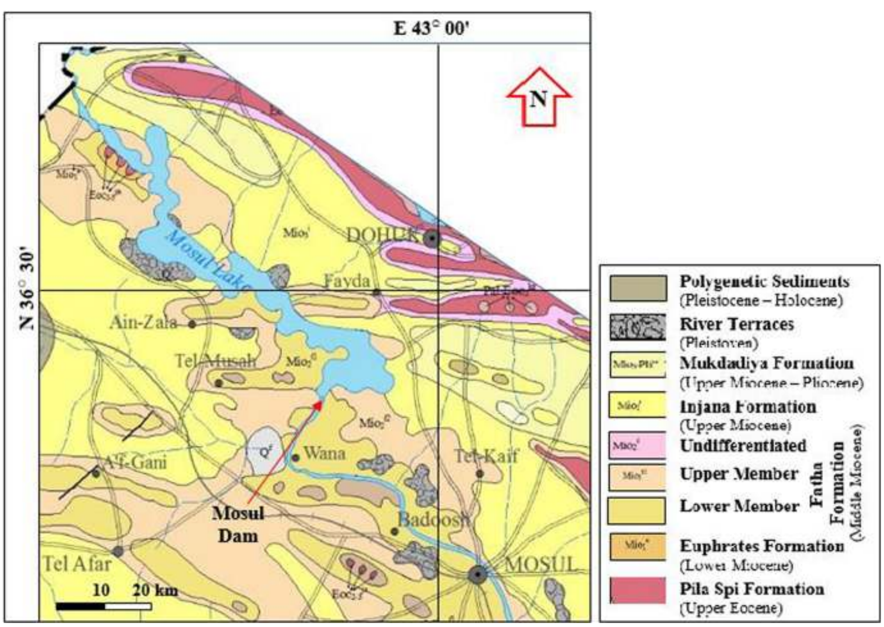

Fig. 6 Geological map of Mosul Dam and reservoir area (after Sissakian and Fouad 2012)

Platform of the Arabian Plate. The Outer Platform is also part of the Zagros Fold–Thrust Belt (Fouad 2007). Although many deep seated faults and surface faults occur in the dam site and reservoir area, but without any significant effect on the stability of the dam.

4.4 Karstification Problems in Mosul Dam

The geology of Mosul Dam site is characterized by the presence of four layers of brecciated gypsum (GB 0, GB 1, GB 2 and GB 3) within the Fatha Formation. These layers have thicknesses which range of (8–18) m (Swiss Consultants Consortium 1984, 1989). The GB 0 is at a depth of 80 m from the ground surface in the river section, while GB 3 was uncovered in the excavation of the foundations of the spillway (Fig. 7).

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. Therefore, the grouting process was not effective although it had started with construction of the dam and is still on going. The failing to find proper solutions for the continuous seepage seemed to originate from the miss-interpretation of the basic geological facts, which means not recognizing geological facts, for example the encountered Terra Rosa (a good indication for karstification) in the boreholes of Mosul Dam was interpreted as "Bauxite" although such bauxite also indicates karst depressions. Moreover, miss-judgement of gypsum rock behavior 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 main reason for failing in the grouting process is attributed to miss-interpretation of the acquired data from core description and from applying the Lugeon tests to identify the depth of the karstified gypsum beds below the foundations. Figures 7 and 8 show constructed geological cross sections indicating the karst line running in varying depths along the axis of the dam (Modacom 1984). It is clear that many gypsum beds exist below the constructed karst line; therefore, grouting to fill the karst cavities in the foundations will not be effective because karstified gypsum beds still occur below the depth to which grouting is applied.

Another miss-interpretation is the encountered Terra-rossa (reddish brown clayey soil) in the boreholes and even in the excavations which was described as "Bauxite". The presence of the Terra-rossa is good indication for karstification. Moreover, the used lithological terms (Fig. 9) is good indication that the site geologist was not familiar with karst filling sediments; accordingly, he missed interpreting the existing karst forms below the dam's foundation (Figs. 7 and 8).

5 Discussion

In the current study, we have emphasized the role of the geological investigation in dam siting and the consequences when the investigation is inadequate. This means, the aforementioned instructions and

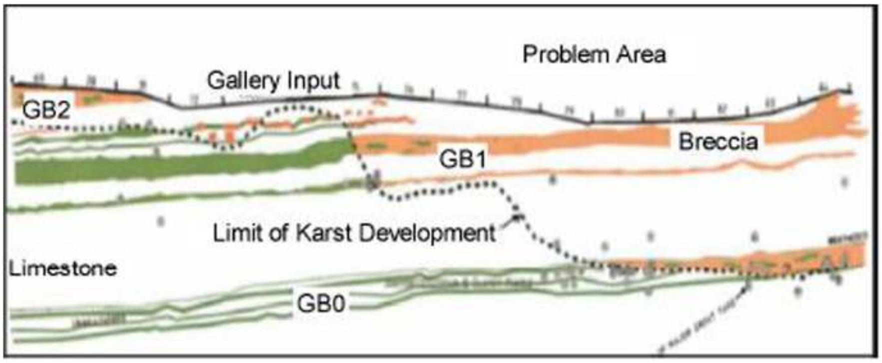

Fig. 7 Karst line location under the dam (after Adamo and Al-Ansari 2016). Note the extension of the karst line which crosses different beds irrespective to the dipping of the beds and the presence of many gypsum beds (GB 0) below the line

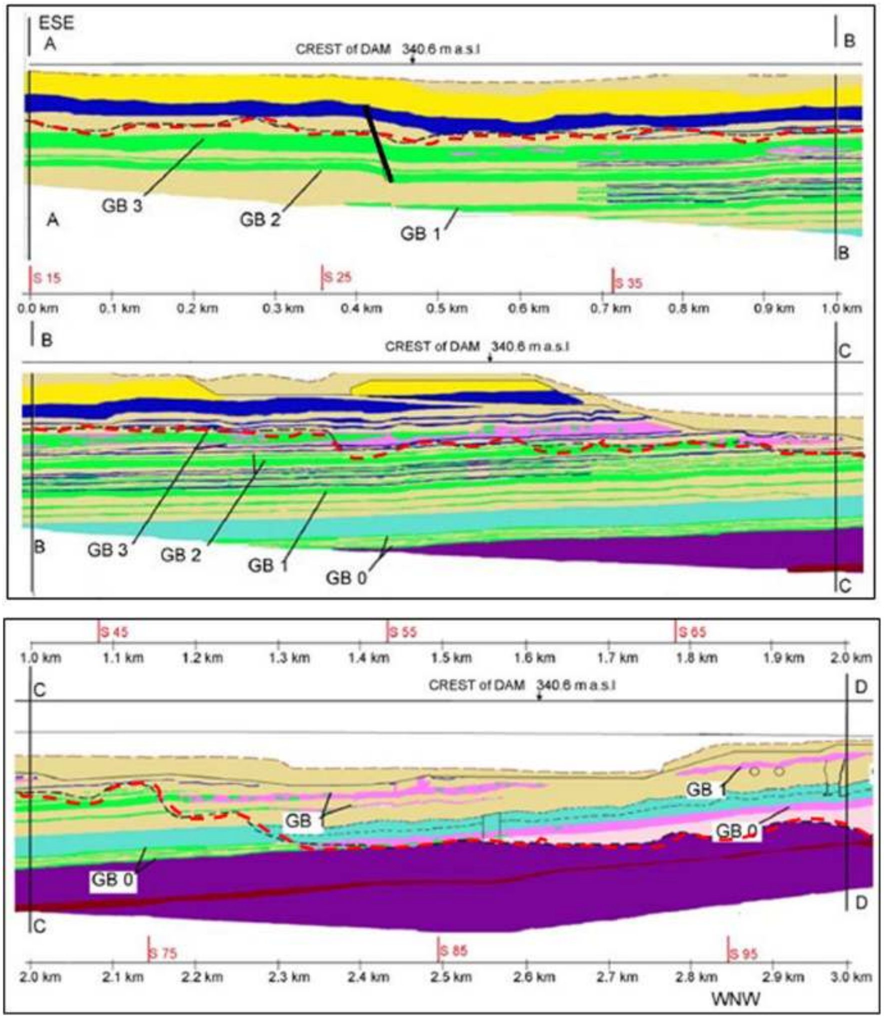

Fig. 8 Geological section starts from (East) at upper left corner to (West) at bottom lower (Modacom 1984 in Adamo and Al-Ansari 2016). Note the constructed karst line (dashed red line) and note the gypsum beds below the karst line. For legend, refer to Fig. 9)

necessary works were not performed, either in quantity or quality. Moreover, we have emphasized on the karstification problems, since large parts of Iraq are karstified and suffer from existing problems.

To have adequate geological investigation and a safe dam site, it is necessary to perform the geological investigation in the following three steps.

1. *Preliminary Investigations* This investigation should provide a first general impression of the engineering and geological aspects of the proposed site(s). The field work generally would include preliminary field geologic mapping, some preliminary hand auger holes for soil and overburden sampling, a limited number of core holes into rock and possibly some preliminary seismic refraction lines. This information would be used to answer questions raised by an office study. The data would also be used to plan the type, location, and amount of explorations and laboratory testing required for future, more detailed investigations. Air photos and satellite images can also give good guide in interpreting the geological forms at the site(s).
2. *Initial Design Investigations* These investigations would be undertaken to provide more detailed information on foundation characteristics on a particular site or several sites, and to provide data

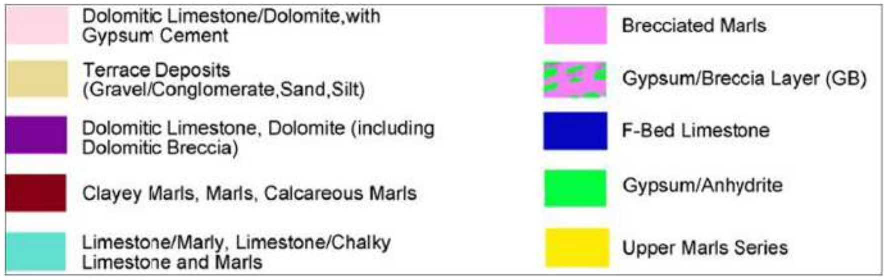

Fig. 9 Lithological legend for Fig. 7

for preliminary considerations of the design requirements and construction methods. This phase of field investigation should include surface and subsurface exploration and sampling through borings, test pits, test trenches, material testing, geologic mapping, and additional geophysical surveys to supplement drilling. Data developed from these activities should be used to compare alternative sites, to analyze different types of structures that might serve the same purpose, and to develop economic evaluations of the sites. An end product of this investigation is to rank the studied sites (usually three sites).

3. *Final Design Investigation* These investigations would be primarily composed of detailed drilling, sampling, and testing concentrated on specific features at the selected project site; and should be specifically planned to provide the engineer with information that is necessary to design structures, estimate quantities, determine rates of construction progress, develop cost estimates, prepare plans and specifications, and obtain bids.

6 Conclusions

The main conclusion of the current study is the performance of geological investigation in different levels is very necessary in dam siting and having a safe dam without or with minimum maintenance works to keep the dam as safe as possible. Moreover, geological investigation should be carried out by well experienced geologists, geotechnical engineers with a relevant consultant firm. Since we have emphasized on karstification and related problems; therefore, the geologists and geotechnical engineers should be well experienced in karst forms and karst filling sediments. The geological investigation should cover the dam site, the structures of the dam, foundation and reservoir area.

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