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Mystery of Mosul Dam the most Dangerous Dam in the World: Karstification and sinkholes

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Abstract

The Fatha (ex-Lower Fars) Formation (Middle Miocene) is the predominant stratigraphic unit in the Mosul Dam area. It is about 250 meters thick near Mosul. Marls, chalky limestone, gypsum, anhydrite, and limestone form a layered sequence of rocks under the foundation of the dam. The foundation of the dam is mainly resting on the Fatha Formation (Middle Miocene) which is highly karstified. Karstic limestone and the development of solution cavities within the gypsum and anhydrite layers are the main geological features under the foundation of the dam. The right (west) abutment is located in the steeply dipping Fatha Formation within Butmah East anticline with SE plunge being in the reservoir north of the dam, whereas the left (east) abutment is located on gently dipping beds of the Fatha Formation, which is overlain by fine clastics of the Injana Formation. These differences in lithology as well the dip amount and direction along both abutments as well upstream and downstream of the dam have certainly affected on the hydraulic pressure and increased the dissolution ability of the gypsum and limestone beds, along the abutments and the foundations, which are already karstified in nearby areas. Consequently, more gypsum, anhydrite and limestone beds are dissolved and karst openings are continuously increasing, as the exerted hydraulic pressure is continuous. First appearance of sinkholes on the right bank down-stream was not until approximately six years after the filling of the reservoir began. The surface expression of the sinkholes suggests that they are caused by an under-ground collapse. Concentric tension cracks appear to have developed around the central void as the sinkholes have developed progressively. Karstification and

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formation of sinkholes are the most dangerous features threatening the safety of Mosul dam.

Keywords: Karstification, Sinkholes, Mosul Dam, Iraq, Fatha Formation

1 Introduction

Karst topography forms due to the dissolution of soluble rocks like gypsum, and limestone and less common dolomite. It is usually characterized by underground system of dolines, caves and sinkholes. This phenomenon is usually associated with different features. They might be large features like limestone pavements, poljes, and karst valleys, or medium size features like sinkholes or closed basins (cenotes), vertical shafts, inverted funnels shaped sinkholes (foibe) and small size features like flutes, runnels, clints and grikes, collectively called karren or lapiez. Internal drainage, subsidence, and collapse triggered by the development of underlying caves are the processes that forms the surface karst features [1]. Rainwater becomes acidic in contact with carbon dioxide in the atmosphere and in the soil. When water infiltrates in rocks it will start to dissolve away the rocks. This will create a network of passages. Over time, water flowing through such network continues to erode and enlarge the passages; this will allow the plumbing system to transport larger amounts of water [2]. Sinkhole is a hole or depression in the ground formed by the collapse of the surface layer or by the karst process. They vary in size, depth and shape. They are more common in areas where the rocks below the land surface are limestones or other carbonate rocks, salt beds, or gypsum, that can be dissolved naturally by circulating ground water.

Sinkholes are either active or inactive. Those, which are still active have one or more outlet in their floors, which extend into shallow funnel shaped caves [3,4] this means that the active sinkholes have the ability to drain the infilling water to deeper horizons, or ground water runs through them. These types of sinkholes are certainly more problematic. The indications of the activity are [3]:

- bare floor or with very rare soil cover
- presence of one or more outlet in the floor
- presence of fallen rock blocks from the rim in the floor
- presence of circular or crescent-shaped cracks around the rim
- presence of ground water in the floor

Those sinkholes, which are inactive, are less problematic, because they exhibit less deformation to the near surroundings. This attributed to the fact that they will not be able to transfer water into deep horizons, or at least the transferred amount is lesser; if compared with those of active sinkholes with same size and same conditions. The inactivity of the sinkholes is indicated by[3]:

- spoon shape
- cover of thick soil in the floor
- absence of fallen blocks from the walls and /or the rims in the floor

- absence of outlets in the floor
- presence of outlets in the rim
- presence of water accumulation after heavy rain showers, in the floor
- presence of vegetation in the floor during rainy seasons
- absences of cracks around the rims

One of the main reasons of the karstification is dissolving of the limestone by carbonic acid, which is formed by reaction of the water with carbon dioxide. However, gypsum is dissolved by sulfuric acid, which is formed by reaction of the oxygen with H_2S. As oxygen (O_2)-rich surface waters seep into deep anoxic karst systems, it brings oxygen which reacts with sulfide present in the system (H_2S) to form sulfuric acid (H_2SO_4). Sulfuric acid then reacts with calcium carbonate causing increasing erosion within the limestone formation. This chain of reactions is:

$H_2S + 2\ O_2 \rightarrow H_2SO_4$ (sulfide oxidation)

$H_2SO4 + 2\ H_2O.\ SO4 – 2 + 2H_3O+$ (sulfuric acid dissociation) (sulfuric acid issociation)

$CaCO_3 + 2\ H_3O^+ \rightarrow Ca^{2+} + H_2CO_3 + 2\ H_2O$ (calcium carbonate dissolution)

$CaCO_3 + H_2SO_4 \rightarrow CaSO_4 + H_2CO_3$ (global reaction leading to calcium sulfate)

$CaSO_4 + 2\ H_2O \rightarrow CaSO_4 \cdot 2\ H_2O$ (hydration and gypsum formation)

It is worth mentioning that the Fatha Formation is an excellent source for H_2S, which is emitted due to the presence of native sulfur; almost everywhere in the formation. The area within the vicinity of Mosul dam (Fig. 1) is characterized by its karst topography and the presence and appearance of sinkholes. In this section these phenomenon will be discussed in Mosul Dam area.

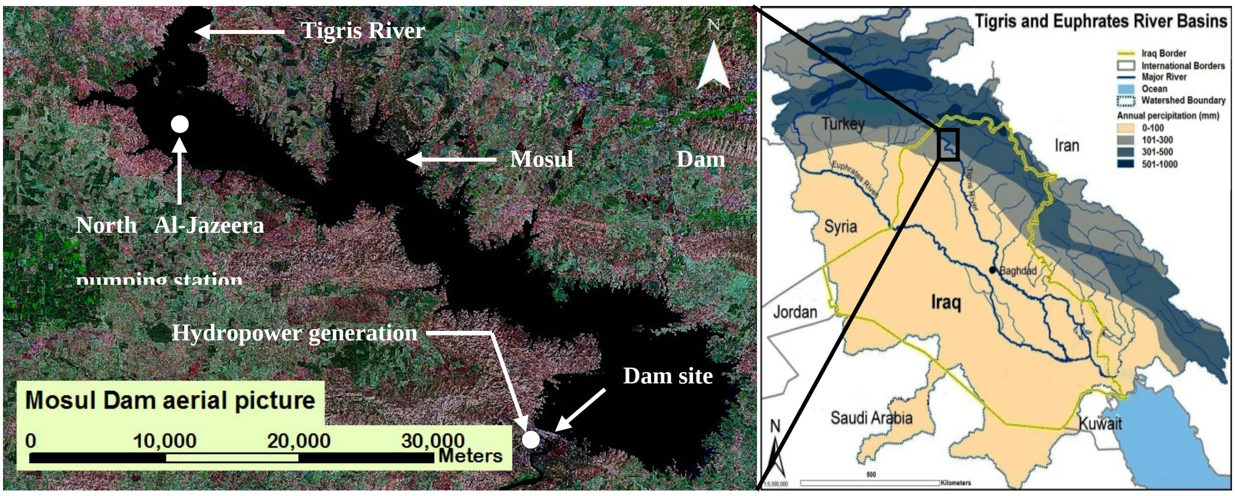

Figure 1: Location of Mosul dam with main facilities.

2 Geology of the dam site

The Fatha Formation (Lower Fars) (Middle Miocene) is the predominant stratigraphic unit in the Mosul Dam area. It is about 250 meters thick near Mosul [5]. Marl, chalky limestone, gypsum, anhydrite, and limestone form a layered sequence of rocks under the foundation of the dam. The foundation of the dam is mainly resting on Fatha Formation (Middle Miocene).

The foundations of the dam are located on the Lower Member of the Fatha Formation and the Jeribe Formation [6,7], although the Jeribe Formation was not recognized during the regional geological survey of the involved area and instead the Euphrates Formation was mapped [8]. Lithologically, there is not a difference between the Jeribe and Euphrates formations, but no karstification is reported in the exposed rocks of the Jeribe Formation, whereas the Euphrates Formation is highly karstified in different parts of Iraq, among them is Haditha vicinity near Hadith Dam site [3,9,10].

The right (west) abutment is located in the steeply dipping Fatha Formation within Butmah East anticline with SE plunge being in the reservoir north of the dam, whereas the left (east) abutment is located on gently dipping beds of the Fatha Formation, which is overlain by fine clastics of the Injana Formation. These differences in lithology as well the dip amount and direction along both abutments as well upstream and downstream of the dam have certainly affected on the hydraulic pressure and increased the dissolution ability of the gypsum and limestone beds, along the abutments and the foundations, which are already karstified in nearby areas. Consequently, more gypsum, anhydrite and limestone were dissolved and karst openings are continuously increased, as the exerted hydraulic pressure is continuous. Figure 2 show the detailed description of the beds at Mosul Dam site.

It should be mentioned however, that karstic limestone and the development of solution cavities within the gypsum and anhydrite layers are the main geological features under the foundation of the dam. The bore holes data indicated that four significant gypsum units were identified during design and construction varying in thickness from 8 to 16m and identified as GB0 (Gypsum Breccia 0), GB1, GB2, and GB3 in ascending order (Fig.3) [7].

The development of voids requires continuous grouting is mainly due to the dissolution and erosion of gypsum by water seeping under the dam.[7] believes that the erosion and dissolution rates in gypsum are related to the seepage velocities and hydraulic gradient. When calcium sulfate saturation is lower than approximately 2,000 ppm in seepage water, gypsum dissolution continues this zone will move downstream as greater quantities of unsaturated water attack a gypsum bed.

At Mosul dam site, major dissolution occurs at the “karstic line”, where anhydrite converts to gypsum and this unit is subsequently dissolved and eroded by seepage (Fig. 4). This phenomenon of evaporites dissolution by groundwater and the void is generally filled with collapse breccias from the overlying beds (Fig. 5) [11].

3 Karstification

The presence of rocks with high dissolution ability; such as limestone and gypsum in the abutments and foundations of dams, will certainly form karstification phenomenon, which will be increased with time, especially when karstification factors are available. Dissolution intensity at Mosul Dam ranged from 42 to 80 tons per day. This process coupled with the karstified limestone, dolomite, and marl as well as the evaporate rocks present the unfavorable foundation conditions under Mosul Dam. The karst line also denotes the transition from the interbedded limestone-anhydrite/ gypsum beds to the less permeable Jeribe limestone [12].

First appearance of the sinkholes on the right bank down-stream was not until approximately six years after beginning of the reservoir filling (Fig. 6). The surface expression of the sinkholes suggests that they are caused by an under-ground collapse. Concentric tension cracks appear to have developed around the central void as the sinkholes have developed progressively [7].

The majority of karst forms are sinkholes (Figures 6) (dolines), developed in gypsum and/ or limestone; however, many other forms are developed too, such as Karren, shafts, channels.

Downstream sinkholes are most likely related to fluctuations in the tail water level of the main dam during operation of the dam and the down-stream regulating reservoir [132]. These sinkholes may be connected to an aquifer on the right bank of the reservoir because before the reservoir was impounded, substantial flows of order of 360 L/sec were encountered from a gypsum layer found during excavation of the tailrace tunnel for the pumped storage scheme; the water had a high sulphate content which was different from the reservoir water (Fig. 7). The karst line also denotes the transition from the interbedded lime-stone-anhydrite/gypsum beds to the less permeable Jeribe limestone (Fig. 8) [12].

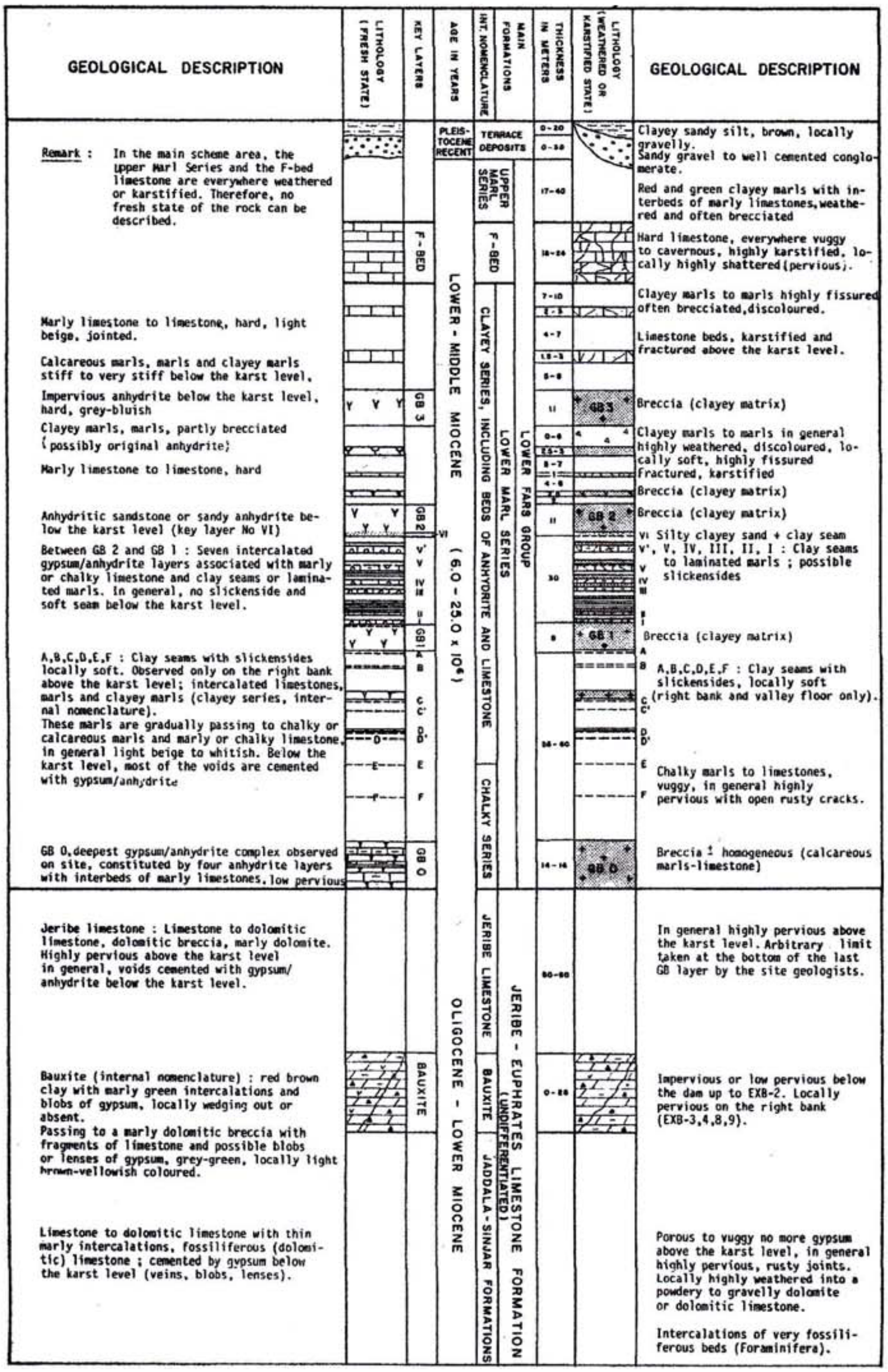

Fig. 2: Lithological column of beds at Mosul Dam site [7].

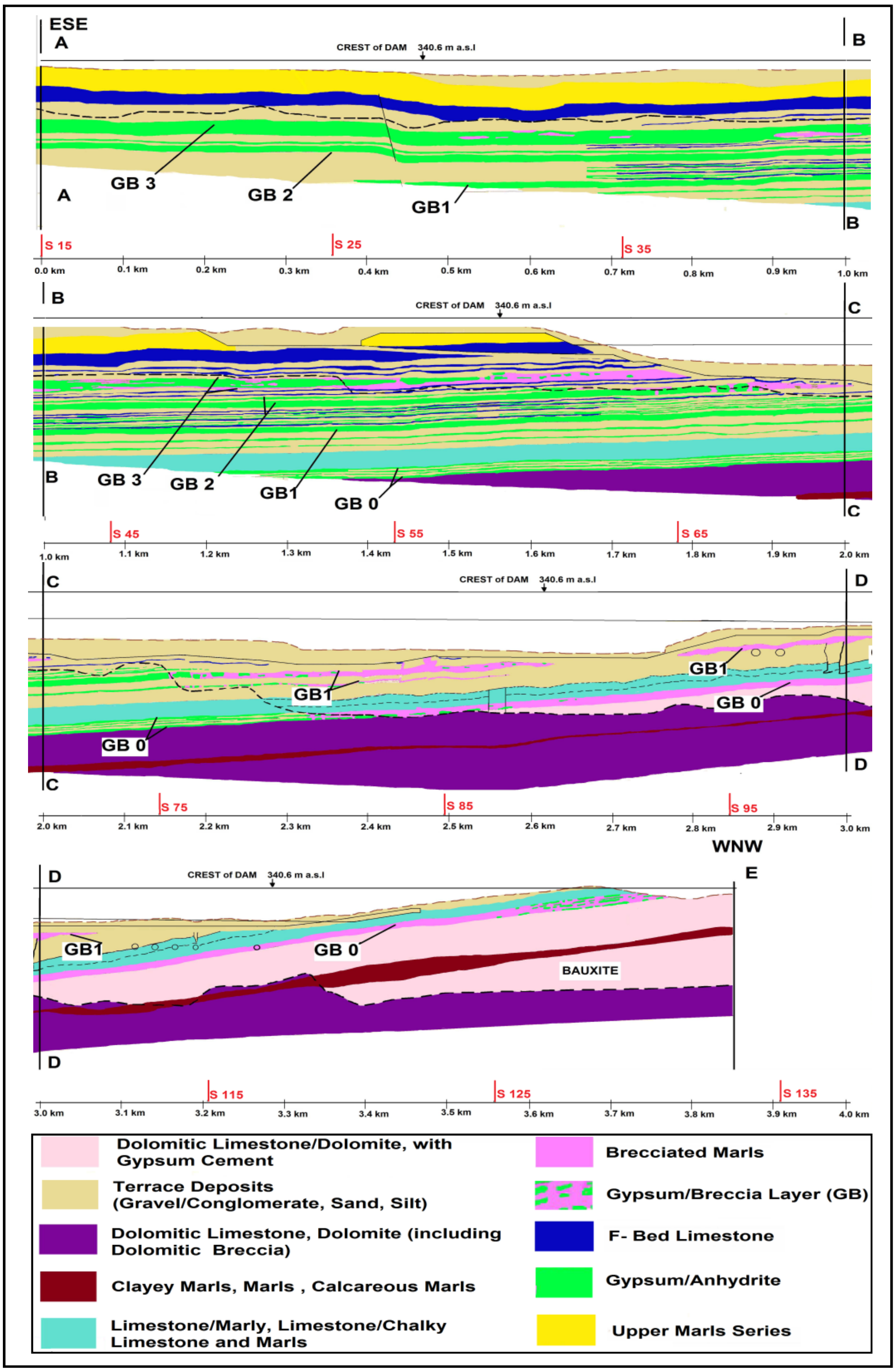

Fig. 3: Geologic cross section along the axis of the dam.

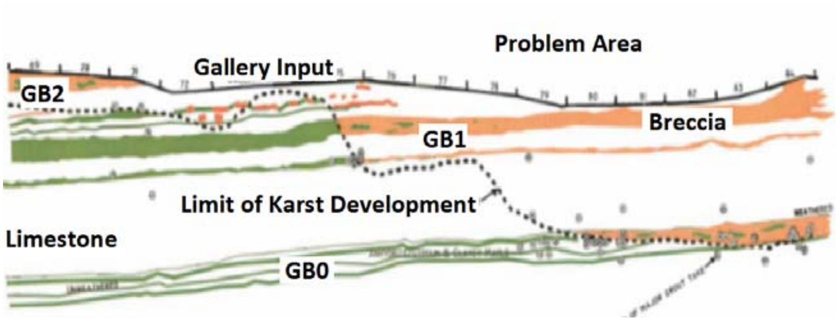

Fig. 4: Major Grout Takes in Sections 69-84 [7].

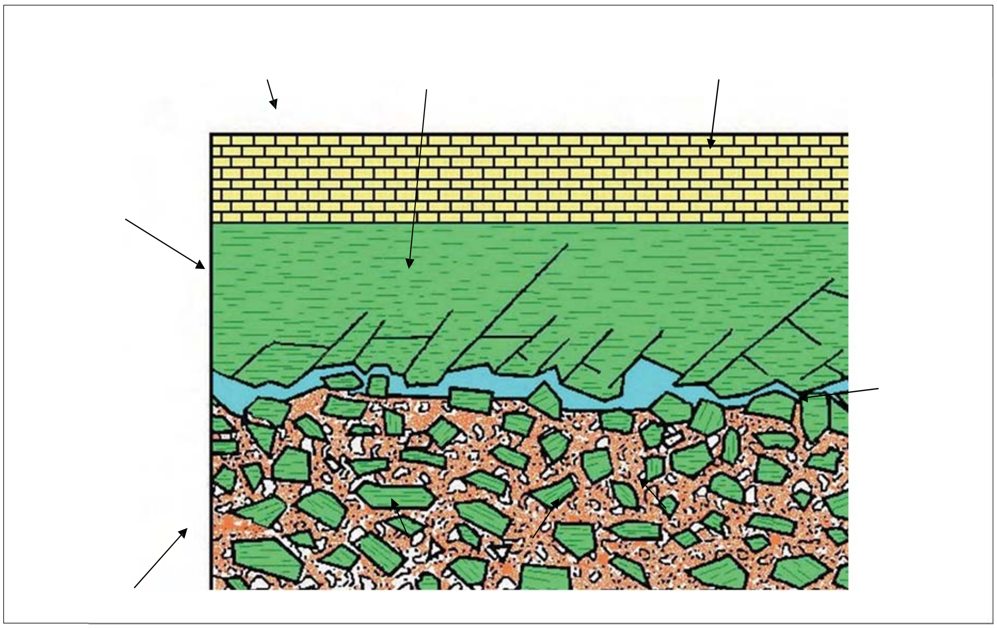

Fig. 5: Development of breccia within a layer of gypsum [11].

Fig.6: A sinkhole appeared during the 90's at the downstream right bank near the contractor yard.

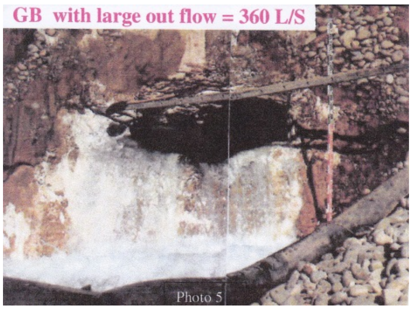

Fig. 7: Spring of discharge 360l/sec which is connected to the ground water aquifer connected to the reservoir

Karst development extends to a depth of about 100 m below the base of the dam. This may be a relict karst from a former climatic regime when groundwater levels were lower. The concerns in the limestone units are basically related to the existing caverns, voids, and fractures and not so much due to the erosion and dissolution process, as limestone generally dissolves at very slow rates. The main drawback to the site is the presence of soluble rocks by the presence of anhydrite and gypsum and the associated karst conditions at the foundation [14]. Karst area has high permeability conduits that convey substantial quantities of water at varying velocities.

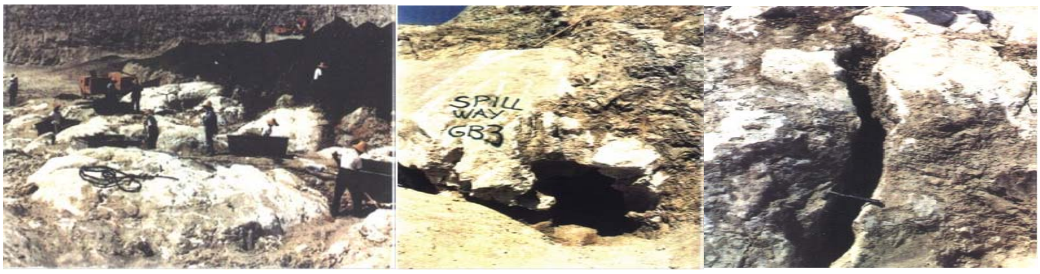

Fig. 8: Karstified gypsum in the foundations of the dam (left and middle), Solution crack (right).

Surface cracking and ground settlement initially developed followed by appearance of sinkholes on the right abutment. Sinkholes on the left flank of the reservoir (in the local tourist village) appeared without warning and developed rapidly with 15 m of settlement and a 15 m diameter depression overnight in February 2003 (Fig.7). The sinkhole was dry, located on a slope on the northern side of a valley feature. The deposits at the surface standing vertically appear to be superficial silty soils, with perhaps bedded marls below. Although the initial sinkhole was filled with 1200 m^3 of loose sandy gravel material and fenced off, but the settlement continued. A further 3000 m^3 of material was required to fill the settled surface of the sinkhole in two separate filling operations in May 2003 and October 2004. By March 2005 there were been a smaller settlement of the ground surface of about 0.5 m.

During the drilling of a piezometer hole near the sinkhole, a rod drop occurred. There was no water encountered in the hole so the piezometer was not installed, and the hole was grouted, taking 250 tons of grout. The suggestion was been made that the sudden appearance of the sinkhole is related to seepage water passing through the left abutment of the reservoir and the sinkhole lies close to the end of the left extension of the original grout curtain. Though possible, an increase in infiltration of surface water, perhaps from heavy rain, could cause a collapse into an existing void by destabilizing the ground [13]. Ground movement or collapse may have been initiated by changes in groundwater on impoundment of water in the regulating reservoir for those in the valley downstream of the main dam. The alignment of the sinkholes downstream of the dam strongly suggests a geological (structural) control and relatively near surface phenomenon. However, it has not been possible to verify this either by carrying out detailed geological field studies at the site or by obtaining high quality aerial photo-graphs [14].

About 100 m up-stream from the dam, on the right abutment of the reservoir, a dipping limestone bed near the margin of the reservoir shows ground settlement. This movement could be partly related to sloping failure and translation of the rock beds as a result of fluctuating reservoir levels and residual high pore pressures in the slope. However, a sinkhole feature seems more likely (Fig.9). Although tested for, no connection has been established between this upstream sinkhole and those downstream [6]. It is believed that in some cases soil failure takes place (Fig. 10), which could be initiated due to over saturation of the soil by rain water. In addition slab failure (Fig. 11) was also recognized, most probably due to fluctuation of the water level in the reservoir.

Fig.9: Left photo show the Ground settlement before the full development of the left bank sinkhole.

Fig.10: Soil failure.

Fig.11: Upstream right abutment, open fissure resulting from slab sliding.

The prediction of sinkhole formation as well as the development of water bearing solution conduits beneath the embankment is obviously a critical issue. Previous surveys using echo sounding near the dam in the reservoir have reportedly not detected any evidence of sinkholes in the reservoir floor upstream of the dam. These surveys have recorded that sediment accumulation in the reservoir is limited to only about 1 m. This helps to blanket the floor of the reservoir and thus reduce inflow into the beds that might outcrop within the reservoir basin [6]. Hijab et.al. [15], however, confirmed that some of the sinkholes are related to the reservoir. Their development is attributed to the development of underground conduits.

It is very clear that the karstification in Mosul dam site is still active. It is also increasing in its activity causing a serious geological hazard to the status of the dam, if no relevant precautions are performed. This is also indicated from continuous grouting in the foundations of the dam. However, location of the sinkholes can be detected by means of geophysical studies [15]. Moreover, it is also possible to delineate the location of the subsurface channels (conduits) that are developed due to groundwater movement and dissolution of limestone and gypsum beds, which are the main rock types in Mosul dam site.

Al-Ansari et.al. and Issa et al. [16,17] conducted a bathymetric survey during 2011 and concluded that "After 25 years of the dam operation following; the thalweg bed slope of the River Tigris had changed from 0.65 $m.km^{-1}$ before dam construction to 0.71 $m.km^{-1}$. The sedimentation rate in the upper section of the reservoir where the River Tigris enters the reservoir was greatest and gradually decreased toward the Mosul dam site. The greatest deposition thickness was 17.6 m in the upper zone of the reservoir. Furthermore, there are many areas like the middle and lower parts of the reservoir that are exposed to erosion (Fig. 12). This is believed to be due to the dissolution of gypsum and limestone beds forming sinkholes that might reach about 20 m in diameter and 9.6 m in depth. The conducted survey also confirms the presence of sinkholes and other karst forms within the reservoir, which are active, and continuously increasing in size, and exerting hazards to the Mosul Dam.

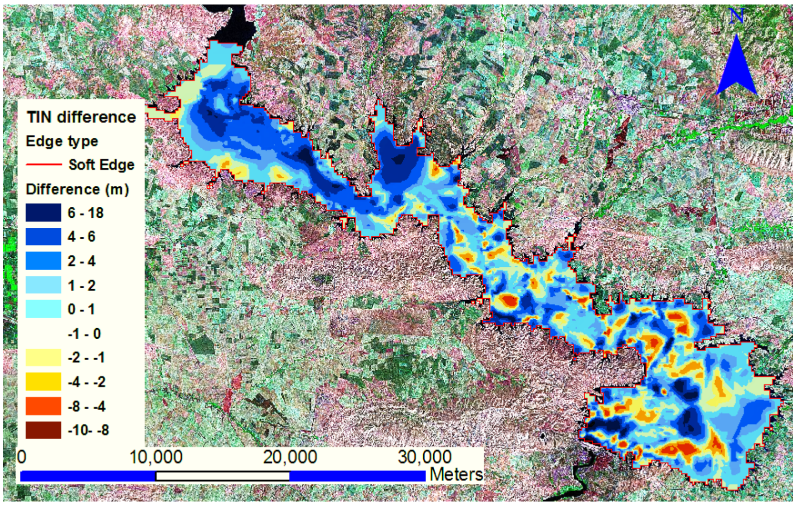

Fig. 12: Holes noticed at the bed of Mosul reservoir [17].

4 Conclusions

Foundation of Mosul dam is resting on the rocks of Fatha Formation. The formation is composed of Marls, chalky limestone, limestone, gypsum, and anhydrite, it is highly karstified. The main geologic features under the foundation of the dam are the karstified limestone and the development of solution cavities within the gypsum and anhydrite layers. The right (west) abutment is located in the steeply dipping beds of the Fatha Formation within Butmah East anticline with SE plunge being in the reservoir north of the dam, whereas the left (east) abutment is located on gently dipping beds of the Fatha Formation, which is overlain by fine clastics of the Injana Formation. These differences in lithology as well the dip amount and direction along both abutments as well upstream and downstream of the dam have certainly affected on the hydraulic pressure and increased the dissolution ability of the gypsum and limestone beds, along the abutments and the foundations, which are already karstified in nearby areas. As a consequence more limestone, gypsum and anhydrite were dissolved. This has caused seepage of water in different parts within the vicinity of the main dam. Sinkholes started to develop after the impounding of the dam. There is evidence that the sinkholes developed even within the reservoir area.

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