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Mosul Dam: Geology and Safety Concerns

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Abstract: Mosul Dam is an earth fill dam located on the River Tigris northern part of Iraq. The capacity of its reservoir is 11.11 billion cubic meters which makes it the fourth biggest dam in the Middle East. From geological perspective, the dam is located on double plunging anticlines. The rocks of the site are mainly composed of highly jointed and karistified alternating beds of limestones, gysum and marls, since the impoundment of the reservoir seepage of water was recognized under the foundation of the dam. To stop or minimize the seepage, intensive grouting operations were conducted. Recent investigations and evaluation of the conditions of the dam indicate that it is in a critical situation. In this paper, consequences of the dam failure are discussed and possible solutions are given.

Key words: Mosul Dam, karst, infiltration, dam foundation, dam failure.

1. Introduction

Mosul Dam, the largest dam in Iraq, is also one of the large dams in the world and the fourth largest reservoir in the Middle East. It is located on the Tigris river in northern Iraq approximately 50 kilometers north west of Mosul city and 80 kilometers from the Syrian and Turkish borders.

Although the dam is about 500 km on a straight line distance to the north from Baghdad a flood wave study showed that such wave resulting from the dam collapse could reach Baghdad within 48 hours causing devastating results for the whole reach and its population.

The maps in Figs. 1 and 2 show the location of this dam.

2. History

Mosul dam site was first investigated in 1952 by an American firm, after which four investigation campaigns were conducted in the sixties and seventies. The first three reports prepared by American, Finish and Soviet consultants agreed on the difficulties involved in the site for the construction of a high dam based on the conditions of foundations due to the presence of gypsum, gypsum anhydride and gypsum breccias. The fourth study report prepared by Swiss consultants concluded that the dam can be built and that the foundation can be sealed by intensive blanket grouting together with a deep grout curtain. A conclusion which proved later on to be very short sighted. The construction of the dam was initiated in 1980 and completed in 1985. The first sign of trouble appeared at the first filling in the spring of 1986 [1]. Maintenance foundation treatment by continuous massive grouting program was envisaged as a solution, but the problem persisted and mass grouting continued ever since as a maintenance measure with no signs of an end in the future. Moreover sinkholes which had started to form since the filling of reservoir evolved into common phenomena [2, 3].

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3. Dams Features

Mosul Dam scheme consists of three parts:

(1) Mosul 1, which is the main embankment dam and main power station.

(2) Mosul 2, the re-regulating dam and power station located 9.1 km downstream of the main dam; distance

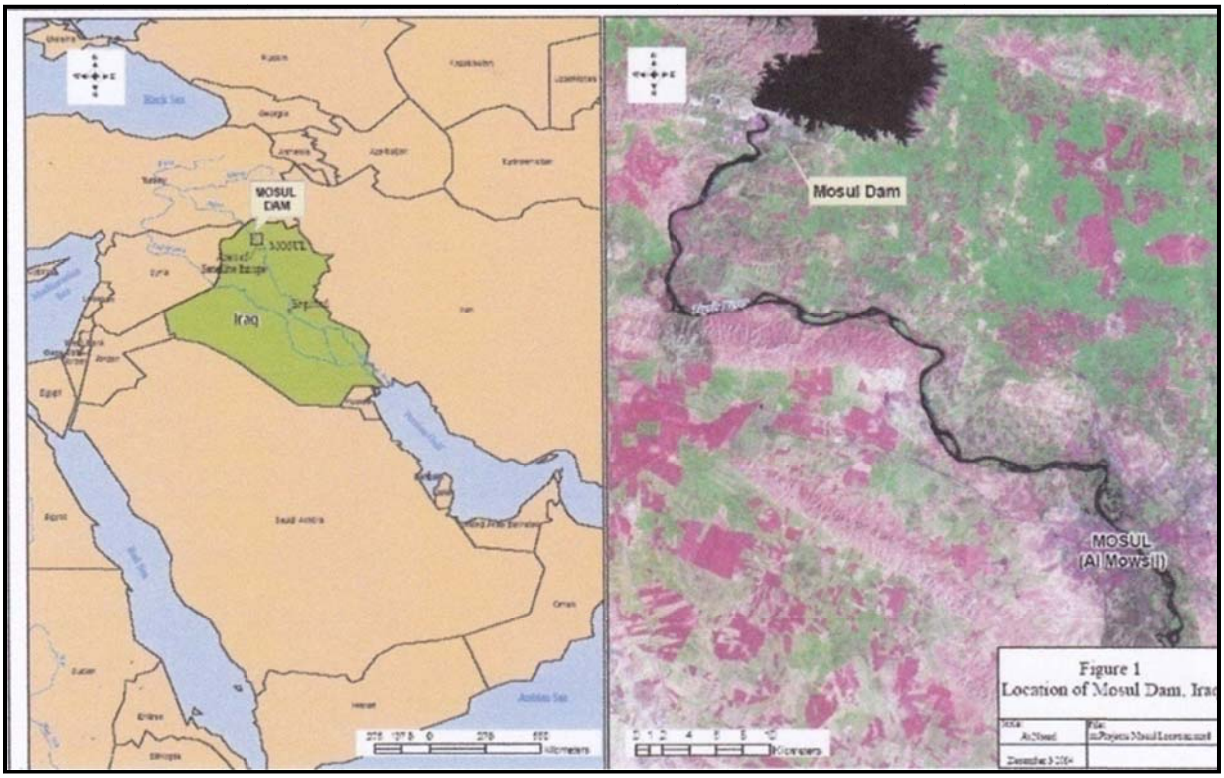


Fig. 1 Mosul Dam location Ma.

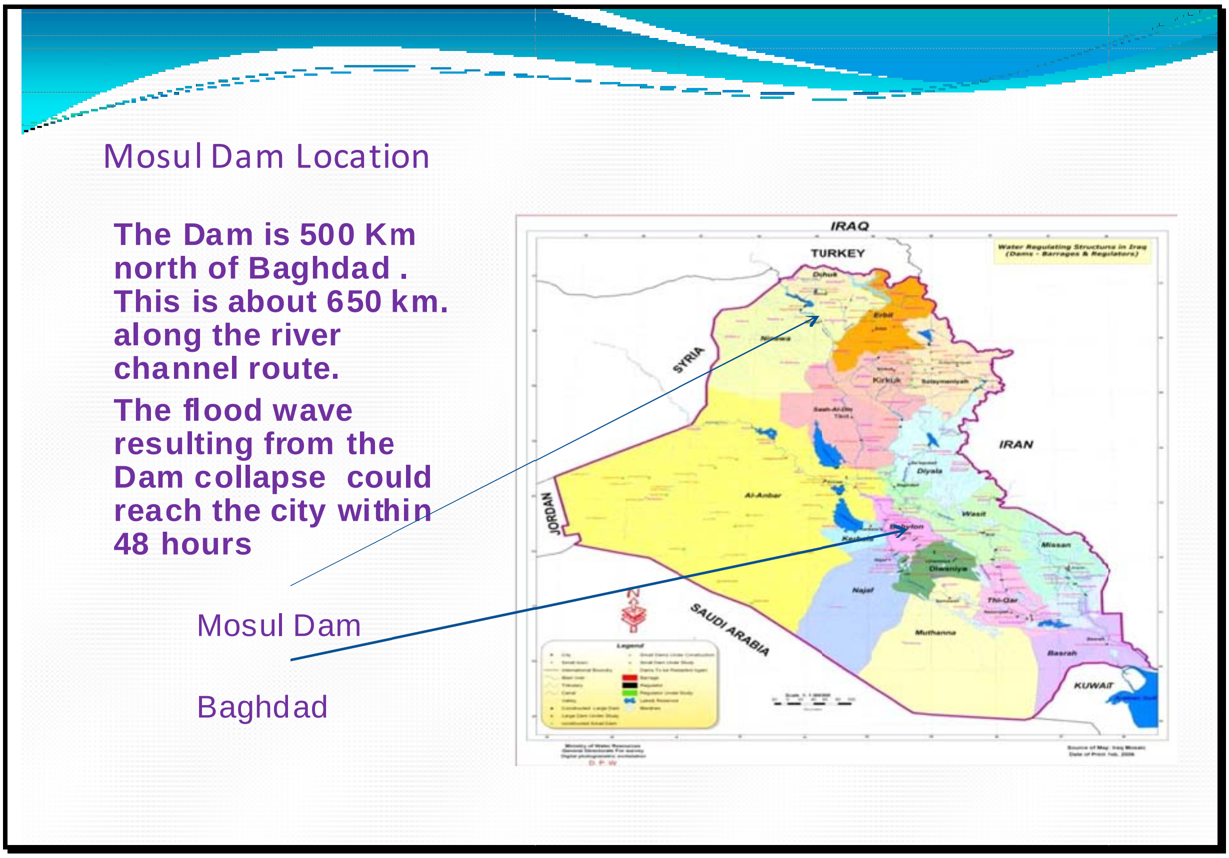


Fig. 2 Map of Iraq indicating Mosul Dam site.

measured along river course.

(3) Mosul 3, the pump storage scheme (200 Mw).

We are focused here on the Main Dam as it is the source of troubles encountered in this Scheme; in the following Fig. 3 both upstream and downstream views are shown. The dam's layout and appurtenant structures arrangement are shown in Fig. 4.

Mosul Dam is an earth fill dam with concrete spillway with a maximum discharge capacity of 12,000 m^3/second and powerhouse. Two low level bottom outlets are provided for emptying the reservoir in case of an emergency. The maximum height of the dam is 113 meters while total length is 3,400 meters, and the total volume of fill is about 38 million cubic meters. The embankment has a clay core in the middle and gravel shells on the exterior slopes and provided with two layers of filters on each side of the core. An emergency concrete/earthfill fuse plug 400 meters long is incorporated in the embankment to safeguard against overtopping. The maximum discharge of this facility is 4,000 cubic meters per second at the maximum water level. The service spillway is a conventional ogee weir

Fig. 3 Mosul Dam: upstream view (left), downstream view (right).

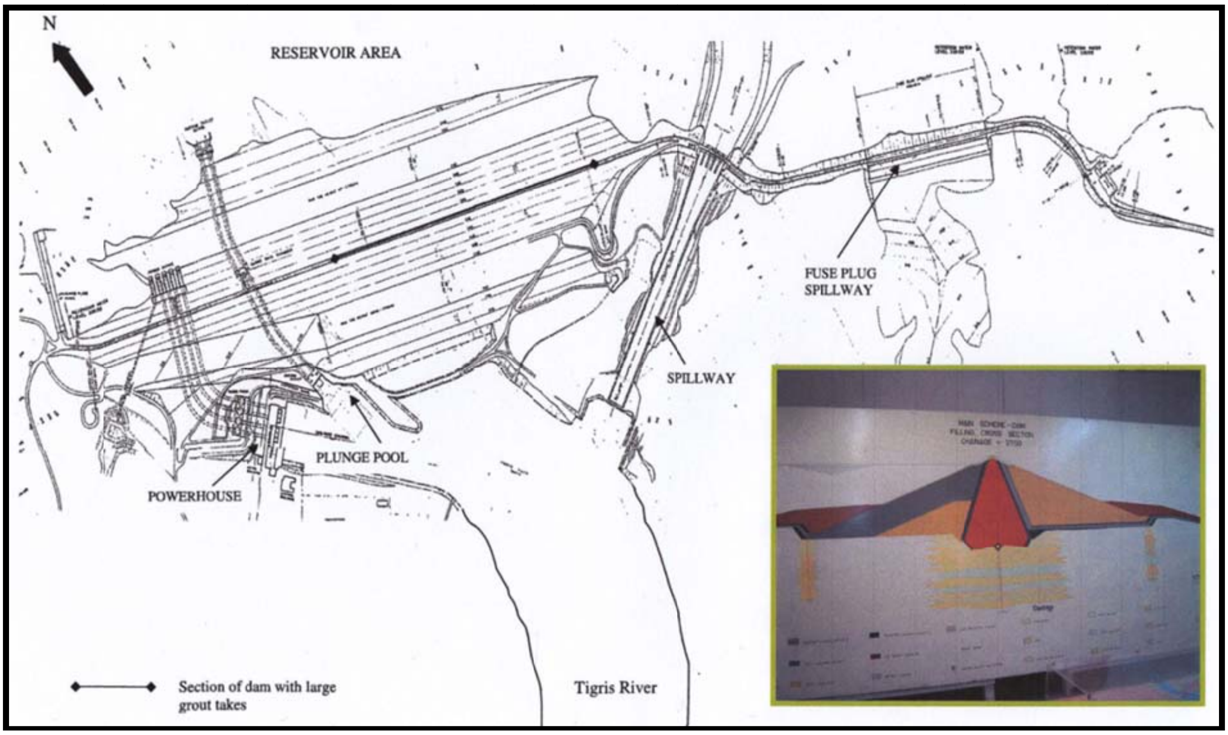


Fig. 4 Mosul Dam general arrangement.

type headwork, rectangular chute and flip bucket structure with discharge capacity of 12,400 cubic meters per second at the maximum flood water level 335 masl and 8,000 cubic meter per second at the maximum operation water level (330 masl).

The dam serves the functions of flood protection, providing irrigation water and power generation. The main power station has an installed capacity of 750 Mw and a 50 Mw PowerStation was planned for the Jazira main canal off take (not constructed yet). Additionally a 60 Mw installed capacity is provided at a re-regulation facility downstream of the main dam, and a pump storage station of 200 Mw installed capacity is constructed on the right hand high bank making total installed capacity more than 1,050 Mw [4].

Main operational features of the dam are as shown in Table 1:

Table 1 Main operational features of Mosul Dam [4].

Description	Unit	Value	Remarks
Dam Height	m	113	
Total Storage at El.330m.a.s.l	Km^3	11.11	
Live Storage (Usable for Irrigation and Power Generation)	Km^3	8.16	
Dead Storage at El.300m.a.s.l	Km^3	2.95	Power Station stops operation
Available Capacity for flood Routing (From El. 330m.a.s l to El.335m.a.sl)	Km^3	2.03	To Route 1:10000 years flood
Irrigated Area (Directly from Mosul Reservoir)	ha	250000	North Jazira,East Jazira and South Jazira Projects
Irrigated Area from dams releases at the middle and south of Iraq	ha	750000	
Total Installed Capacity in the three power stations of the Project	MW	1050	Main dam PS..Reregulating dam PS.& Pump storage Scheme PS.
Total Annual Power Generation	GWH	3400	

4. Regional Geology

The geology of the dam area belongs to the Pleistocene to recent age alluvial deposits overlaying rocks of the Lower to Middle Miocene age Lower Fars Group (Fatha Formation) which is formed of highly karstified layers of limestone and soluble gypsum, followed by Oligocene to Lower Miocene age Jeribe limestone formation. The geomorphology of Mosul dam area is characterized by hilly terrain that rises to low mountainous area. The mountain anticlines trend NW-SE direction and change to almost E-W direction. Fig. 5 is a Google image of the dam and surrounding area.

Another significant morphological aspect in the area is karstification in the area and in the dam site [5, 6]. Typical dissolution karstification phenomena close to the dam site and sinkholes are shown in Figs. 6-9. While sinkholes have developed very close to the dam during and after operation, and similarly sinkholes were discovered in the reservoir later on as shown in Fig. 10 [7].

5. Geological Conditions at the Dam Site

The main geological factors influencing the dam safety are given below and their effects will be discussed later on. These factors are:

(1) The karsts prevailing in the dam site and in the reservoir area.

(2) The existence of gypsum/anhydrite rock formations in dam foundation alternating with soft marl layers and weathered and cavernous limestone beddings.

(3) The presence of extensive ground water aquifer called Der Wadi Maleh aquifer in the dam site.

Figs. 9 and 10 shown already indicate the extent of the karsts phenomena in the form of sinkholes upstream area of the dam and in the reservoir.

The continual development of such sinkholes will open new connections with the groundwater aquifer running below and around the dam site causing more dissolution problems.

The existence of highly karstified and jointed limestone layers in the dam foundations gave rise to the

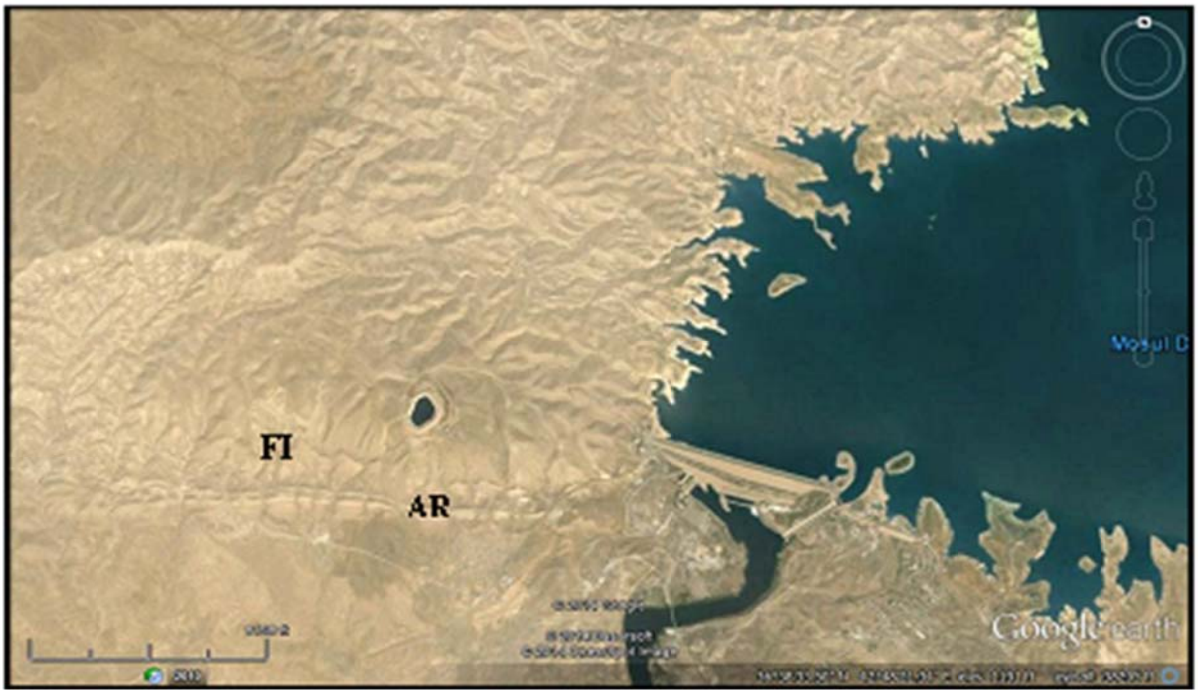


Fig. 5 Google Earth image of the Mosul Dam site, located within Butma east Anticline. AR = anticlinal ridge, FI = flat iron [5].

Fig. 6 Karstified gypsum in the upper member of the Fatha formation [6].

Fig. 7 Karstified gypsum within the Fatha formation at Atshan anticline, South of Mosul Dam [6].

Fig. 8 Karstified gypsum within the Fatha formation at Atshan anticline, south of Mosul Dam [6].

Fig. 9 Enlarged Google Earth image showing many sinkholes (dark spots encircled by red color), in the upstream area of the dam site [5].

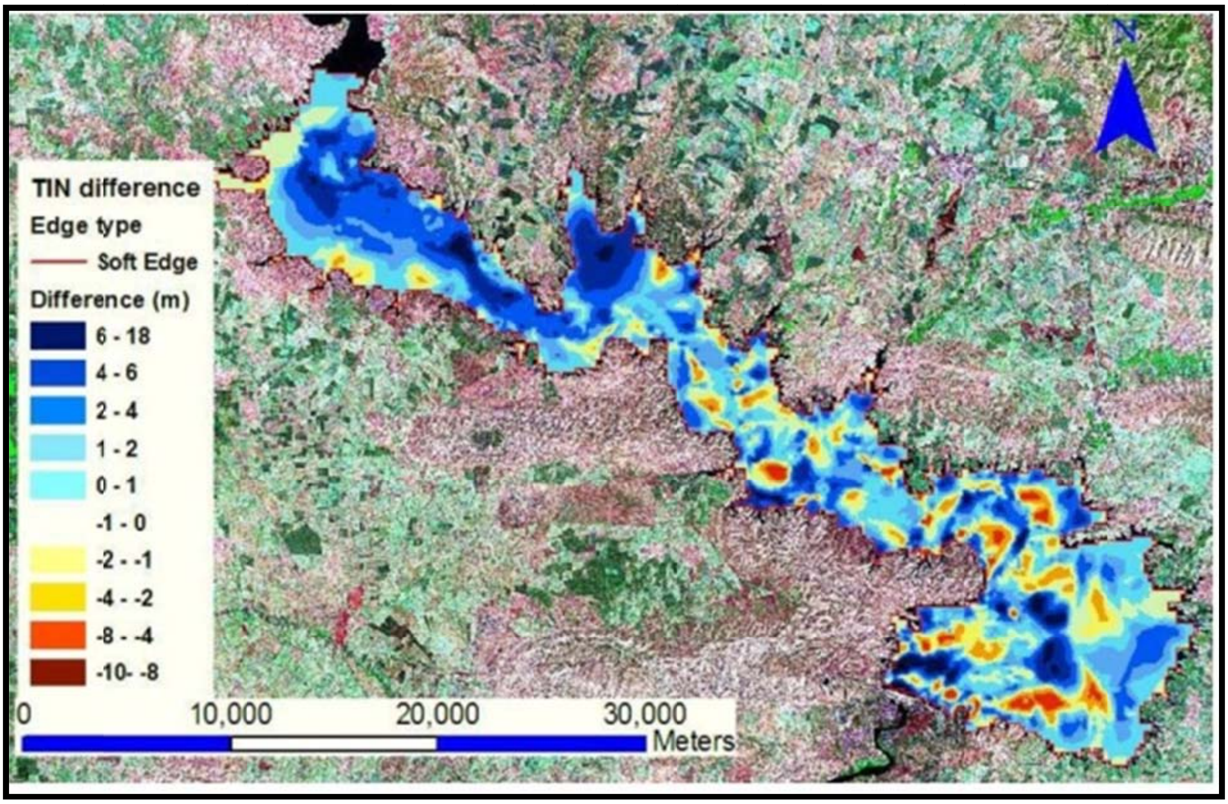


Fig. 10 Results of bathymetric survey of Mosul Dam reservoir carried out in 2011 by a Luleå university PhD student [7].

formation of highly developed conduits and caverns which form easy passages to the flow of ground water and the reservoir water. This had caused extensive dissolution of gypsum and gypsum anhydrite rocks present above and below these limestone layers. These dynamics had caused the collapsing of whole layers of clayey marls and gypsum anhydrite into the underneath cavities forming beds of brecciaed gypsum particles and anhydride blocks embedded into a loose clayey matrix. Four such layers where discovered during the geological investigations and they were termed as the Gypsum-Breccias layers which had thickness ranging between 8 meters and 16 meters. The first layer was found at a depth of 80 meters in the river section and it was marked as the GB0 layer. The other three layers were at higher levels. The last one i.e. the GB3 was discovered at the foundation of spillway chute ski jump. The GB layers proved to be very dangerous due to their erratic behavior during the grouting of the deep grout curtain under the dam. Fig. 11 shows the geological cross section under the dam. Fig. 12 gives the lithological column under the Mosul Dam central part.

During the excavation works of the spillway chute and flip bucket the GB3 layer was exposed showing spectacular cavities and open joints and cracks. These are shown in the photographs in Fig. 13.

In Fig. 14 the dotted line is the estimated karsts line development in sections 69-87 which is the most problematic area as visualized by the designers, the estimation of this line was based on the results of boring and field permeability testing. The black spots in this figure indicate some of the points of major grout take. Below this line according to the designer's judgment karsts cease to exist and this depth should define the end of the deep grout curtain. The design criteria of the grout curtain, however, called for extending the curtain 20 meters below this line for more safety. In actual fact the depth of dissolution extended below this line after impounding the reservoir. The design criteria and full details of the grouting works are given in Ref. [8].

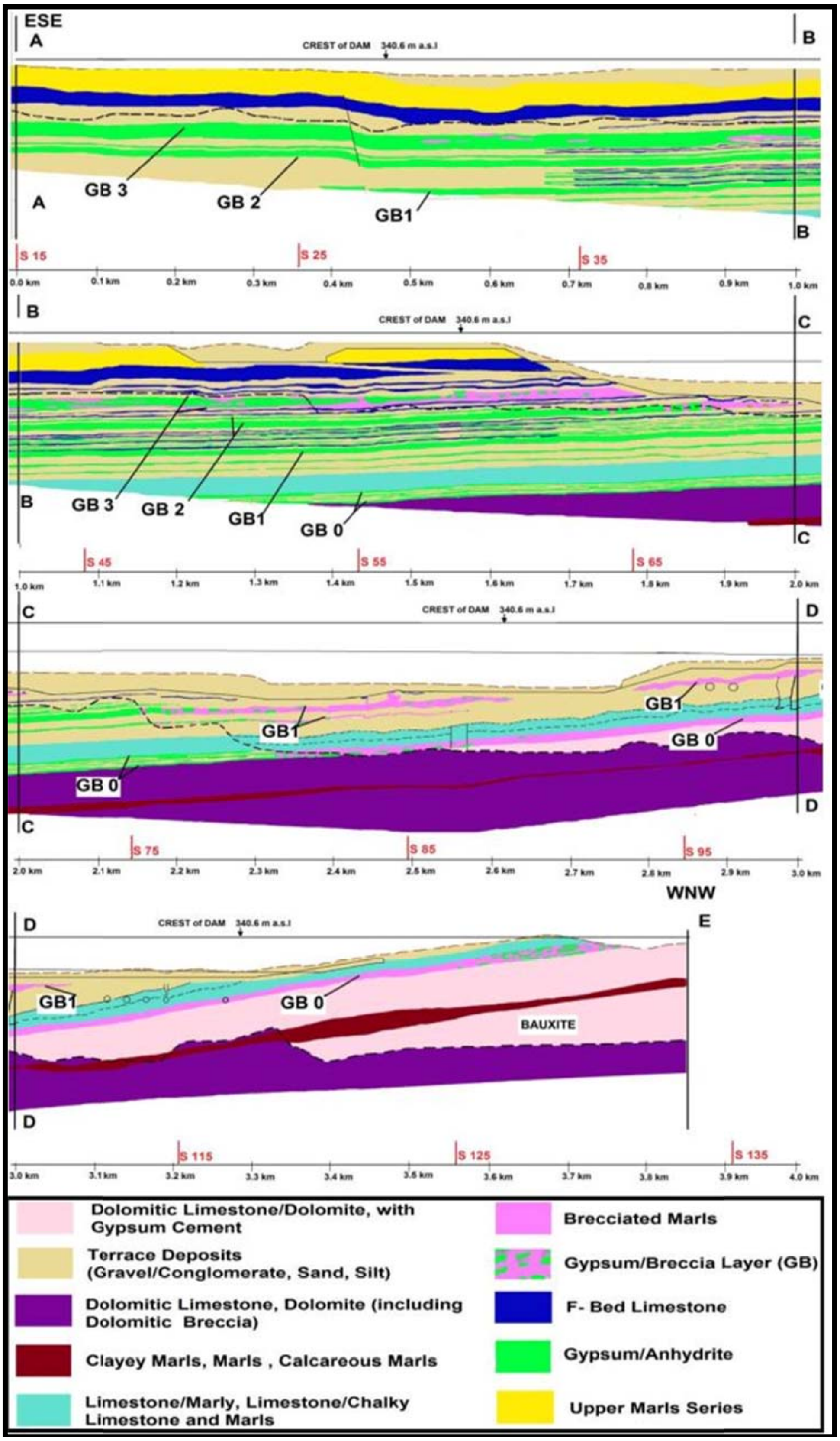


Fig. 11 Geological long section under dam axis (the long extending from east to west shown has been divided in parts from east to west which are stacked together in the above figure) [4].

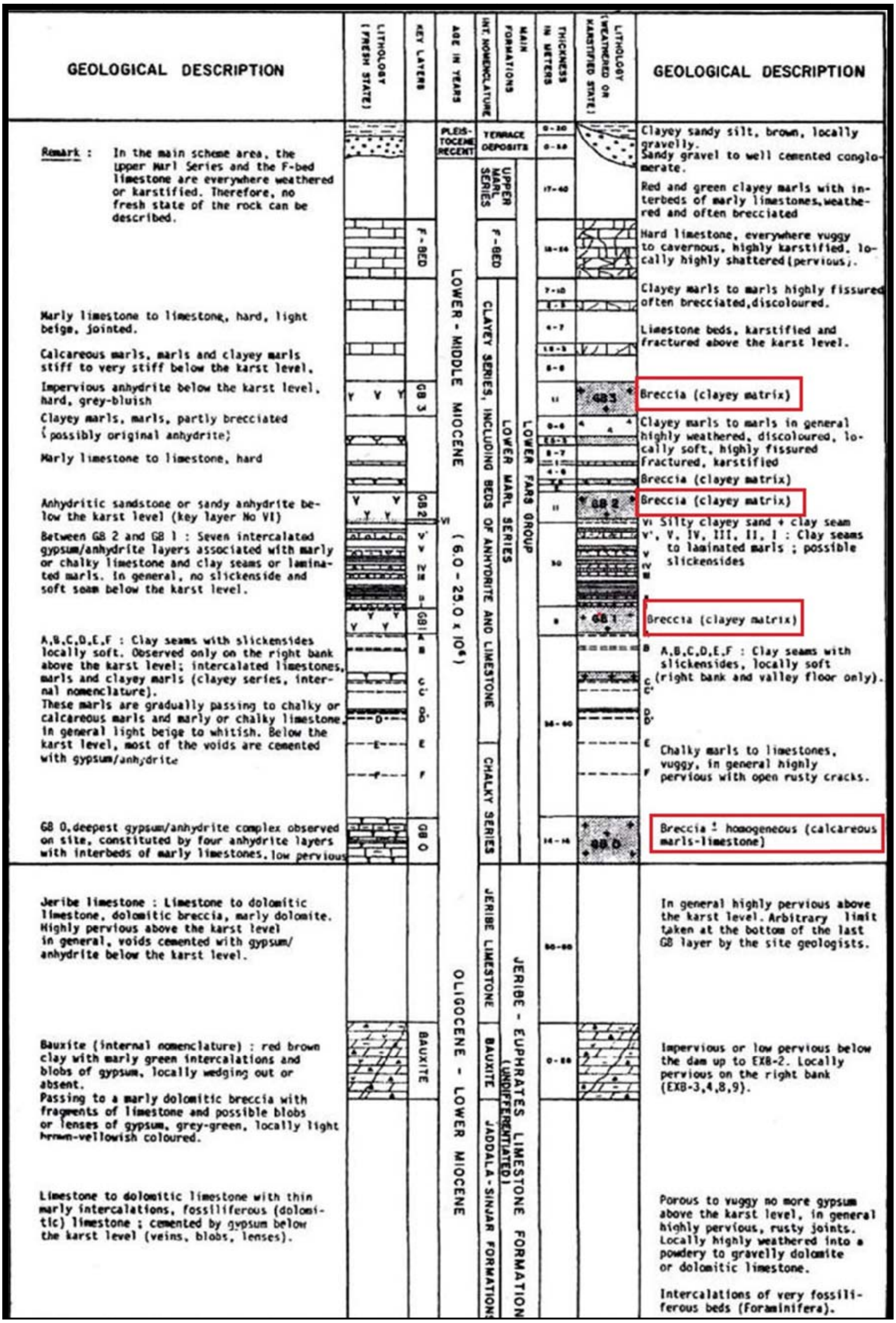


Fig. 12 The lithological column under the Mosul Dam central part (red rectangles indicate the Gypsum Breccia layers) [4].

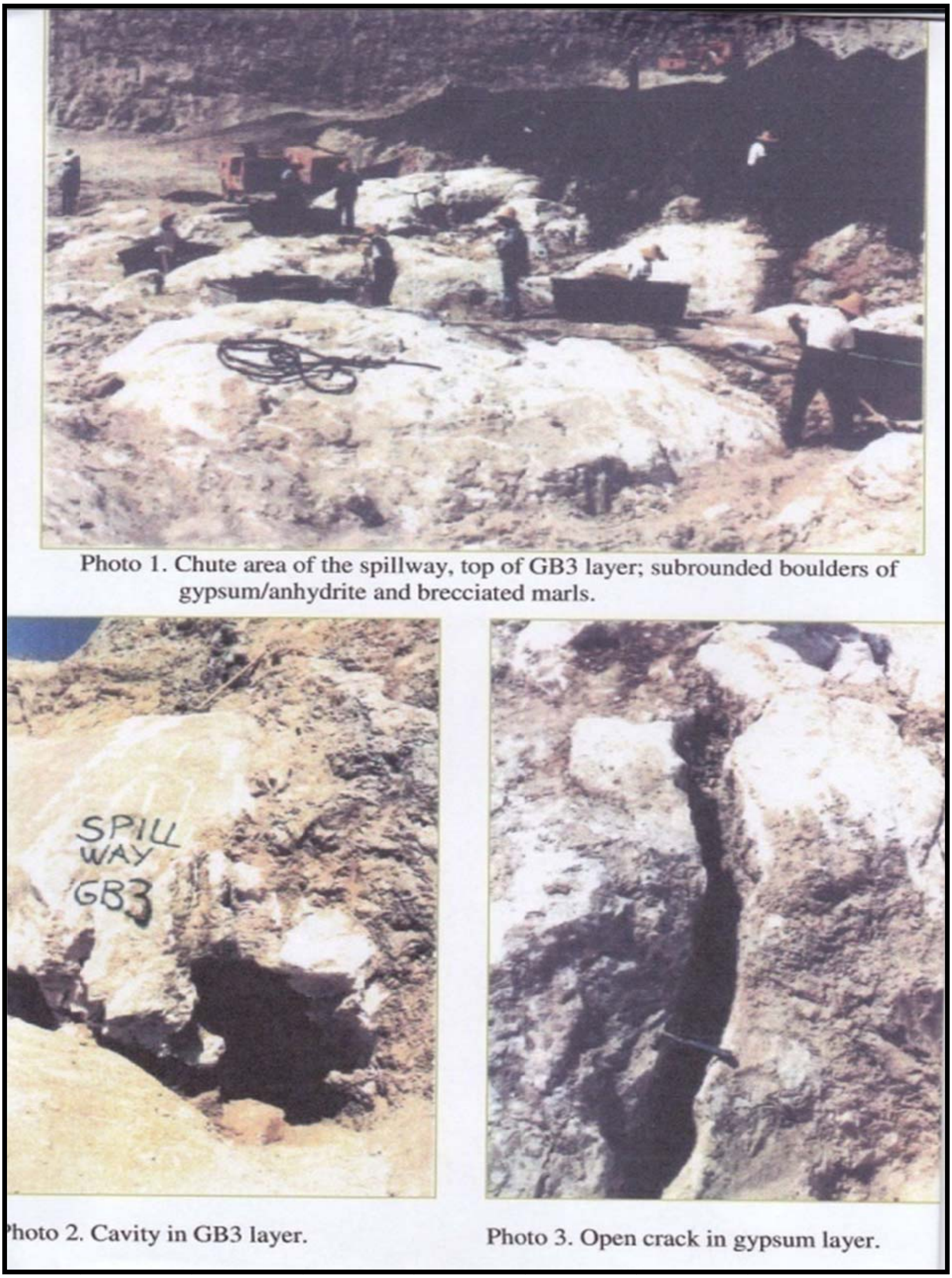


Fig. 13 Cracks and cavities in the GB3 layer below spillway's chute and flip bucket [9].

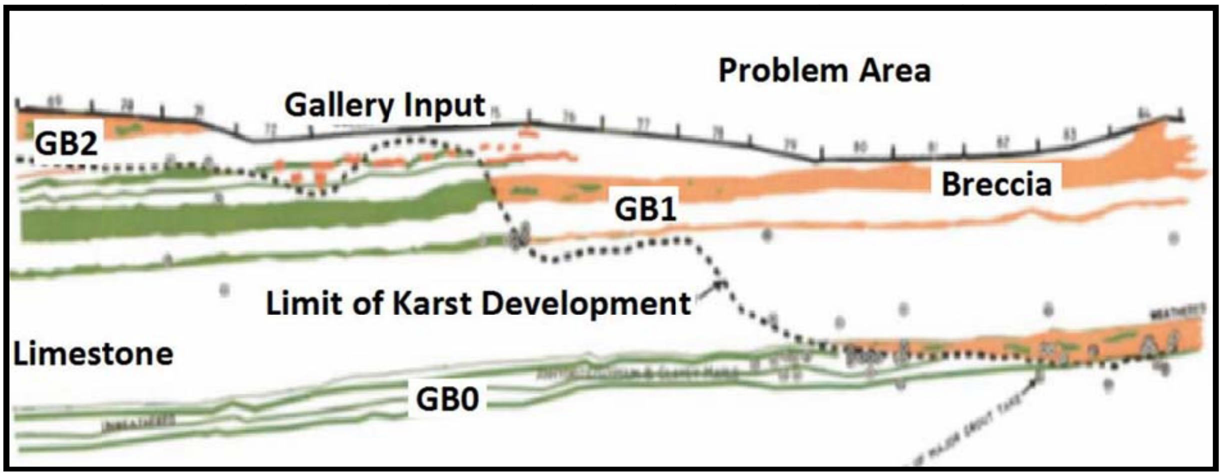


Fig. 14 Estimated karsts line in the problem area (sections 69-87) (The black spots show locations of some of the major grout take locations) [9].

The schematic diagram Fig. 15 shows the mechanism of the gypsum/breccias layer formation. Groundwater flowing through cavernous limestone can wash the Marley clay from above into cavities already formed in gypsum/anhydrite layers and causing the collapse of more gypsum/anhydrite into these cavities forming continuous layers of the breccias.

The groundwater regime was studied carefully during construction especially in connection with the construction of the pump storage scheme underground cavern structures and the intake/tailrace tunnel. The amount of seepage flow was tremendous and the excavation of the caverns was only possible after performing extensive grouting work all around these caverns in the form of boxes which also served as a protection shells around theme, in addition to driving drainage tunnels all round the caverns. Due to the large amounts of seepage flow the driving of the intake/tailrace tunnel was only possible after grouting the excavation face ahead of excavation work. The quality of seepage water was much different from the river water quality and it contained a much higher concentration of sulfates indicating the passage of water through gypsum and gypsum anhydride layers. Further studies showed that this water belonged to the very large Wadi Der Malih aquifer which is being fed from long distance upstream and which was running below and independently from the river aquifer. This aquifer was also fed directly from the reservoir after impounding. Fig. 16 is a photograph of the water flow of one spring which had erupted during the excavation of the tunnel and could only be stopped after performing much grouting works. The Importance of the Wadi Der Malih aquifer is not only due to the great difficulties it had caused during the construction of the pump storage scheme, but it is also believed it contributed to the formation of a series of sinkholes at the right bank downstream of the main dam as explained later on.

6. Grouting of Gypsiferous Formations (General)

Grouting such formations is very tricky operation. As such grouting begins to seal some seepage paths, this will result in an increase of the hydraulic gradient locally in adjacent parts. Water passing over gypsum becomes chemically saturated within a flow path and in this zone of saturation no further dissolution occurs. As flow continuous, the zone moves downstream and eventually passes from the exit. At this stage, dissolution rates accelerate again sharply. From experience it is known that seepage velocities of 10^{-4} cm/sec in a 2 cm wide gypsum vein, it should dissolve at a rate of few centimeters per year from an advancing front. If the velocities were about 10^{-2} cm/sec gypsum could dissolve at a rate of 9 meter per year. Dissolution

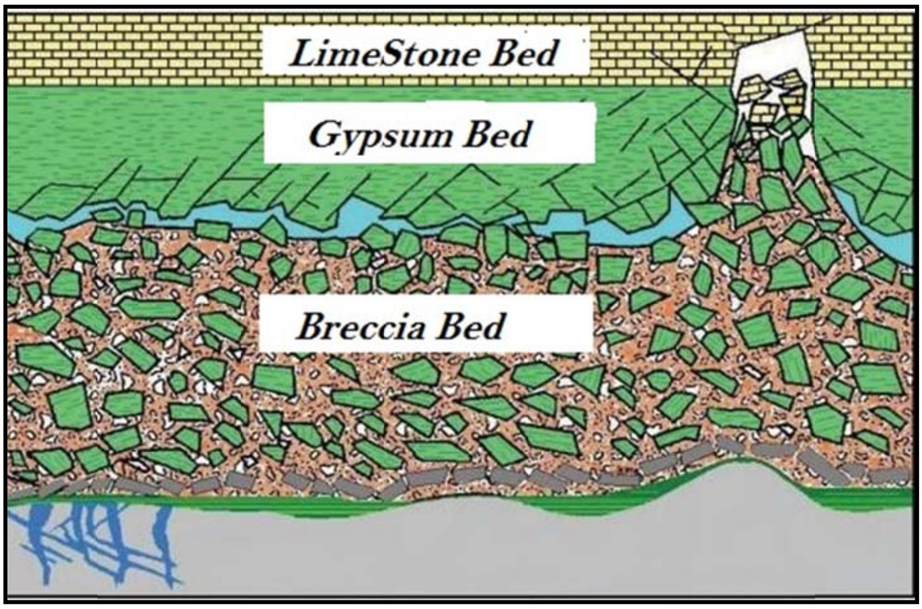


Fig. 15 Schematic diagram showing the formation of a breccias layer.

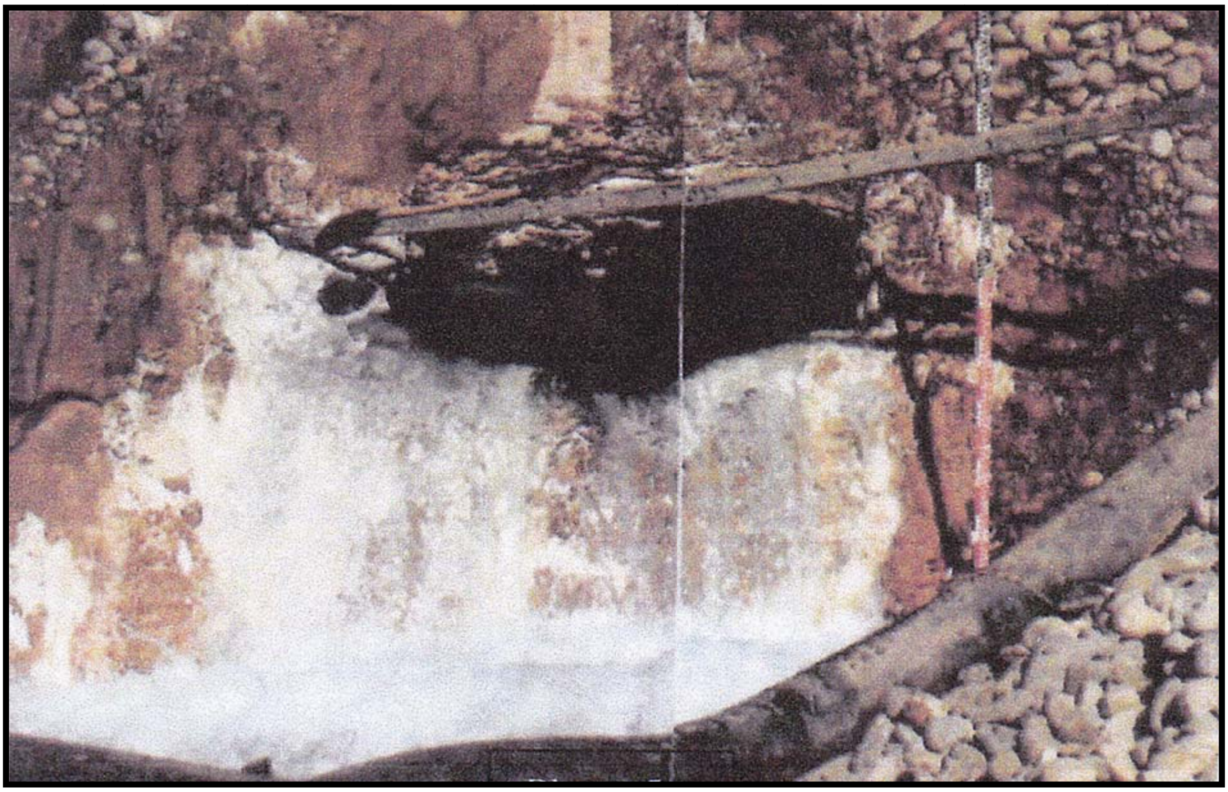


Fig. 16 The flow (360/sec) from underground aquifer into the intake/tailrace tunnel of the pump storage scheme originating from Wadi Der Malih aquifer [9].

occurs until seepage water reaches a calcium sulfate saturation of 2,000 ppm. Hence the dissolution zone moves downstream as greater quantities of unsaturated water attack a gypsum vein [10, 11].

From this it seems that it is most difficult to seal a cracked or fissured gypsum formation permanently, especially in the presence of other formations which are also jointed, cracked and highly conductive to flow as in the case of Mosul dam foundations especially in view of the very high heads created by the reservoir.

Nevertheless, the designers of the dam considered that grouting should be used as the anti-seepage element for the deep cutoff under the dam, while construction of positive cutoff in the form of concrete diaphragm could have been used instead. A better choice of anti-seepage measure should have been the construction of concrete diaphragm especially that hydro-fraise machines which could go to a depth of 140 m for the construction of such diaphragm were available and the work could have been done from river bed level.

7. The Grouting Works Program

An extensive grouting works program was anticipated by the designers in view of the soluble nature of the foundation and its configuration. One report in 1991 estimated that dissolution intensity at Mosul dam foundations ranged from 42 to 80 tons per day. This process coupled with the presence of karstic limestone and calcareous marls as well as anhydrite presented a very problematic and difficult foundation, which was anticipated by everybody since the beginning, and the consultants and the IBOE (International Board of Expert) which had been appointed to follow the design and construction of the dam agreed the design outlines of the grouting works and their acceptance criteria only after extensive discussions and lengthy meetings.

The first element of grouting works is the contact blanket grouting covering the contact area of the clay core with the foundation surface to close all preferential seepage paths by filling all fissures and joints and protect from concentrated seepage flows directly under the core. The second is the deep three rows curtain which extends down to the karst line.

A concrete grouting gallery was constructed at the bottom of the cutoff trench so as to continue the grout curtain works without interfering with the embankment construction. It was also meant to be used for continuous observation of the curtain performance during operation. Pairs of open pipe piezometers were installed upstream and downstream of the curtain, one pair at each section of the gallery in order to be able to measure the efficiency of the curtain. The gallery proved to be of immense usefulness to carry out maintenance grouting of the curtain in what was to be defined as massive grouting, a process which has continued from the first filling of the reservoir up to now. The required efficiency of the grout works was to reduce the seepage flow to safe limits to allow the water upstream the curtain to be saturated with calcium sulfate and therefore stopping any further dissolution of gypsum or t hydration of anhydrites. In the limestone beds grouting was to plug and seal all anticipated cracks and joints and hinder the free flow of seepage. The criteria were expressed in terms of Lugeon units of rock mass permeability values which were defined specifically for each of the blanket grouting, and the various depth and parts of the grout curtain. During the progress of the work it was evident that while cracks and cavities in limestone could be reasonably filled, the criteria could not be achieved over many locations in the GB beds in the deep curtain at depth which remained open to seepage and were described at the time as windows. These windows remained open in many locations under the central part of the dam even after the full scale impounding of the reservoir had started in the spring of 1985 when the grouting problem was not yet settled; a thing which could not be stopped due to the early closure of the river in October 1984.

The beds where this problem had severely occurred were the breccias aforementioned which proved very difficult to grout, and if temporarily sealed they opened again to the flow after the dispersion of the grout mix within the loose matrix. This situation led later on to accelerated dissolution and formation of large cavities during the lifetime of the dam.

In spite of the many grouting techniques that were tried to solve this problem including changing grout mix designs and using different pressures, the problem persisted and even the use of chemical grouting with different solutions was equally unsuccessful [8].

8. Problems Encountered during First Filling of the Reservoir (1985-1988)

The first filling uncovered many serious problems requiring much serious attention and studies and resulted in remedial works. All is summarized in the following:

8.1 Seepage Springs in Left Bank

As water level in the reservoir increased many springs began to develop in this bank. The more serious once were close to the right and left sides of the spillway bucket structure and chute and others were at further left. The seepage water was collected for measurement and chemical testing. The total quantity of seepage was 830 l /second (on 22nd March 1986) which corresponded with a reservoir level of 304 masl. This could yield, if extrapolated to 2 cubic meters per second at full reservoir elevation of 330 masl. Chemical tests showed an increase in salts content indicating leaching of gypsum at a rate of 30 tons/day. This is equivalent to void volume of 10-15 cubic meters. Fig. 17 shows the obtained test results of water seepage from the most important five springs as the water level was raised during the period February-August 1986 [12].

Further hydro geological investigations by installing more open pipe piezometers and use of tracers to discover seepage paths showed the need for extending the depth of the grout curtain at certain sections and adding another line of grouting holes in others. Arrangements were made to catch some springs by pipes to discharge away the water safely and others were covered by filter material. Anew deep curtain was also constructed along the left side of the spillway's chute to stop seepages flowing underneath the chute and across it from the upstream direction. An extension to the left bank grout curtain along dam axis was performed also to protect the left bank from being outflanked by water seeping around the executed curtain.

Although these additional works reduced the amount of seepage and the dissolution of gypsum, they could not eliminate them.

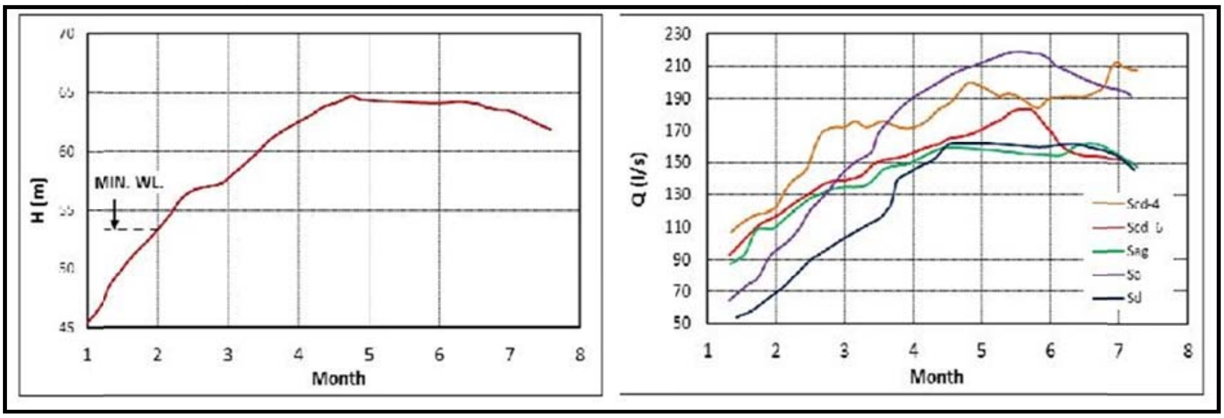


Fig. 17 Chemical test results of water seepage from the most important five springs vs. water level was raised during the period February-August 1986 [12].

8.2 Deterioration of the Grout Curtain under Main Dam

Similar measurements of seepage water quantity and quality from under the dam at the river channel section, which was collected from the pond created by the coffer dam no 6 used during river diversion, showed alarming dissolution of gypsum and increased transmissibility during the same period [12], as indicated in Fig. 18.

The increase in seepage quantity was accompanied by reduction of the grout curtain efficiencies in many sections in the river channel and could be attributed to the increased size of the aforementioned windows due to increased dissolution. Grout curtain efficiencies at various parts were measured by observing the difference in the hydraulic head between the upstream and downstream piezometers that were installed in pairs in the grouting gallery. These piezometers were and still are up till today as the only means to discover the formation of cavities in the foundation and to indicate the need for filling grouting as a maintenance procedure.

As water level was reaching higher elevations the formation of large cavities was posing a constant threat to the stability of the dam. This required the introduction of introducing a new technique which was called (Massive Grouting) to inject thick grout (by adding 3 weight sand to 1 weight cement, 4% of bentonite that needed to be activated using sodium carbonate using 1:1 water/cement ratio). It also required the fast transport of the grout mix in dry conditions by truck mixers to the location of three deep boreholes lined with steel pipes that penetrated the core from the crest of dam to the gallery, where it was mixed and injected in the required treatment zones. This operation known as "Massive Grouting" continued from 1986 up to the present days in addition to other forms of conventional grouting as needed. The use of this procedure is probably a unique case in the whole world. Grouting records shows that the quantity of injected grouting from 1986 up to and including 1988 was 25,000 tons of injected solids out of which 12,200 tons are of massive grouting and even larger quantities were pumped in the following years [8].

8.3 Development of Sinkholes

In September 1986 an inspection of the right rim of the reservoir was carried out when the water level had been drawn down to EL.316.4m from El.309m which it reached during the previous flood season. This inspection revealed the development of a series of sinkholes at the right bank at many points at about 150 meters from the contact of the dam with the right abutment. One sinkhole of major proportions was located also at about 1 kilometer or so away. These

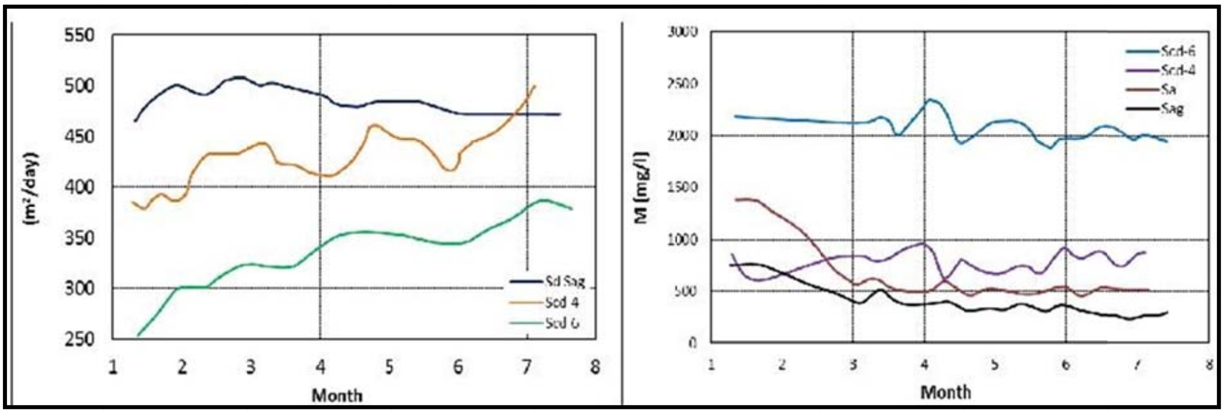


Fig. 18 Increased transmissibility vs. time (February-August 1986), and continuous dissolution of gypsum in the same period for the increased head shown in Fig. 17. (Dissolution had leveled off after the initial increase in the first three months which was due to the washing away of gypsum particles fillings in the cracks and joints of the rock formation) [12].

sinkholes showed dramatic solution of the gypsum layers which were exposed on the shore line. During the operation years of the dam and specifically from 1991 to 1998 new series of sinkholes began to form in the downstream area of the dam. These sinkholes followed a straight line alignment parallel to the axis of the dam and at about 400 meters away. These sinkholes were indication of an active process of rock dissolution. Careful observations and measurements indicated that the ground surfaces at the sinkholes locations had settled gradually and collapsed in enlarged underground cavities which were formed partly by the fluctuation of the water level resulting from the operation of the reregulating dam 8 kilometers to the south of the main dam and partly due to the connection to Der Maleh underground aquifer which runs under the dam area and being charged from the right rim of the reservoir through the gypsum layers day lighting at the right rim. The location of these sinkholes is shown in Fig. 19, and the photographs of sinkhole (SD2) given in Fig. 20 show the initial phase of its formation in the contractor's concrete paved work area and the final shape after full development.

The chemical composition of the water in the sinkhole gave the same results as those from Der Maleh aquifer encountered during the excavation of the pump storage scheme tailrace tunnel not very far from the sinkholes location. Further from this area on the same alignment at the river bank one spring was discovered after the erosion of the alluvium cover due to spillway operation. This spring seems to follow the same sinkhole phenomena and its water has same composition of Der Maleh aquifer (Fig. 21).

By contrast to the right bank sinkholes which began by ground surface cracking followed by ground surface settlement until the occurrence of the full collapse, one sinkhole at the left bank very close downstream of the dam of dam shown in Fig. 22 occurred suddenly in February 2002 without previous warning. It was situated close to housing colony 150 meters downstream of the left flank

In Fig. 23, this sinkhole seems to be located on the

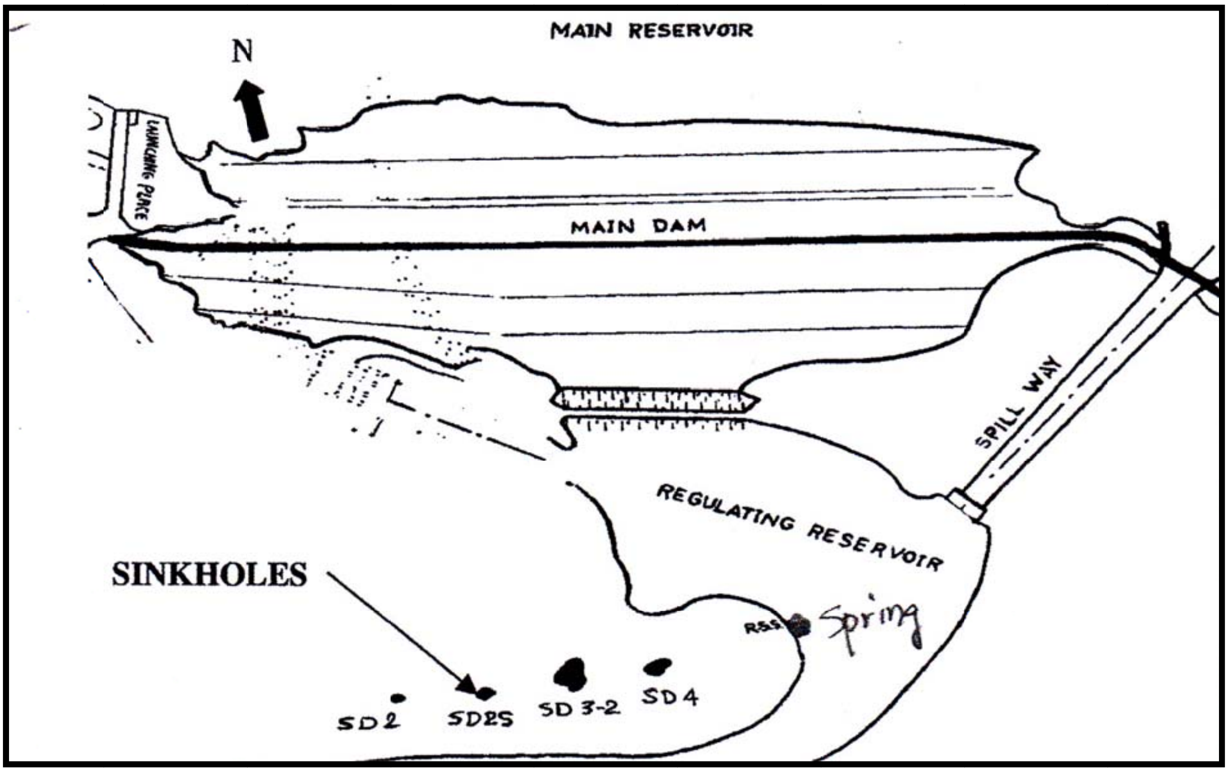


Fig. 19 Location of downstream sinkholes which had developed during the period [9].

Fig. 20 Two views of sinkhole SD2 at the initial stage and final stages of development [9].

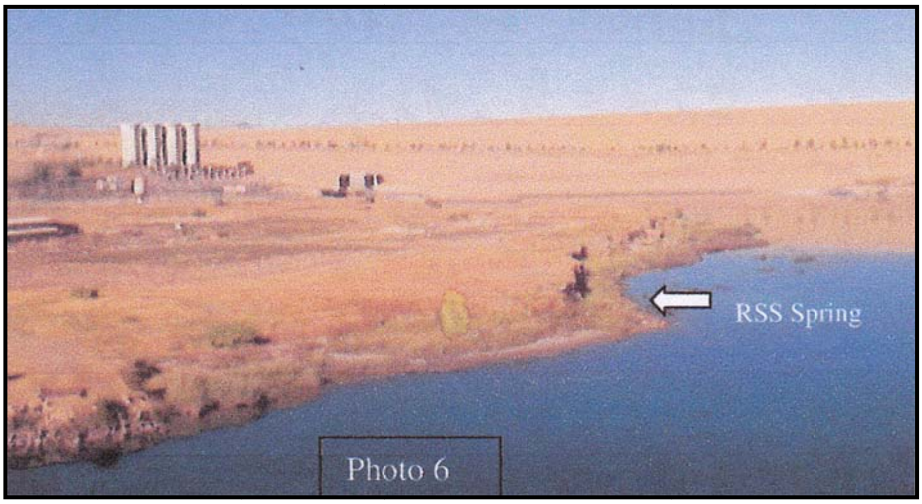
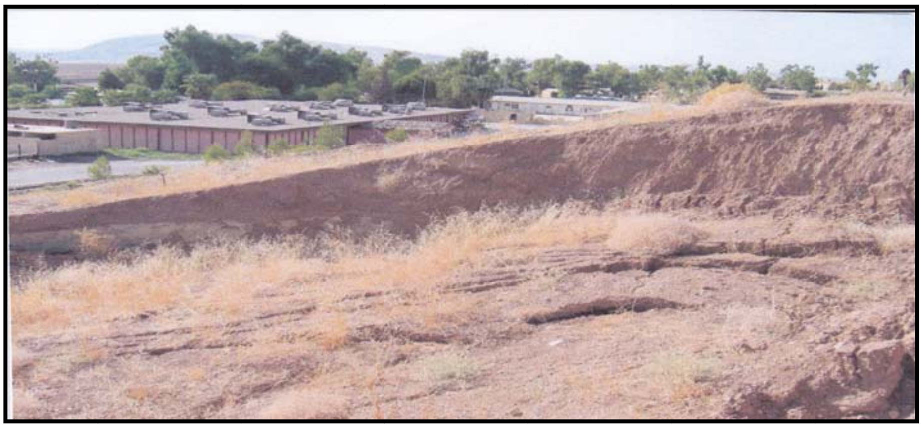


Fig. 21 Spring downstream of dam [9].



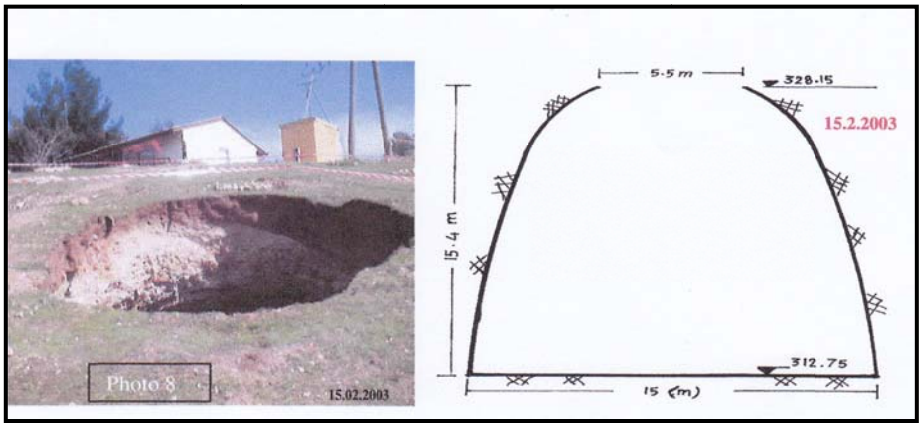


Fig. 22 Photographs of the right bank sinkhole showing development stages and sketch indicating mapped dimensions [9].

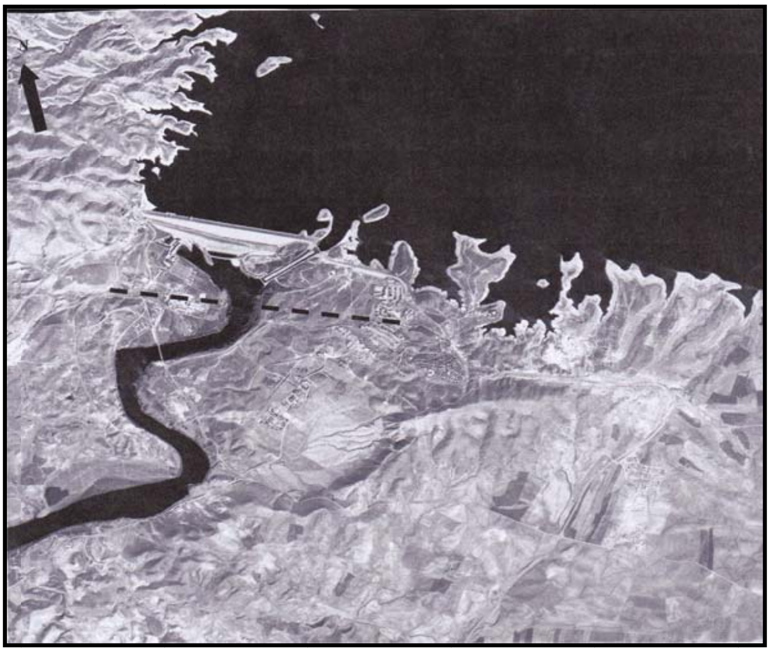


Fig. 23 Aerial view of the Dam area showing alignment of downstream sinkholes [9].

same line of the other sinkholes on the right bank .One suggestion to the sudden collapse of this sinkholes is the possible infiltration of

9. Mosul Dam Flood Wave Study and the Question of Badush Dam

In early 1984, the Ministry felt the need to assess the possible damage that could be incurred as result from Mosul Dam failure and the subsequent flood wave released in the Tigris River valley. So it signed a contract with the same consultant of Mosul dam to do such study. The study being done, and the report being ready in 1985 showed the colossal damages that could result in such an event to both human lives and material properties and infrastructures with its impact reaching beyond Baghdad. The main conclusions of the study showed that: (1) if failure would occur at all, the most probable cause would be the foundation geology; (2) for the various scenarios of the reservoir water levels at failure, the initial wave hydrograph would be as shown in Table 2, with peak discharge of 551,000 cumecs can be expected (Scenario A); (3) the calculated travel times to various cities on the river, max height of wave, and flooded areas are shown in Table 2 and Fig. 24 [13].

These alarming results prompted the Ministry of

Table 2 Flood wave hydrograph at various initial conditions of failure.

Hours/Case	A	B	C	D
0	1	1	1	1
1	13	13	13	13
1.5	80	80	80	80
2.0	215	210	215	212
2.5	372	356	335	325
3.0	474	452	422	404
3.5	535	499	480	453
4.0	551	510	509	475
4.5	538	469	497	460
5.0	507	469	497	460
6.0	405	382	435	405
8.0	271	266	186	278
10.0	186	192	195	198
12.0	123	136	130	142
18.0	37	47	39	49
24.0	18	2	19	22

Table 3 Flood wave discharge, time of arrival and flooded areas at various locations in the Tigris River Valley.

Location	Discharge (m^3/sec)	Time of arrival (hr)	Wave height (m)	Distance (km)	Flood area (Km^2)
Dam site	551,000		54	0	
Regulating Dam	545,000	1.3	48	9	
Eski Mosul	481.000	1.6	45	17	
Mosul City	405,000	4	24	69	74.044
Hamam Ali	370,000	5	18	97	
Tikrit	185,000	22	15	422	68.985
Sammara	162,000	25	10	479	30.100
Balad	115,000	28	9	516	
Khalis	81,000	31	6	566	
Tarmiya	72,000	33	4	597	
Baghdad (North)	46,000	38	4	638	216.934
Baghdad (Center)	35,000	44	4	653	
Baghdad (South)	34,000	48	3.5	674	
Diyala Confluence	34,000	>48	3	685	
Salman Pak	31,000	>48	3	708	

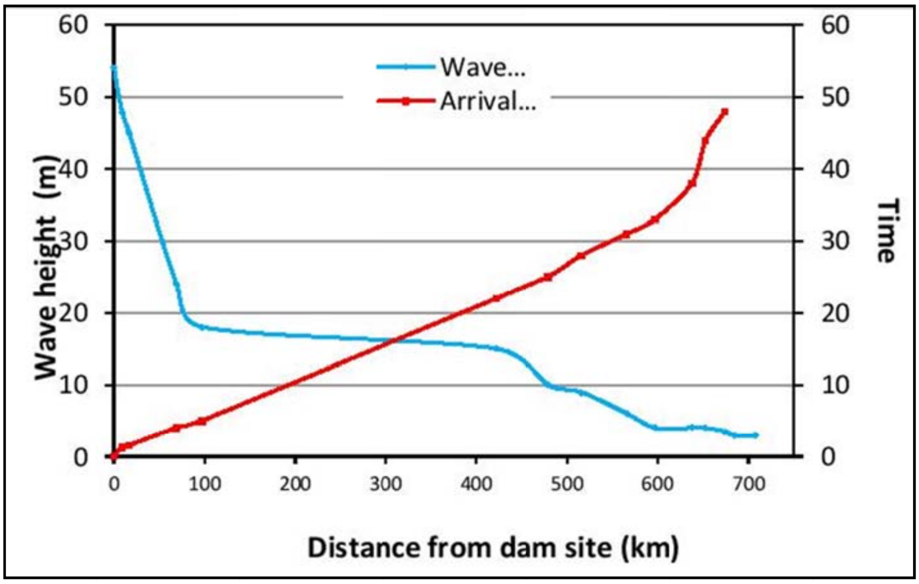


Fig. 24 Wave height at various distances downstream of dam and time of travel time of arrival.

Irrigation, when it was clear that the dam presented a grave hazard on the population, to design and start construction of a protective dam 40 km downstream from Mosul Dam to contain the full volume of Mosul Dam flood wave in case of its failure. This is the dam called Badush Dam which is probably a unique case of this size in the history of dam construction. Unfortunately the works were suspended in 1991 after completing 30-40% of the works, which was due to the UN economic sanctions imposed on Iraq after its invasion of Kuwait.

10. Safety Evaluation of the Dam

10.1 Evaluation of the Dam Safety Conditions in 1988

From the beginning of the detailed design phase until the completion of Mosul Dam, it was followed closely by the International Board of Experts appointed by the Owner; the Ministry of Irrigation; later the Ministry of water resources. This Board helped tremendously in reaching safe and sound design and construction of the dam. The Board however did not have any saying in the final selection of the dam site which was done previously by others, nor of selecting positive concrete diaphragm for anti-seepage measure instead of grouting, as the last detailed geological investigation works were not ready when the Consultant had their preliminary planning report approved by the Owner. But the Board recognized the problem of gypsum in the foundation and gave early warnings and all necessary advice to refine the grouting criteria; it stopped, short however, from reaching the design criteria required to seal the brecciaed gypsum in the foundations once and for all, these breccias beds are recognized now not to accept any form of grouting. The dam as completed was considered by the dam as safe from in all aspects except for its foundation. The conclusion reached in 1988 by both the Board and Consultant at the completion and operation of the dam was that grouting treatment works, massive and conventional, should continue for the whole life of the dam. This conclusion was supported by training an Iraqi grouting team by the contractor at the urging of both the board and Consultant to fulfill this task. This team was successful in treating many grave cases of very large dissolution cavities, of which the case of one that took 5,000 tons of solid grouting materials is well documented.

10.2 Evaluation of the Dam Safety Conditions in 1995

No general review of the dam safety was carried out until 1995. A general inspection of the dam and a review of all the accumulated data and all available reports and measurements were conducted by two

Bulgarian Specialists. They judged that the dam condition was generally acceptable, but they recommended taking the actions which are summarized in Table 3.

10.3 Evaluation of the Dam Safety Conditions in 2004-2005

After the 2003 war, and the occupation of Iraq by the United State and Britain, the US army corps of engineers performed a quick survey and a safety of Iraq dams and concluded that Mosul Dam was in a precarious state and formed severe threats on the occupation forces stationed in the Tigris River Valley. A complete safety assessment study was then initiated in which Washington group International & Black and Veatch (JV) were contracted in 2004 to do. Their report was submitted in August 2005 and included the results of thorough investigation of the dam conditions; it even included the assessment the dam safety conditions that was carried out by a PoE (panel of experts) which was formed especially to carry out this task. The panel assessment was based on potential FMA (failure mode analysis) and recognizing the usefulness of Badush Dam.

The PoE summary of the findings included the following main points:

(1) Construction of Badush Dam between Mosul Dam and the City of Mosul would address downstream loss-of-life risks for all possible positional failure modes.

(2) Construction of a diaphragm wall from the crest of the dam using current technology is an unproven alternative that could not, therefore, be relied upon to reduce loss-of-life risk sufficiently, considering the very large downstream population-at-risk. In addition, this alternative would be more costly than building Badush Dam.

(3) Construction of an upstream diaphragm cutoff wall and upstream impermeable face might reduce loss-of-life risk sufficiently, however, it would require an extended reservoir lowering and it would be more costly than building Badush Dam.

(4) Foundation grouting does not provide acceptable long term loss-of-life risk reduction, considering the very large downstream population at risk.

(5) Continued and improved foundation grouting and careful monitoring and visual inspection would be reasonable risk reduction measures to extend the economic benefits of the Mosul Dam (power generation and irrigation) as long as practical

From the above it is clear that the PoE recommends the necessity for continuing the maintenance grouting works, the usefulness of Badush dam, but it rules out the use of diaphragm wall as a replacement of the grout curtain. It is worth mentioning that the diaphragm alternative was proposed in 1987 by two consultants during construction and that it was rejected by the International Board of Experts of the Dam.

Table 3 Summary of recommended actions.

	Item examined	Recommended action
1	State of gypsum dissolution	Continue the grouting programs as before as maintenance work for the whole life of the dam and never atop
2	Deep grout curtain	Breadth of curtain is not sufficient according to Soviet and Bulgarian standards. Add two more grouting rows, one at each of the U/s and D/S of existing curtain
3	Instrumentation	Readings were judged acceptable, no action is required except routine maintenance
4	Seepage and dissolved salts quantities	The quantities of these seem to increase with rising water level of reservoir, so it is recommended not to accumulate water above Maximum Operation Water Level (EL. 330 masl). If such event occurs in the event of very high floods, then the reservoir is to be drawn down immediately below this level. WL should not be kept for appreciable length of time at this level in any event
5	Ground water measurement at downstream	Many more open pipe piezometers should be installed at the near vicinity of the dam at the downstream. I is most important to observe ground water movement there and relate this to reservoir water level fluctuation

10.4 Evaluation of the Dam Safety Conditions in 2006-2007

A new PoE was formed by the Ministry of Water Resources in 2006 to follow up the dam safety question. This PoE was formed mainly from Engineers from Harza Engineering (USA) and one member from Italy; but it shall be referred to as the (Harza PoE). The PoE had a series of meeting extending over 2006 and 2007. The main worries of this PoE were about the seepage under the dam and the possibility of the formation of new sinkholes; this was highlighted by the formation of the sinkhole on the left bank very close to the dam in 2002 (Fig. 22). During these meetings the following conclusions and recommendations were forwarded:

(1) The dam safety was questionable even with the continuation of the maintenance grouting program.

(2) There was g a very high possibility of the occurrence of sinkholes on the left bank close to the dam body.

(3) The need for intensive new geophysical investigation to be carried out using Geo-Radar in addition to the other conventional investigation that was ongoing at the time.

(4) Install many more open pipe piezometers at this bank to observe ground water movement and give early warning of the formation of new sinkholes and take action by emptying the reservoir.

(5) Limit the maximum operation level of the reservoir to (319 masl) instead of the maximum designed operation water level of 330 masl.

(6) Construct a positive cut-off in the form of concrete diaphragm as a permanent solution as the protracted grouting had not been sufficient to stabilize the situation. Admitting that such a cut-off would have unprecedented depth, therefore its implementation should be studied by uniquely specialized contractors and equipment manufacturers.

(7) The PoE went further to cast doubts on the usefulness of Badush Dam stating that the current design of the clay core may not be sufficient to sustain the Mosul Dam flood wave and that the bottom outlets may get clogged by debris leading to overtopping of the dam.

While the limitation of the reservoir water level was enforced during the subsequent years the question of the diaphragm was not settled and maintenance grouting work was continuous by the site crew as previously done until June 2014 when the Mosul City fell to ISIS terrorists. Even the dam site was captured by them but only for 20 days before they were repelled back by government and coalition forces. However the grouting works activities as the crew left and did not go back to site again.

10.5 Evaluation of the Dam Safety Conditions in 2015-2016

The repercussions of the halting of the grouting maintenance work was visualized and sensed sharply by USACE who were very much aware of the fragile situation of the dam foundation and their reaction to this was prompt. An interagency team from many United States agencies was formed in the beginning of 2015 which was lead by the USACE to carry out measurements, surveys and observations to follow developments that might lead to the dam failure. The following was done: (1) An early warning system consisting of remote sensing instruments was installed to check for movement and settlement in important locations on the embankment and structures; (2) Installing observation cameras on the dam crest and downstream berms for the same purpose; (3) A bathymetric survey upstream and downstream of the dam was conducted by socialized divers.

The findings of the US interagency team were alarming and may be summarized in the following:

(1) There were signs of increased formation of caverns and sinkholes under the dam. The discontinuation of grouting works from August 2014 until beginning of 2016 has resulted in an increased loss of gypsum and formation of new cavities of about

10,000 cubic meters more than what normally would have happened with the continuation of grouting shown in Fig. 25.

(2) Increased concentration of sulfates in the seepage water was measured indicating increased dissolution of gypsum.

(3) Signs of increased monolith movement in the grouting gallery and cracks opening were observed and measured. It was concluded that they were direct results of settlement in the gallery and hence in the foundations. The cumulative record of settlement in the grouting gallery which was kept from 1986 and extended to the end of 2015 showed sharp increase in settlement in the last year which indicates a worsening situation in the dam foundations.

(4) A SPRA (screening portfolio risk analysis) was performed to obtain the relative risks imposed by Mosul Dam relative to large dams in USA. The screening process considered loading frequency, an engineering rating to estimate a relative probability of failure, and both human life loss and economic. The evaluated risk results were compared to the risks in a total of 563 dams and 108 other with separate consequence structures which belonged to the USACE portfolio of dams. This ranking showed Mosul Dam to be in a state of extreme relative risk as shown in Fig. 27. In fact it shows that Mosul Dam is in a state of extreme and unprecedentedly high relative risk.

The US Interagency Team concludes its report by the following statement shown in Fig. 28.

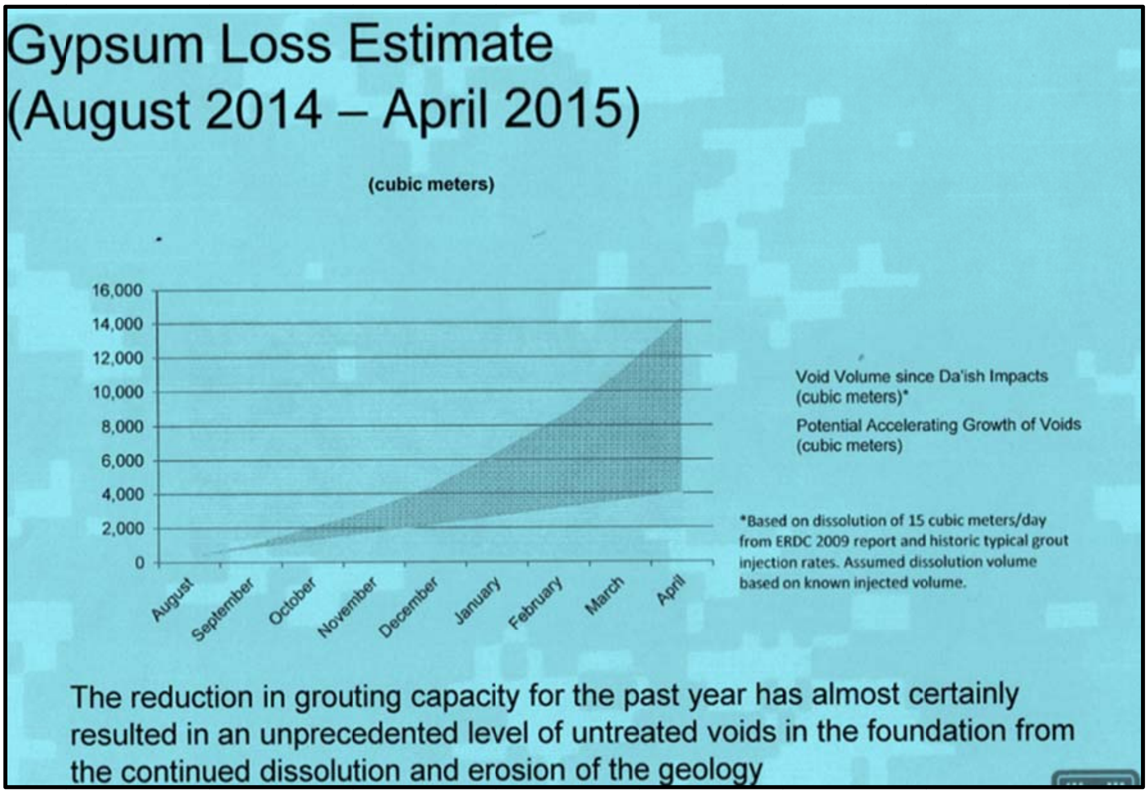


Fig. 25 Dissolution of gypsum without grouting (lower curve: estimated and without grouting; upper curve: measured) for the period (August 2014-April 2015).

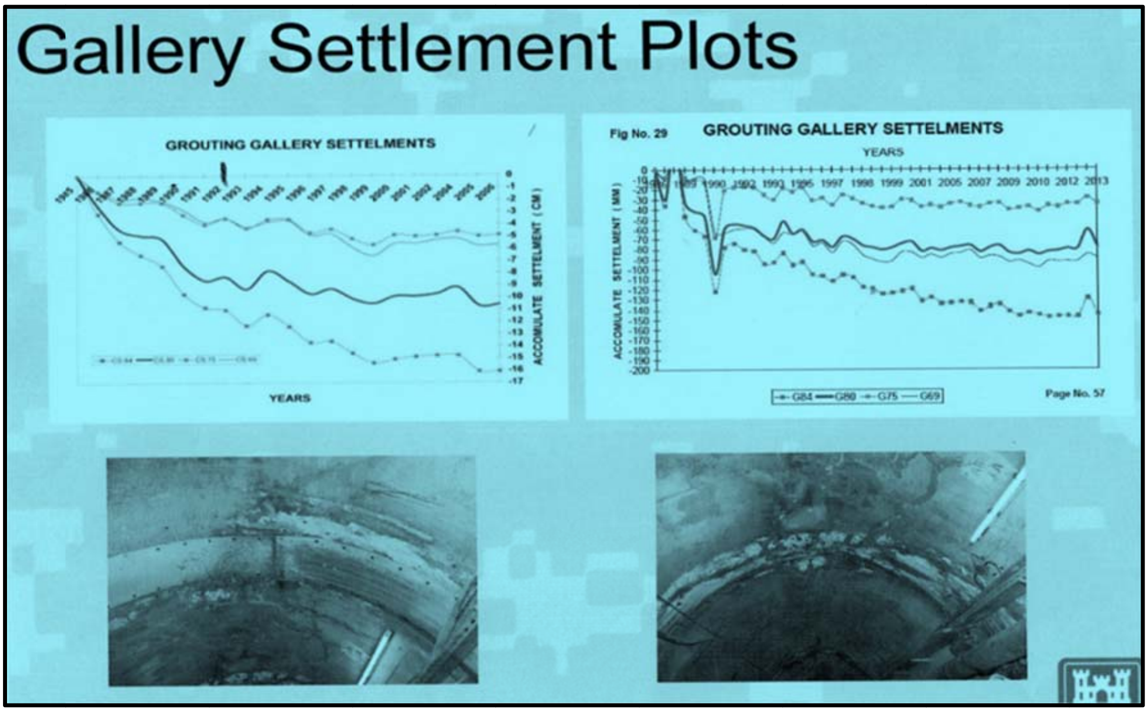


Fig. 26 Cumulative settlements in the grouting gallery recorded in sections 69, 75, 80, and 84 from 1986 till end of 2015.

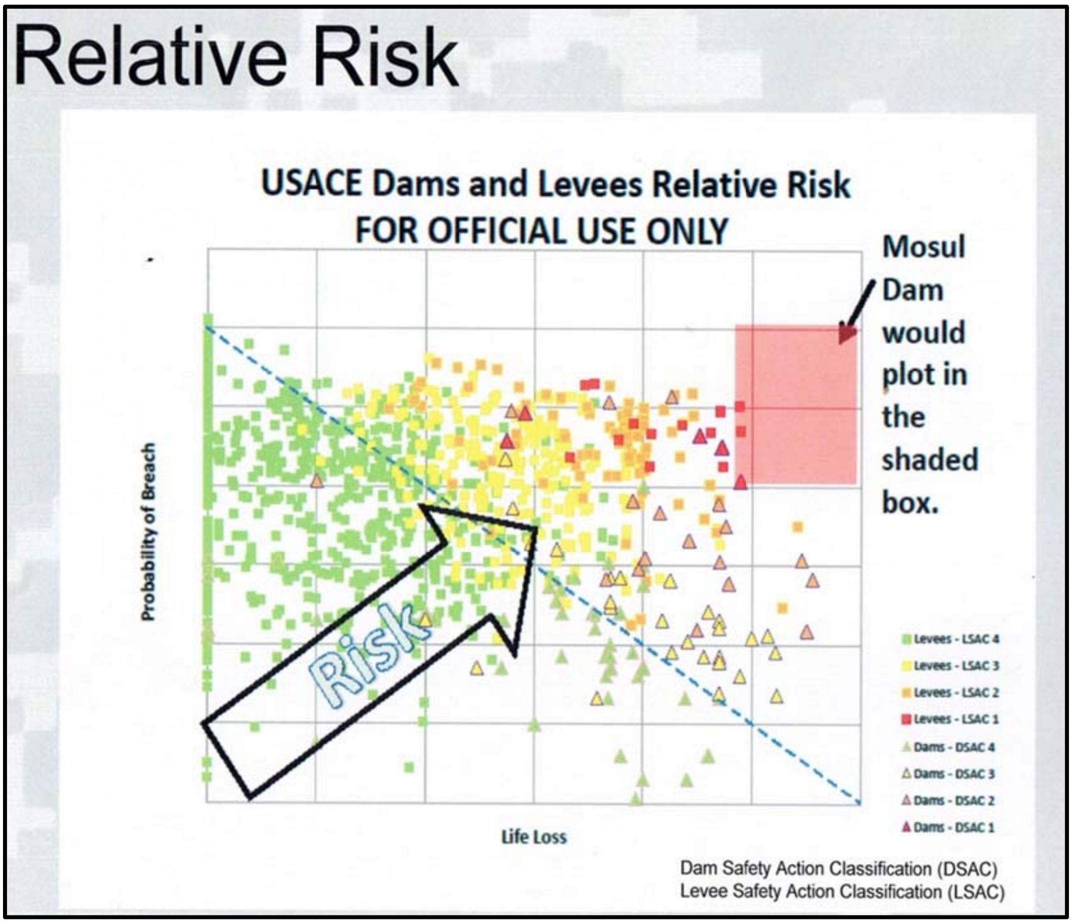


Fig. 27 Plot showing the severe relative risk of Mosul Dam.

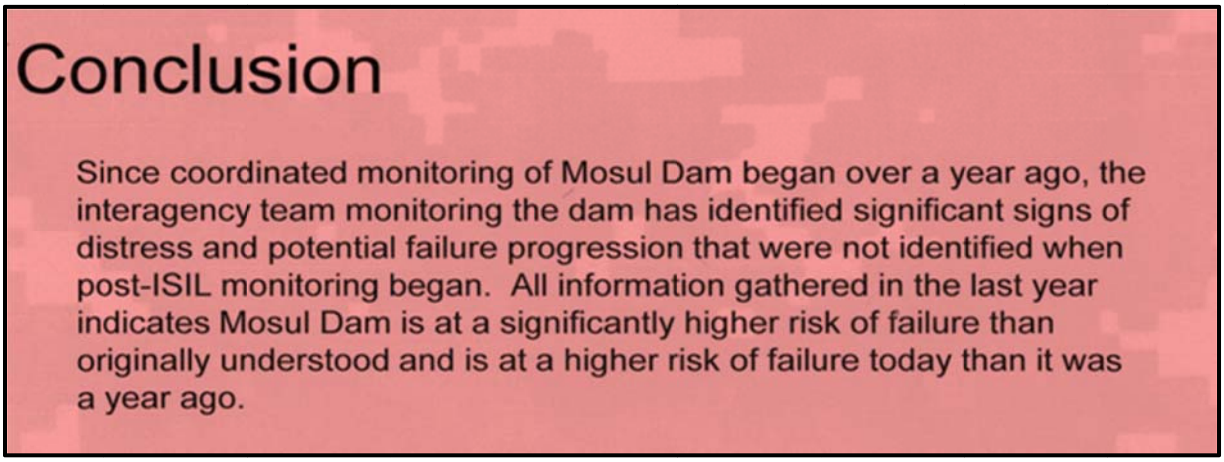


Fig. 28 US interagency report conclusion.

11. Present Situation and Final Remarks

The safety condition of Mosul Dam justifies its description of "The Most Dangerous Dam in the World" [14, 15]. A study of the dam break flood wave was carried out by the JRC (Joint Research Centre) of the European Commission and issued its report issued the report of a study which was carried out in April 2016. This study showed that the number of affected people can reach up to 6,248,000 and can inundate an area of 7,202 square kilometers. Apart from the immediate losses of lives and material properties and infra structure, stagnant water can remain over these areas for as long as 12 days. Such water polluted with disintegrated human and animal corpses and mixed with sludge and sewer water can cause the spreading of infectious diseases of various sorts [16].

With such grave consequences, the Iraqi government was pressured by the USA government to conclude a multibillion dollar contract with an Italian firm, which was to be financed by the World Bank. The objectives were to carry out an enhanced grouting program employing modern equipment's and digital observation and recording system enabling enhanced follow up, in addition to training an Iraqi crew in carrying out the work in the future.

The works of this contract have been done under the supervision of the USACE and the participation of Iraq engineers. The works are coming to a close next July and the Iraqi crew will continue these works.

Recent word from the site gives an optimistic evaluation of the conditions at the site at the present, but the question that remains without answer is what could happen in the future, and whether driving a diaphragm or construction of Badush Dam will be pursued. One thing remains for sure; the continual replacement of parent rock in Mosul dam foundation by weaker grouting materials will not result in better conditions than the first days of dam operation, nor will it contribute to lower possibilities of sinkholes formations. The dam will continue to pose a threat to Iraq even with continuous grouting [17] and this must be pondered by the Iraqi policy makers in any future planning regarding the dam. The dam should be decommissioned sometime in the future or a permanent solution other than grouting must be pursued.

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