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# Mosul Dam Full Story: Safety Evaluations of Mosul Dam

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## Abstract

Mosul Dam is the second biggest dam in the Middle East due to the capacity of its reservoir. Since the operation of this dam in 1986, it is suffering from seepage problems in the foundation of the dam due to the dissolution of gypsum and anhydrite layers under the foundation. This phenomenon has raised concern about the safety of the dam. Studies done during the recent years showed that grouting works can only be considered as a temporary solution at its best. It is clear now that while grouting must be continued search for long term solution must be sought if dam failure consequences are to be avoided. This must be done as soon as possible as the dam is showing more and more signs of weakness. It is further considered that the suggestions and recommendations forwarded by the team of Lulea University of Technology and the Panel of Experts in the Stockholm Workshop 24-25 May, 2016 give the most practical and suitable solutions for this problem.

**Keywords:** Mosul Dam, Iraq, Dam safety

## 1 Introduction

Mosul Dam is one of the most important strategic projects in Iraq for the management of its water resources. The dam abutments are located on the Upper Member of the Fatha Formation (Middle Miocene). The Upper Member, as the Lower Member of the Fatha Formation consists of cyclic sediments, marls, claystone, limestone and gypsum; however, in the uppermost part the claystone ratio increases as compared with the lower part. These inhomogeneous rocks; in their mechanical behavior will certainly behave differently when are loaded. The

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gypsum and limestone beds are usually karstified, but the karstification is less in the Upper Member as compared to Lower Member of the Fatha Formation. This is attributed to the presence of more clastics in the Upper Member than that of the Lower Member of the Fatha Formation, besides that gypsum and limestone beds become thin in the uppermost parts of the formation.

Karstic limestone and the development of solution cavities within the gypsum and anhydrite layers are the main geological features under the foundation of Mosul Dam. The bore holes data indicated that four significant gypsum units were identified during the design and construction varying in thickness from 8 to 16m and identified as GB0 (Gypsum Breccia 0), GB1, GB2, and GB3 in ascending order. At Mosul Dam site, major dissolution occurs at and above the "karstic line", where anhydrite converts to gypsum and this unit is subsequently dissolved and eroded by seepage. This phenomenon takes place in Mosul Dam where evaporites are dissolved by groundwater and the voids are generally filled with collapse breccia from the overlying beds.

In view of the complex geology of the site, tremendous amount of investigations were carried out concerning the evaluation of the stability of the dam which will be reviewed and discussed in this paper.

## 2 Evaluations of Dam Conditions (1979-1989)

During all the years since the start of Mosul dam construction many opinions and proposal were forwarded and discussed. The International Board of Experts (IBOE) which was appointed by the Ministry to follow the designs and the construction of the dam met either at the site or at the designer's office in Switzerland at regular intervals and issued. 34 meeting reports, which covered all the discussions with the designers and contractors and it contained the Board recommendations as well. Therefore these reports may be considered as very useful source of information on the dam planning report and the follow up of construction in the period from 1979 till 1989.The problems on grouting works and other works were reported at length in many of these reports. These included all the studies submitted by other consultants and experts who were invited by either the Contractors, or the Board and the Owner. So it was clear from these reports that there was no possibility of reaching the acceptable design criteria in grouting the brecciaed gypsum in the foundations of the dam, and the inability to stop the dissolution processes as grouting certain area resulted in concentration of flow in adjacent areas and opening of new seepage paths there.

One study in 1986 on the grouting problems [1] examined the quality of the ongoing work in the grout curtain and gave recommendations to use silica gel in the grouting of the left bank curtain in order to reduce seepage appearing in the left bank. Another study [2] explored the very high takes of cement grouts and the use of sand gravel mixes in a number of zones which were causing concern. Solution channels and cavities were developing at such a rate that the grouting program was not capable of maintaining an adequate curtain. The question raised in this study was whether the dissolution in gypsum/anhydrite beds was taking place at a faster rate than the sealing effect of grouting processes. The theoretical analysis on the enlargement of small passage within a soluble rock showed that the equivalent pipe volume of such passage was proportional to the cube of the solution potential, so that if the concentration of sulfate is for example 500 mg/ l instead of the 750 mg/ l assumed in the analysis representing the typical concentration opposite problematic sections, then the pipe would enlarge from 60 mm to 300 mm in the same period of time. As a conclusion, the dissolution that had occurred since impounding was substantial, but not so great as to preclude a successful completion. The study then suggested number of alternative grouting materials which were rejected on technical and / or economic grounds.

The next question was to examine the use of upstream barriers. This included the following alternatives:

i) Blanketing of the dam and certain length of the reservoir upstream of the dam. Figure (1) shows the proposed arrangement. Effective blanket would affect the piezometric profile in the foundations but impervious upstream blankets would normally be installed only by drawing down the reservoir. Their success depends on the entry points of seepage to the foundations and lengthening of seepage paths.

Blanketing the bed can be done without drawing down the reservoir by dropping the lining materials through pipes lowered to the bottom of the pond. Bentonite pellets are dropped in place first, and as bentonite absorbs water a highly impervious layer is formed. Sand is placed on top to hold the clay in place against any disturbances. But, as far as it is known this method has been used for small ponds and not for a reservoir of Mosul Dam reservoir size.

ii) Positive-Cutoff. This arrangement is shown in Figure (2).The difficulties in using this method are due to the combination of depth and the hardness of pervious strata, presence of cavities and voids in the foundation, in addition to maintaining the verticality of the diaphragm panels at these unprecedented depths. These would make trenching operations very problematic and tricky. The depth of the required trench has a great effect on the cost in the form of the very high cost of such large hydromill machines and their running costs. A location near the upstream toe of the dam or from the berm would give the least depth but it requires the drawing down of the reservoir. A trench from the crest through the core is a tricky operation and it extends for a considerable depth into the foundation, which may be technologically questionable and very costly.

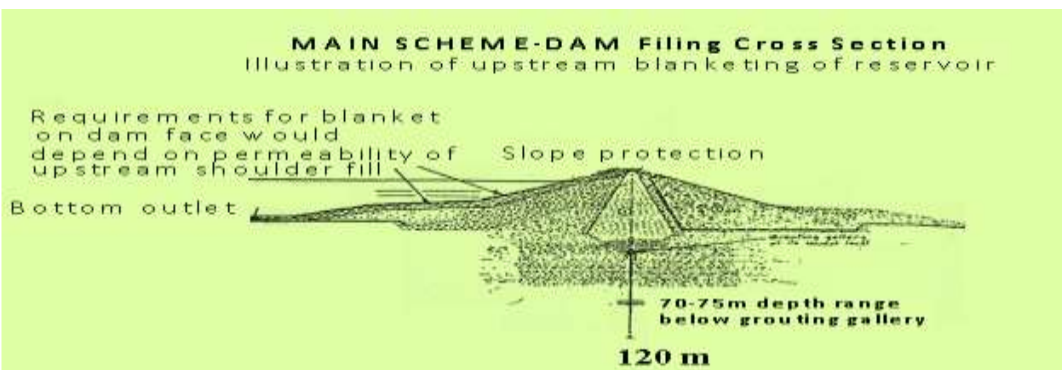



Figure 1: Illustration of upstream blanketing arrangement

**iii)** Construction of a new curtain as a direct reinforcement to the present one, this assumes that it could be done in a better geological location in the upstream of the dam in order to provide any improvement. But, such better geology does not exist and because the construction requires the drawing down of the reservoir then such proposal had no value.

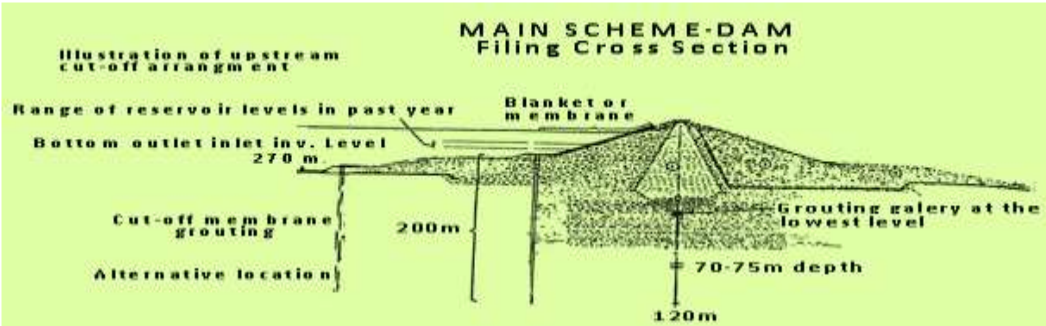



Figure 2: Illustration of upstream cut-off arrangement from the berm or a new grout curtain in the upstream toe as described in (iii) below.

This study showed that all the discussed alternatives were not practical and some of them were even not feasible. The logical conclusion was to continue the works on the present curtain by improving the mixes and injection procedure to combat large take areas, sealing large pipes and channels, providing a new array of piezometers taping the known solution areas especially the contact between the pervious limestone and GB layers to monitor the efficiency and the long term performance of the curtain in these soluble layers where windows were most likely to develop.

This study also gave rise to a new concept: that is, a satisfactory grout curtain may be deemed either as one which had been so tightly grouted as to allow negligible dissolution in the long term or, one in which dissolution may take place but is kept under control by comprehensive, appropriate and effective maintenance grouting works. Therefore means to facilitate and guide maintenance grouting work must be developed.

The three major consequences of the study were:

1. It gave a new dynamics to the “groutability test program” which had been started to improve currently used mixes and develop new ones.
2. It introduced the concept of “Maintenance Grouting” as a long term safety and repair procedure.
3. It emphasized the importance of piezometric measurements as a mean of checking local solution areas for prioritizing the repair works.

In a continuing effort by the owner to look for more suggestions a new expert Mr. Mariotte from a reputable geotechnical firm was called on to study the case.

His report was attached to the IBOE report issued in 1989 with the Board commentary [3] and it contained the following suggestions:
**a)** In the context of strengthening the grout curtain in the problematic areas where massive grouting had to be repeated widening the curtain was recommended. Additional rows of boreholes ought to be drilled consisting of one row upstream of the present curtain and slightly inclined towards the upstream, another row in the downstream of the present curtain and inclined towards downstream, and finally a vertical row in between to be done in the center. The central row was to be grouted first followed by the upstream row and then the downstream.
Finally, the central row would be re-drilled and fine grouting to be done using silica gel. The Board did not object to this proposal as machinery and grouting capacity were available.
**b)** The second solution was to construct a tunnel as long as the length of the chalky series from which grouting would be performed. The Board thought that such work was very specialized and would need expert studies to check its feasibility.
**c)** The third solution was to construct a series of tunnels and galleries to replace risky materials. This alternative received the same comments as in (b) above.
**d)** The fourth alternative was to construct a diaphragm wall from the upstream berm and a sloping concrete facing from the top of diaphragm to the top of the dam. Or even to remove part of the top of the dam and install the diaphragm through the core in a location upstream of the gallery as in Figure (3). This arrangement was neglected due to the unavailability of machines that could cut to the desired level. In a later update the removal of the dam top was thought unnecessary due to new development in diaphragm machines. The Board; however, judged this solution undesirable due to the required lowering of the reservoir level, which may extend 2-3 years in addition to the very high cost.

## 3 Evaluation of Dam conditions (1989- 2003)

No general review of the dam safety was carried out until 1995. During this period and even afterwards the dam management kept full records of the grouting quantities and locations in addition to all the instrumentation recordings, piezometric readings, seepage quantities and results of chemical analysis of seepage water samples. No attempt was made to analyze these data in terms of the overall safety condition of the dam. 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 who stayed for two months at the site in 1995 and then submitted their report containing their findings and recommendations [4]. The report covered all aspects of the dam performance up to that time, but no attempt was made to analyze the grouting process implications on the dam foundation, and instead they carried out calculation on the required width of the curtain according to current Soviet and Bulgarian codes and recommend the increase of the width of the deep grout curtain by performing two more grouting rows upstream and downstream the existing curtain and they stressed the importance of continuing the grouting program as maintenance work for the whole life of the dam. They also stated that all the instruments readings and measurements were judged acceptable, but noted also that the seepage quantities and the quantity of dissolved salts seem to increase with higher water level elevations so they recommend not to go above EL.330 for any appreciable length of time. Finally the report recommended the installation of many more piezometers along the dam downstream for better observation of the ground water movement at the downstream of the dam. Otherwise they judge the dam was generally in good conditions.

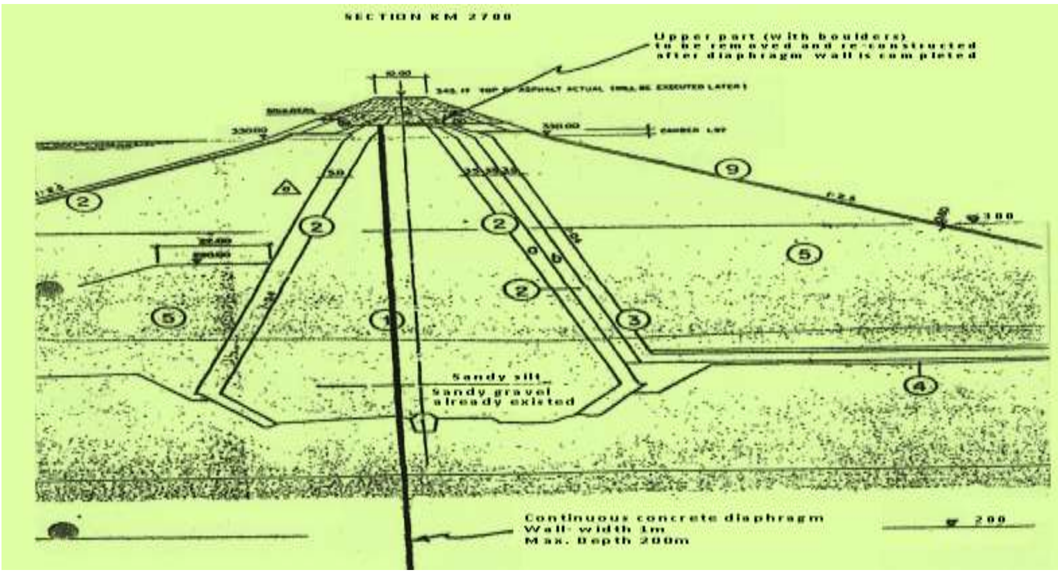



Figure3: Proposed Diaphragm driven from the dam crest.

## 4 Badush Dam

In 1984 the Iraqi Ministry of Irrigation tasked the Swiss Consultant Consortium to perform a hypothetical dam break and flood wave study in line with international practice where all owners of large dams require such study done to get an idea of what could happen in such unthinkable event. Neither the Ministry nor the consultant suspected at that time of anything wrong in the dam design or its future performance. The Swiss Consultants fulfilled this task and presented their report on the hypothetical dam failure in1985 [5]. But as the first impounding continued in1986 problems of seepage in the river section and left bank were observed and these were coupled with gypsum dissolution in the foundation which was evident from the rising concentration of gypsum in seepage water. At the same time the construction of the deep grout curtain was undergoing also many difficulties in obtaining the design criteria. All these matters caused great worry and much concern in the Ministry and pushed the Government to take the decision in 1987 to construct the Badush Dam downstream of Mosul dam. This dam would act as flood retaining structure to protect from the resulting flood wave in case of Mosul Dam failure. The design of Badush dam was backed up by mathematical and physical models which justified the selection of the final location of the dam's axis as well as other design parameters such as the height and the required free capacity [6]. The Badush Dam site is located on the Tigris River, approximately 40 km downstream from Mosul Dam site and about 15 km upstream of Mosul city Figure (4).

The construction of the dam began in 1988 at time when no final solution was in sight for Mosul Dam grouting and seepage problems. The construction; however, was halted in 1991 due to the economic sanctions that were imposed on Iraq as a direct result of Iraqis' occupation of Kuwait. The percentage of completion of the works in the dam at that time was 40%.

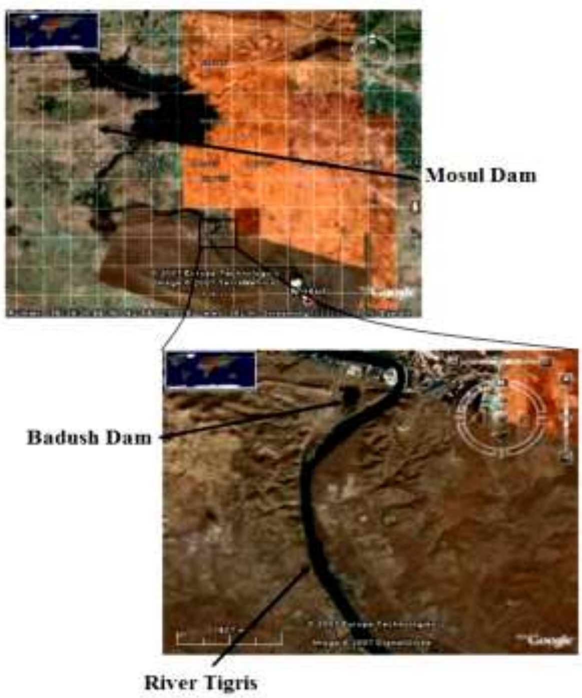



Figure 4: Badush Dam location in relation to Mosul Dam [7]

In later studies that were carried out on the safety conditions of Mosul Dam the importance of Badush dam was highlighted. More details shall be given later on in this paper.

## 5 Evaluations of Dam Conditions (2003-2014)

In April 2003 Iraq was occupied by the Coalition of USA and Britain. A team of the USACE visited the site the summer of that year to investigate Mosul Dam safety situation. The main reason was to check for any safety threats for their many bases located along the Tigris River which could come from Mosul Dam.They concluded that the dam was suffering from real problems and urgent need for detailed review was needed. As a result a contract was concluded in 2004 between the Project Contracting Office (PCO) of the Coalition Provisional Administration Authority (PCA) and Washington Group International and Black and Veatch acting in joint venture under the acronym of (WII/BV JV.) to carry out the new review. The terms of reference included:

**a)** The compilation of all available data on Mosul Dam including the designs and studies and all other related reports.

**b)** Review and analyze these data.

**c)** Conduct site visits and hold meetings with site personnel and ministry officials.

**d)** Forming of panel of experts to discuss and study and come up with solid recommendations for improving the situation.

This was all done and as a comprehensive report was submitted in August 2005 [8].

One chapter of this report contained the Potential Failure Mode Analysis (PFMA)) for Mosul Dam which followed procedures required by the U.S. Federal Energy Regulatory Commission (FERC) in their dam safety program. This study was conducted by experts from WII/BV and URS Corporation in addition to Skip Hendron (Professor Emeritus, University of Illinois). In their analysis the group established thirteen modes of failure for Mosul Dam which was grouped into three categories according to their greatest significance considering need for awareness, potential for occurrence, magnitude of consequence, and likelihood of adverse response. Table (1) gives the highest and worst potential failure modes obtained from this analysis.

The other ten potential failure modes were judged either physically possible but unlikely to progress to failure or very unlikely. From the details given in this study it was established that these three potential failure modes were all related to the geology of the dam foundation and may result from formation of cavity/cavern upstream in one of the GB layers at various depths with resulting increased piping flows either at the dam /foundation interface or at depth and the collapse of a section of the dam.

The adverse conditions leading to this can be the:

**a)** Presence of GB3, GB2, GB3 or even GB0 at depth.
**b)** No grouting under dam shells and even doubts on the effectiveness of the consolidation grouting under the core.
**c)** The possibility of development of sinkholes under the shells without the possibility of advance warning or detection.

Table 1: Results of the highest potential failure mode evaluations.

| Failure Mode No. | Description | Category | Basis For Category Assignment |
|---|---|---|---|
| N1 | Usual Loading – Shallow Foundation Seepage in the Main Valley | 1 | Judged to be possible, and also judged able to develop with limited or no warning of development |
| N2 | Usual Loading – Intermediate Foundation Seepage in the Main Valley | 1 | Judged to be possible, and also judged able to develop with limited or no warning of development |
| N3 | Usual Loading – Deep Foundation Seepage in the Main Valley | 1 | I Judged to be possible, and also judged able to develop with limited or no warning of development |

The study was concluded with an overall discussion of risk reduction measures, considering all failure modes; the appointed panel of experts came up with the following conclusions and recommendations:
1. Construction of Badush Dam between Mosul Dam and the City of Mosul would address downstream loss of life risks for all PFMs.
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 much more costly than building Badush Dam.
3. Construction of an upstream diaphragm cutoff wall and upstream impermeable lining might possibly reduce loss of life risk sufficiently, however, it would require an extended reservoir lowering and it would be much 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 measure to extend the economic benefits of the Mosul Project (power generation and irrigation) as long as practical.
These risk reduction measures and conclusions of the PFMA team are included in the conclusions and recommendations presented in task order No.8 final report by the Panel of experts appointed by WII/B [8].

At the beginning of 2006 the Ministry of Water Resources commissioned another Board of Experts to carry out an independent evaluation of the dam. The
At the beginning of 2006 the Ministry of Water Resources commissioned another Board of Experts to carry out an independent evaluation of the dam. The new board 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 worry about the seepage under the dam and the possibility of the formation of new sinkholes was very clear in this PoE’s report [9], a thing that led them to recommend increasing the number of piezometers in the downstream of the dam and to carry out a geo-radar survey in the left bank in an attempt to understand the seepage water regime and predict the formation of new sinkholes in time. This recommendation was made in spite of the fact that geophysical investigation was being carried out in the same area by a team from the Iraqi geological department. All required instruments for the geo-radar survey were purchased and site geologists were trained to carry out such surveys. But not waiting for the outcome of these investigations results the PoE at the mean time decided to limit the maximum operation water level to EL.319. instead of EL. 330 as a precautionary measure in order to limit the dangers facing the dam.

Following this the PoE had two more meetings the last of which was in May 2007. Their last report again expressed much concern on the sinkholes developments judging from the quantities of filling materials which were used to fill the left bank sinkhole number SD5 in two successive years indicating the continuation of dissolution activity. Furthermore the PoE examined the results of the geophysical investigation and the geo-radar survey of the left bank which were supportive to the same conclusion: i.e. the extensive presence of voids, fracture zones, and karsts permeable conditions. As a result the board recommended to continue the geo-radar survey to look for more evidence that might help to refine the ongoing grouting program and reiterated its previous recommendation not to exceed EL. 319 as the maximum operation water level at the Mosul Dam.

The PoE even went further and urged the project management to give a try to the use of the INTELGROUT systems which had been delivered to the site by the American side the previous year and to start laboratory tests on new mixes required by these systems .According to the PoE, this could improve the overall grouting situation. The PoE added in the light of the progressing of the sinkhole phenomena to recommend taking action on a permanent solution as soon as feasible. **A positive cut-off was recommended** as 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. The PoE even went further to name two such manufactures-contractors, one of which was German and the second was Italian. The report 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.

In Summary this report recommended the following:

"The Ministry and its consultants should examine the following items for Badush Dam.

a. To concentrate efforts on enhancing the reliability of Mosul Dam through the implementation of the foundation treatment measures recommended. Under such a plan it suggested that a smaller size dam at Badush be studied, which would function only as a re-regulating and power generation facility.

b. The Ministry should examine the consequences of a catastrophic failure at Mosul Dam on the current proposed design for Badush Dam. Appropriate changes need to be implemented even if such modifications require the removal of existing structures at the Badush site.

c. A revised feasibility report for Badush dam to change it to a low re-regulating dam should be completed and presented to the board before undertaking any detailed engineering work".

In following the other recommendation of constructing a positive-cutoff the Ministry invited the two diaphragm contractors nominated by this (PoE) and negotiation resulted in signing a letter of understanding with the German firm to pursue this goal. An announcement was made on the Media which stated:

"News agency (Reuters)) announced the following statement in relation to Mosul Dam on 4th November 2011, "German construction and engineering company Bauer said it signed a letter of understanding on a $2.6 billion (3.1 trillion Iraqi dinar) contract to refurbish a dam in Iraq".

"We expect the contract to be ready for signing within the next few months, after some final details have been clarified," Chief Executive Thomas Bauer said in a statement on Thursday".

"The project, the company's biggest ever, was scheduled to take about six years to complete It will involve Bauer building a cut-off wall to seal the Mosul Dam in northern Iraq. The ground beneath the 3.6 kilometer-long dam has become increasingly water-permeable, Bauer said.(Source: Reuters)" [10]

The letter of understanding was put on hold for unknown reasons and it did not materialize in any further work so far. But In pursuance of the Badush Dam issue, the Ministry signed a contract with another consultant to fulfill the PoE's recommendation to redesign this dam. The new report was submitted in January 2009 [11] and it contained the following:

"1. The Badush dam should not be designed for storing water in case of Mosul Dam failure.

2 Badush dam should be completely redesigned for the only purpose of power generation and with crest level of 260 m.

3. The design peak flow should be increased in lieu of newly obtained hydrological information and more refined probability distribution techniques.

4. If the Client still desired to design Badush Dam for retaining Mosul Dam's water in case of a failure, then numerical modeling should be carried out in order to:

a. Precisely define the ultimate maximum water level;

b. Precisely define the risk that the proposed bottom outlets might be blocked due to sediments deriving from Mosul Dam's failure;

c. Precisely analyze the effect that Badush Dam might have on the groundwater at Mosul city;

d. Precisely identify the risk posed by seepage and stability at the intersection between the concrete and the earth fill dams.

e. Study of the possibility of emptying Badush dam within a period of 40-60 days and studying whether Tigris River can pass these discharges downstream the dam and at the city of Mosul.

f. Coordination should be done with the final remedial works proposed for Mosul dam by constructing the diaphragm wall".

This report was followed by submitting a new design and tender documents to fulfill the above requirements.

In a parallel work the USACE completed a review of all information on Mosul Dam in December 2006 and it was concluded that the dam presented unacceptable risks and recommended that assets be removed from the Tigris River flood plain in the Mosul area in addition to other measures.

In addition to all other works done by the USACE, the Engineer and Research Center (ERDC) of the Corps investigated the geological setting of Mosul Dam to assess the lasting effects of dissolution within the dam foundation; results were compiled in a study report which was published in September 2007 [12]. This report gave very deep insight of the dissolution process resulting from seepage under the dam and downstream of it. It showed that:

1. The dissolution zones are moving vertically and horizontally towards the east and downstream and this was occurring at faster rate than natural geological processes and causing the appearance of sinkholes in the left bank.

2. It also showed rock quality degradation as indicated by obtained (RQD) values.

3. The continuing loss of the deep grout curtain efficiency.

The report emphasized the previously known fact that grouting at one location in the curtain only diverted the seepage flow to the next nearby location where it opened a new seepage path causing more loss of rock volume and lower (RQD). From grouting take quantities that were recorded on the long section of the dam during the previous years the authors used Geo-statistical spatial software (ESR1) to determine spatial correlation, and by predicting values from the observed known locations spatial patterns were defined and plotted. As can be observed in Figure (5), the highest grout take (shown in red) were located within the historic river channel. Other areas of high grout take were within the highly permeable F-bed Limestone in the left bank. The sinkholes formation phenomenon in the left bank was also addressed and shown that it was a direct result of the movement of this dissolution front as already been mentioned in the Harza PoE report. Examining the quality of rock cores recovered from drill holes in the vicinity of the left bank sinkholes SD5 (2005) and SD6 (2006) and comparing them with cores from nearby drill holes which were performed during the 1980 investigation marked decrease of the RQD values. This indicated clear loss of volume of rock in these areas as a result of dissolution. The trend of grouting and re-grouting in the deep grout curtain during the previous year indicated that the dissolution front had moved eastward possibly as much as 10 grouting sections of the dam or approximately 350 meters in 20 years, averaging > 17 m per year. As a whole this study gave very dangerous indications for the future as the dissolution would continue in spite of grouting. It also supported the decision taken to limit the maximum operation water level to EL319 m.

Feeling the urgency of the situation the American Embassy in Baghdad sent a letter to the Iraqi Prime Minister on 3$^{rd}$ May 2007. [13]. The letter was signed by the Ambassador Rayan Crocker and the General Commanding of US Army General David Petraeus drawing his attention to the unacceptable risks presented by Mosul Dam condition and recommended that assets be removed from the Tigris River flood Plain in the Mosul Dam Area. The letter also warned that citizens are equally at risk from such an event and urged the Iraqi Government take such recommended actions as, keeping reservoir water level at EL 319, continue grouting works with no interruption, continue the ongoing foundation investigations, develop a dam break warning, evacuation and recovery plan for downstream communities and coordinate dam emergency action plans with dam personnel. Finally the letter stressed the need to continue development of permanent solution at Mosul Dam and completing the engineering review initiated by the Ministry of Water Resources of the partially completed Badush Dam which in the Embassy's words "If constructed it would serve as a safety backstop in the event of failure of Mosul Dam".

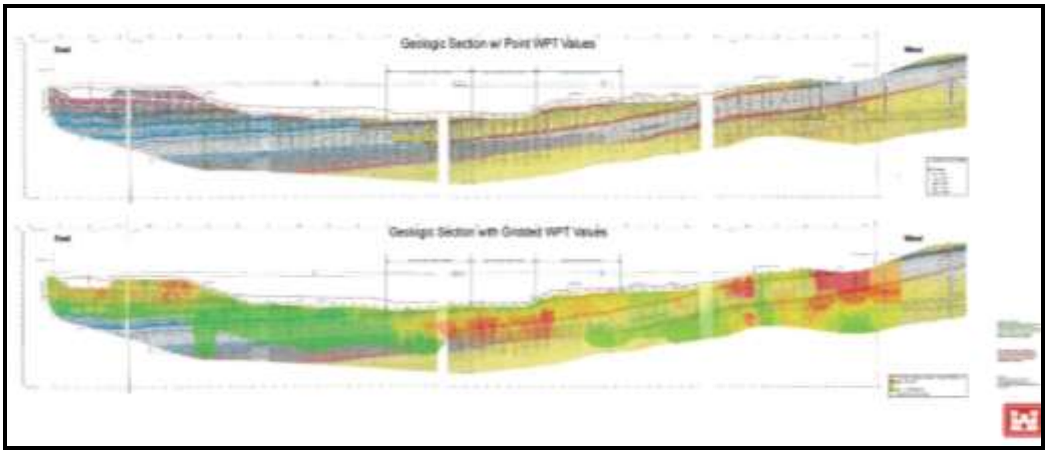



Fig 5: Geologic sections with water-pressure test values (upper figure) and kriging statistical analysis (lower figure) indicating areas of dissolution at the time of construction. The sections are from boreholes of the grout gallery under the dam. In the kriging (lower) section, red areas indicate zones of prehistoric and historic dissolution.

As it can be seen from the foregoing the question of Badush Dam as a protection measure from the potential break of Mosul Dam witnessed conflict of opinion. First there was the WII/BV and their Panel of Experts report (2005) indicating Badush Dam as the only solution giving full security from the potential Mosul Dam break and describing the construction of positive cutoff as economically and technically unfeasible and one which give no full protection: an opinion supported by the USACE and reiterated in the American Embassy's letter to the Prime Minister. Then, the second opinion of Harza PoE adopting the positive cutoff solution as the required solution calling to reduce Badush Dam to only a low power generating facility and stripping from it the flood protection advantage for which it was originally designed.

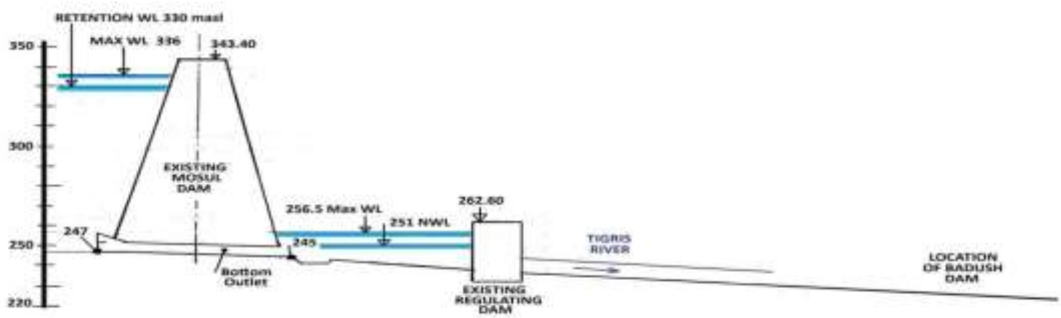
In all this the Ministry seemed as having no independent opinion and so following the second PoE recommendation the Ministry of Water Resources signed a contract of two phases with El Concord, Paul Rizzo Consortium in 2008. Phase A was to examine and analyze the existing works and documentation of the Badush dam [14, 15], and Phase B was to carry out hydraulic design verification in one volume [16] and finally to submit a new design and tender documents for the low level dam.

The plan of work assumed that for the first stage, the dam should be built for hydropower purpose only. Nevertheless, the design should be provided in such a way to leave open the opportunity to raise the overall dam's crest level to elevations adequate to create a lake upstream the dam capable of storing the Mosul Dam flood wave as shown in Figure (6).

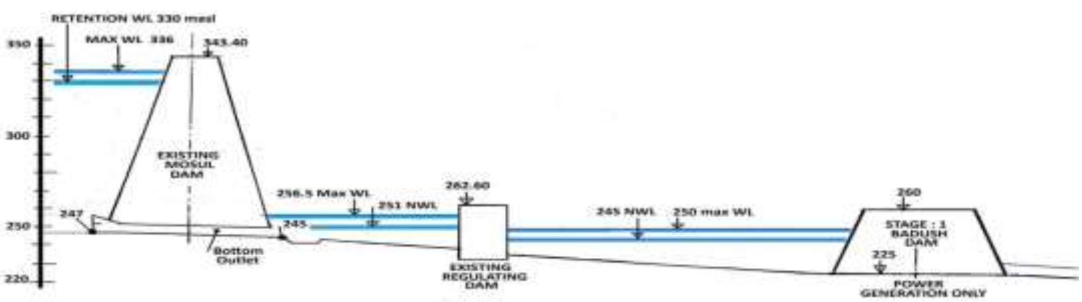
In this plan of work the dam was to be built to EL 260 allowing power generation at this low level with an installed capacity of 170 MW and at normal operation water level of 245 and maximum flood level of 250; and then to go on in constructing the dam to full height to EL 312 to allow the routing of the Mosul

Dam wave when required. Although this scheme of work looks logical it is not clear when to take the decision to build the second stage and so the question might be asked when to build this second stage and if then there would be enough time to do so. El Concorde also came to the conclusion that all existing concrete structures should be removed and reconstructed from scratch. For the First Stage of operation the implementation of a diaphragm wall has been proposed in order to reduce seepage under dam. Sections where the embankment dam already exists have been designed to be sealed completely by diaphragm walls.

The new design and tender documents involved substantial part of the existing structures to be removed and accordingly serious concerns regarding a high cost estimate, so the Ministry of Water resources engaged later on another consulting group i.e. Joint Venture of EDR and Team International to evaluate the design proposal from El Concorde and examine the possibility to integrate more of the existing structures into the final structure.




**1 : EXISTING MOSUL DAM**




**2: WITH BADUSH STAGE 1**

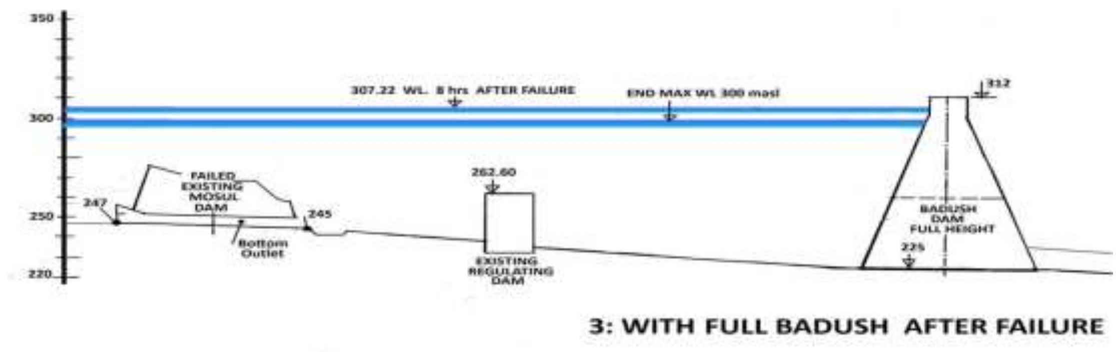



Fig 6: Badush Dam Schematization with three different Conditions

In their study which was submitted in October, 2014 [16] the new consultants looked seriously on the current problems of Mosul Dam and decided it was worthwhile to convince the Ministry that Badush dam should retain its original function for which it was designed; at the same time carrying out revisions of the El Concord new design retaining most of the works originally constructed in the dam and even introducing some improvements. The following paragraph is quoted from this study report:

“Although Badush Dam is not a profitable project, we should focus on its second, but very important purpose (protection from flood risk). Consequently, it is inhuman and even uneconomical to consider the project just an electrical plant generating only 170 MW. Furthermore, the Ministry of Water Resources is the concerned party or employer to be obligated by the government to complete it”.

# 6 The Last Updates

In 2014 a dramatic turn of events took place in regards of The Mosul Dam. On the 10th of June of that year the Islamic State of Iraq and Syria (ISIS) terrorists group seized control of the city of Mosul and its surroundings cutting the daily supply route of cement required for the dam foundation grouting and causing all workers and personnel leaving the site in a great rush fearing for their lives. The worst occurred and the dam did fall in ISIS hands on the 8th of August which caused great alarm all over the world on the possible consequences of the misuse or destruction of the dam at their hands. Just giving some examples of the world wide alarm; The Washington Post newspaper described the great dangers if the dam falling in ISIS hand in an article published on 8th August under the headlines “This could happen if the Islamic State destroy Mosul Dam”, and a CBS news update on the 9th of August announced

“Mosul Dam- a Ticking Bomb in Terrorists’ hands”. Other news media went to describe at length the volume of the resulting flood and the destruction and loss of lives that could follow. It is, therefore, not surprising that the Dam was seized back from the hands of ISIS on the 16th of the same month by a very swift and determined action by the Iraqi government special force and the Kurdish Peshmarga under air support from the US and so not giving ISIS enough time for any demolition act.

The end result of all this was the halting of the grouting operations which had continued for the past 30 years and had consumed more than 95000 tons of solid grouting materials which was considered, even if temporary solution, the only one necessary to stabilize the foundation for some more time. The repercussions of such halting 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 led by the USACE to carry out measurements, surveys and observations to follow developments that might lead to the dam failure. 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 in addition to observation cameras on the dam crest and downstream berm for the same purpose. A bathymetric survey upstream and downstream of the dam was conducted by divers who were brought in especially for the job. Figure (7) gives some details of this early warning system.

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

i) There were signs of increased formation of caverns and sinkholes under the dam. The discontinuation of grouting works from August 20014 until beginning of 2016 has resulted in an increased loss of gypsum and formation of new cavities of about 10000 cubic meters more than what normally would have happened with the continuation of grouting shown in Fig (8).

ii) Increased concentration of sulfates in the seepage water indicating increased dissolution of gypsum.

iii) Sign of increased monolith movement in the grouting gallery and cracks opening. One example is shown at the joint between sections 75 and 76 where recorded movement ranged between 0.05 inch and 0.15 inches as shown in Figure (9).Investigation of movement showed they were not caused by on site activity such as nearby works that might affect reading calibration issues or thermal expansion. The only reasonable conclusion is they are caused by settlement.

Continuous recording of cumulative settlement in the grouting gallery from 1986 to the end of 2015 showed also sharp increase in settlement in the last year which indicates a worsening situation in the dam foundations. Figure (10) shows the plots recorded in gallery sections 69, 75, 80, and 84 from 1986 till end of 2015.Photograps in the same figure show locations of distressed concrete in one joint.


Fig 7: Early warning system showing locations of instruments and cameras

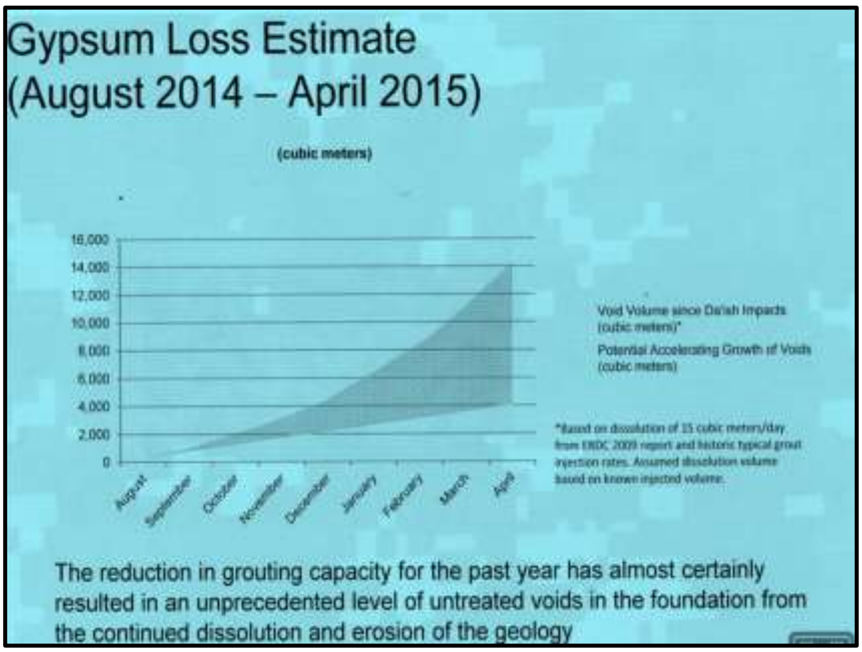



Figure 8: Dissolution of gypsum with grouting and without groutin

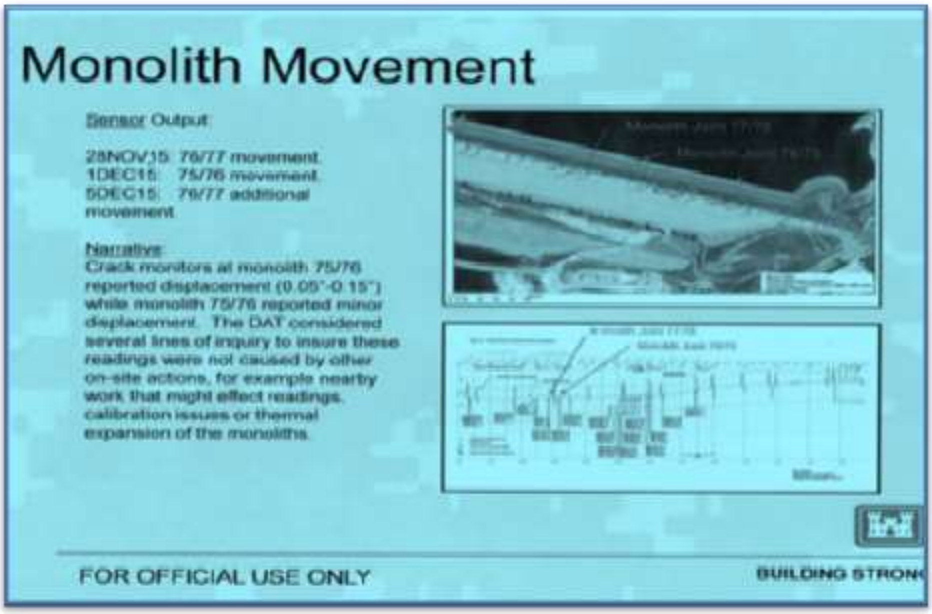



Figure 9 Displacement between sections 75 /76 in the grouting gallery

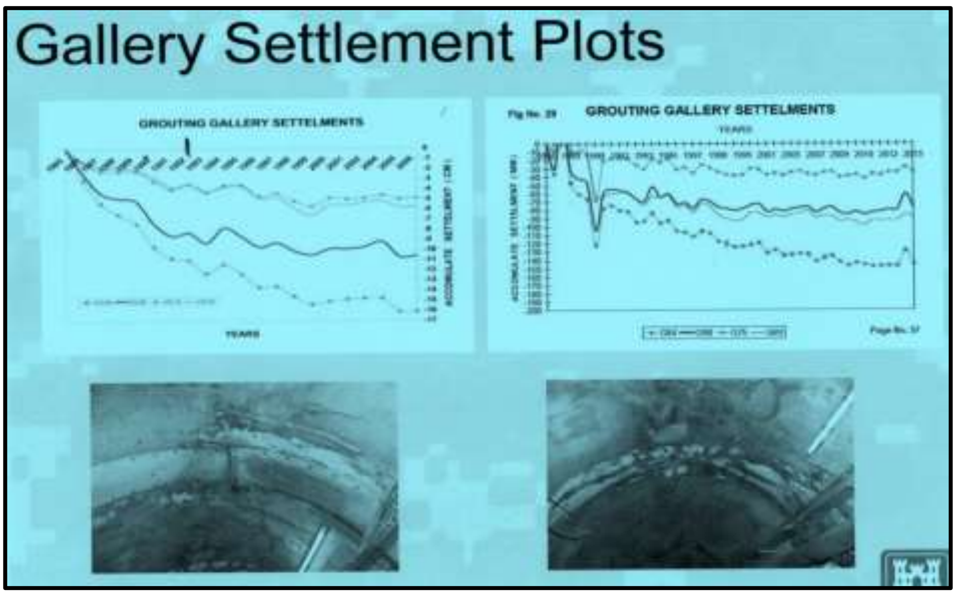



Figure 10: Cumulative settlements in the grouting gallery

In 2005 the U.S. Army Corps of Engineers (USACE) developed and implemented a screening Portfolio Risk Analysis (SPRA) process for Dam Safety. The screening process considered loading frequency, an engineering rating to estimate a relative probability of failure, and both human life loss and economic consequences of failure. The relative probability of failure, relative risk to human life, and relative economic risk from the SPRA process were used to determine a relative ranking of the projects evaluated. Dams have been screened in the following years of 2006 through 2009 for a total of 563 dams and 108 other structures with separate consequences in the USACE portfolio. The results were used to determine initial ratings in the Dams Safety Action Classification (DSAC) system. The dams evaluated included flood control, navigation, and multipurpose dams. [17], similarly the United State Bureau of Reclamation had developed methods for safety evaluation of dams and particularly loss of life risks involved [18].

So it may be stated that the United State Interagency Team working on Mosul Dam could have used these procedures to evaluate the relative risks in Mosul Dam case based on all measurements and observations done in 2015 and arriving to a relative risk ranking for the dam. This ranking showed that Mosul Dam is in a state of extreme relative risk as shown in Figure (11). This diagram shows all the dams and levees of the USACE indicating their relative risks and also where Mosul Dam stands. In fact it shows that Mosul Dam is in a state of extreme and unprecedented high relative risk.

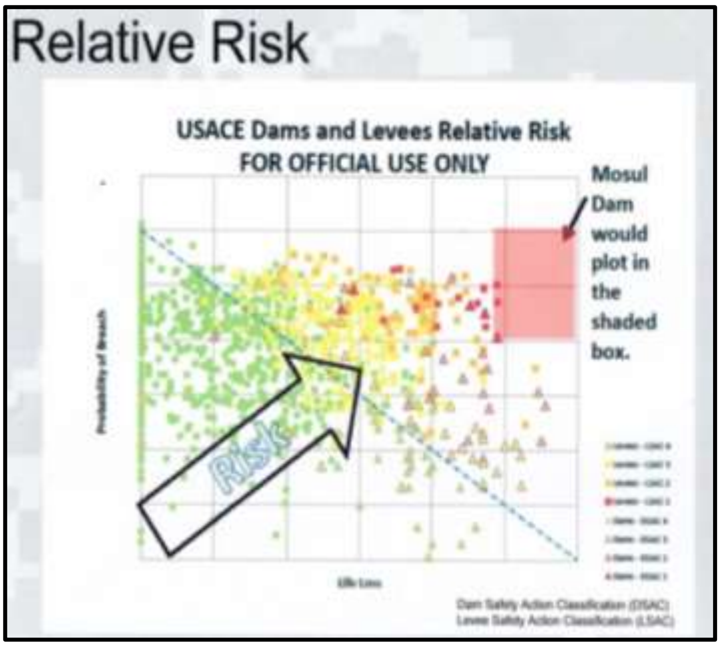



Figure 11: Plot showing the severe relative risk of Mosul Dam

The US Interagency Team concludes its report by the following statement which is shown in Figure (12).

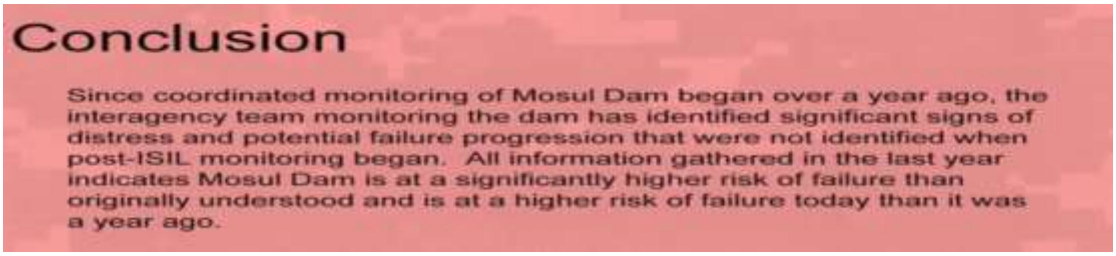



Figure 12: US Interagency Report Conclusion

The findings of the U.S Interagency Team were all documented in a report which was ready for official use only by the end of 2015, but it was updated and sent with a stern warning to the Iraqi Government with all other previous USACE reports on 30 January 2016. The warning resulted in an uproar in World Media and Newspapers which were all talking about the incipient failure of the dam and the catastrophe which would follow. This caused also discussions in the Iraqi House of Representatives which took a decision to delegate one of its members to meet with the American officials in the American Embassy in Baghdad to clarify this matter. The details given above were extracted from the report of Shurook Al-Abayachi who was (is) the deputy chairman of the Agriculture, Water and Marshes sub-Committee in the house; and which was published in Arabic on her website consequent to her meeting in the Embassy with American officials [19]. The meeting occurred on 7$^{th}$ February and involved in addition to Al-Abayachi each of the Economic attaché in the Embassy and a representative from USACE and another from USDA -Emergency Program, and it concentrated over the continuous warnings given by the American side on the near failure of the dam which was fully explained and documented.

The reaction of the Government to all these seemed to be very weak , which implied either that it was very busy with other issues like the ongoing war with ISIS, or the continued rivalry and animosity between the competing political blocks or it was oblivious to the coming dangers. The reaction which came out was a shy and ambiguous general statement to the population living in the Tigris River flood plane to move in case of danger to high grounds or to five kilometers away from the river without bothering to give more details; and under pressure from the American side the Government signed a contract with an Italian engineering group to start grouting treatment again and to repair the regulating gate of one of the bottoms outlets which was out of order since 2013 to allow possible use of the bottom outlets to empty the reservoir in case of an emergency. The contract was worth 273 million Euros to be financed by a loan from the World Bank. [20]

In full awareness of the dangers posed by Mosul Dam the Luleå Technical University of Sweden invited one of the authors of this paper to visit the university in the fall of 2014 and give lectures on the dam's deficiencies and the risks of a disaster. The arrangements to the visit were made by the research group in Soil

Mechanics and Foundation Engineering under the direction of Professor Sven Knutsson who organized the lectures. Two lectures were given on 17th October 2014 to practicing dam consultants and Engineers and PhD students [21]. This was followed by the formation of the Luleå University Research Team which took up the job of collecting and analyzing all available data on the dam and to come up with solutions to its problems.This work materialized in writing eight papers on the subject which were published in a special issue of the Journal of Earth Science & Geotechnical Engineering in March 2015 [22-29]; and then issued as a book in the same year under the title ( Geological and Engineering investigation of the Most dangerous dam in the World) Figure (13). [30].

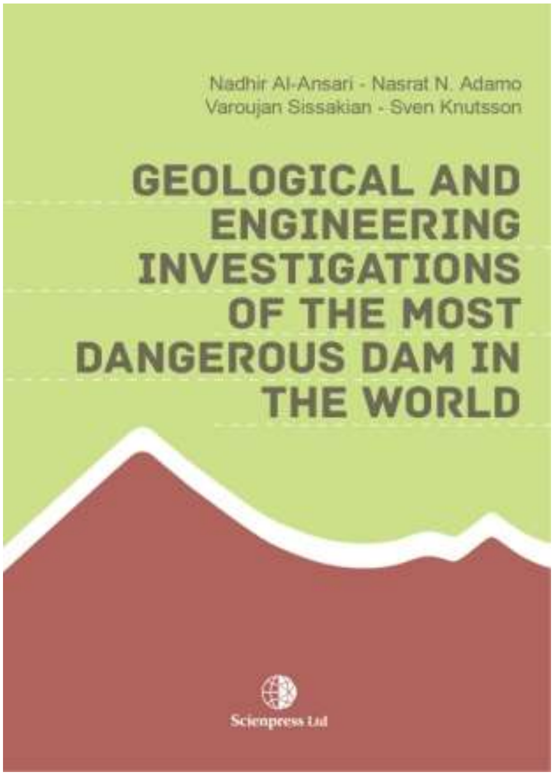



Figure 13: Book Cover

The Luleå Technical University Team continued the pursuance of Mosul Dam question and organized an International workshop which was convened in Stockholm on 24-25 May 2016. World experts on dams and geotechnical engineers from USA, Canada, Sweden, Norway France and Austria were invited to take part as Panel of Experts in addition to other top practicing consultants, contractors, machine manufactures from Norway, Sweden and Germany.

In the two days' workshop the team gave presentations on the geology and karsts problem at the area and the site, detailed history of Mosul Dam problems and studies done on these problems during construction and operation, probing the flood wave question and its consequences and even presenting suggested action plan to mitigate the consequences by adopting preventive and protective measures.

Others participants presented their ideas on the questions of grouting use of diaphragm, dam settlement observation using Radar- Satellite data. After lively discussions and debating, the PoE and Luleå Team succeeded to formulate an action plan to be suggested to the Iraqi Government to solve this complicated problem. A final statement was issued at the end of the workshop which included the details of the proceedings [31]. Attachment 5 of the statement contained the comments of the Panel of Experts (PoE) and LTU team. In the following a concentrated summary of the PoE and LTU team suggestions is given:

- Lower the reservoir water level as low as possible for such a period that may be necessary subject to updated risk analysis.
-Grouting works needs to be resumed as quickly as possible. The sequence of works shall be such to address areas of great concerns. It must be recognized that grouting works are only to extend the service life of the dam and not to provide a long term solution.
- With respect to dam monitoring, it is necessary to evaluate present monitoring program and augment it with other necessary instrumentation to determine locations for grouting program, and most critical locations to be given priority, to assess Potential Failure Modes developing in and under the dam now and in the future, and to provide possible early warning system for changing conditions that may indicate where and when a failure mechanism is developing. Therefore all existing instrumentation should be maintained, repaired, upgraded and new ones should be installed to enhance the monitoring of the dam (Full list of the types of required new instrument was given).
-Carry out bathymetric surveys to determine the points of excessive leakage from the reservoir. Similarly such surveys should be done close to the upstream slope of the dam and extended few kilometers in to the reservoir using best available technology to detect any sinkhole, spring and seeps downstream. After analysis results of such surveys it is likely that divers or Remote operated Vehicles (ROV) inspection will be needed to look at areas of suspected water inflow or discharge.
- An Emergency Action plan (EAP) should be developed and implemented as soon as possible to reduce the impacts on the downstream population. At the same time the existing Breach Assessments should be reevaluated to determine need for updating, especially in the light of new developments and urbanization of the river reach downstream.
-It is highly recommended to form a Panel of Experts to meet every three months to review the status of the grouting program and the works being done to fulfill the recommendations given in this statement. The PoE will provide support to the Iraqi Government and other international support to help assure that their interests are being addressed throughout the process.
- Recognizing that the grouting of Mosul Dam foundation is a “stop-gap” measure for which the success of durability is uncertain. Therefore evaluation, comparison, and assessment of the alternatives to rehabilitate or decommission Mosul Dam

should not be delayed. With most cost-effective and technical acceptable long-term solution finalized, then the later phase of grouting program could be curtailed with the remaining budget applied towards the long term solution. Potential alternatives:

**1. Install Diaphragm Wall** through the Mosul Dam which should extend deep into the foundation below the lowest gypsum/anhydrites (GB0) layer. Such solution has never been used in the world before in a dam site (250m depth). Comprehensive evaluation, testing, and geotechnical assessment will be required to prove the viability and effectiveness of this method for Mosul Dam. Such diaphragm will be the deepest in the world and it will introduce risks associated with the required depth and complex foundation conditions. In addition, there would be complex issues associated with contact with bottom outlets and power tunnels and the length and depth of the Diaphragm Wall in both the left and right abutments, particularly the left abutment where the Diaphragm Wall may need to extend for kilometers beyond the spillway, saddle dam, and fuse plug. The extension in the right side must also be studied carefully taking into consideration the results of the hydrological numerical model that was done previously. Total cost must be given considerable considerations. Although it may be possible to construct the diaphragm wall, it may not fully solve the problems with Mosul Dam.

**2. Complete Construction of Badush Dam-** The downstream Badush Dam could potentially be completed to prevent widespread disaster from the failure of Mosul Dam. It is understood that Badush Dam was 30-40 percent complete when construction was stopped in the late 1990's. Because of question about the foundation of Badush Dam, this issue should be considered and the likelihood of gypsum and anhydrite at depth beneath the dam should be considered in the evaluation. It is likely that the design of Badush Dam should be modified before construction begins with consideration of diaphragm wall and other design changes, the cost to construct the Badush Dam would need to be revised accordingly.

**3." Hybrid Approach"** – The safest alternative may be a "hybrid" approach with utilization of both Mosul Dam and Badush Dam for a period of time, transitioning the Badush Dam serving as the long term solution. For example, the Badush Dam could serve for a period of time as a back up in the event of failure of Mosul Dam. This would essentially mean that the Badush Dam reservoir stays nearly empty for this period of time to allow enough storage to retain the Mosul reservoir if the Mosul Dam fails. This would allow the Al Jazera and other irrigation and water supply systems to rebuild for change in water elevations. Not waiting for failure of Mosul Dam to fill Badush Dam reservoir and the ensuing issues and risks that would result, Badush Dam could be completed and the Mosul Reservoir could be released into Badush Reservoir in a controlled manner. Following that, Mosul Dam could be decommissioned with an engineered breach to allow the new Badush Dam to hold the new reservoir.

# 7 Conclusions

1. Mosul dam site is not the best of sites for a dam of Mosul Dam magnitude; on the contrary it suffers from severe problems due to the presence of badly jointed and cavernous soluble gypsum/anhydrite layers, gypsum breccias layers, weathered and jointed limestone and soft marls. The creation of the reservoir has accelerated the dissolution processes and has led to the formation of sinkholes which now threatens the stability of the dam.
2. The construction of Mosul Dam at this site was a result of accumulated errors and misjudgments from all the consultants who had studied the region and the site. They have all admitted the presence of soluble gypsum rock in the foundations yet they did recommend the construction of the dam and use grouting showing lack of knowledge of the behavior of gypsum or of the proper methods of treatment ; a diaphragm construction for example.
3. During Construction and operation of the dam it was clear that the gypsum breccia's layers were very much resistant to grouting at the deep grout curtain zones, and much work was done to solve the problem leading to intensive maintenance program. In spite of all this dissolution of gypsum continues and the rock quality in the foundation deteriorated with grouting and re-grouting. This will lead inevitably to formation of sinkholes under the dam and settlements of the embankment resulting in the end in cracking and collapse of the dam. Similar situation may be expected to occur under the shells where no grouting is done, or close to u/s and d/s toes of the dam.
4. Studies done during the recent years showed that grouting works can only be considered as a temporary solution at its best. It cannot stop permanently the dissolution occurring all over the foundation, it is causing weakening the rock by the re-grouting process, it cannot stop the progressive formation of sinkholes and, moreover it is giving a false sense of security.
5. The three dimensional picture of dissolution and cavity formation in the foundation is not known clearly. This lack of knowledge might lead to a surprise failure; and such situation requires continuous observation and vigil. Watching over the dam condition must be done while preparation for the worst must be planned at the same time.
6. It was endeavored in this paper to give a complete history of the various ideas and opinions presented towards finding a solution. It is clear now that while grouting must be continued search for long term solution must be sought if dam failure consequences are to be avoided. This must be done as soon as possible as the dam is showing more and more signs of weakness. It is further considered that the suggestions and recommendations forwarded by the LTU and its PoE give the most practical and suitable solutions

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