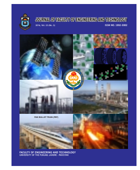
JFET 23(2) (2016) 59-67

Journal of Faculty of Engineering & Technology

journal homepage: www.pu.edu.pk/journals/index.php/jfet/index



DISCUSSION ON THE REMEDIATION TECHNIQUES FOR EARTH DAMS IN KARST GEOLOGIC ENVIRONMENTS

M.F. Ahmed*, M.S. Khan

*Department of Geological Engineering,
University of Engineering & Technology, Lahore, Pakistan:

Abstract

The placement of dams is not always by choice but by the most suitable location to meet expectations from the dam. Common geotechnical investigations are often not to the extent necessary to design the dam and perform a full scale analysis. Karst topography can sometimes underlay the dam and prove to be a major issue. The nature of karst topography is very complex and at times nearly impossible to model. Upon the appearance of issues developed due to karst topography it is imperative to perform a full scale geotechnical subsurface analysis within the area of the proposed dam, downstream of the dam, within the embankment of the dam, and within the reservoir itself. Upon first filling the cavities can become washed out and an increase in seepage could be observed. There are a number of techniques available for minimizing or to completely stop the seepage. The following paper discusses common practices for grouting and treatment of seepage in case of specific circumstances.

Keywords: Karst Topography, Earth Dam, Reservoir, Grouting, Lugeon Value

1. Introduction

The nature of karst topography is very complex and at times nearly impossible to model. With the placement of a dam or large reservoir on top of these areas can lead to a large number of problems [1- 4]. With the large increase in surcharge pressure and flow of water, cavities once filled by silts and clays become washed out and the flow of water becomes unchallenged. May it not be immediately obvious, the seepage can continue downstream to distances nearly half a mile from the dam [1, 5, 6].

After the initial filling of the dam, it can take from a few months to years for the fines to wash out of the cavities below the dam and within the area. The total capacity of the reservoir has been measured to lose up to 20% of its ultimate capacity due to seepage [5]. Flows from springs have been measured to increase to sometimes 100 times their natural flow rate. At this point in the life of the dam, it is imperative to begin a full-scale subsurface exploration within the vicinity of the dam and reservoir.

Upon the appearance of issues developed due to karst topography it is imperative to perform a full scale geotechnical subsurface analysis within the area of the dam, downstream of the

* Corresponding Author: mfageo@hotmail.com

dam, within the embankment of the dam, and within the reservoir itself [4, 7, 8]. Common practice experience and areas where noticeable problems are being derived can limit the magnitude of the investigation. The geometrical layout of the area is important so borings can be performed in directions relative to the underlying topography. The underlying layout of the site is typically well unknown and some cases have led to cavities below the surface to be nearly 60m by 60m by 20m in volume [7].

2. Site Characterization

Soil characteristic and rock characteristics should be determined at every relative point as they will be key in determining techniques for remediation. Of the characteristics that are of the highest importance is the permeability of the soil and the underlying rock outcrops. A Lugeon factor is assigned to the underlying soil by every meter or every five meters in common practice. The testing should be performed based on the risk level of the dam being analysed. The Lugeon value is a measure of the flowability ratio between your planned injected material and water [9]. It is determined by boring a hole to the necessary depth that grouting measurements are found to be necessary.

From placing an apparatus at the bottom of the boring, the cavities are flushed with water to remove any foreign material within the joints of the bedrock. This is performed throughout the length of the borehole. The water flow is measured at a location that is relevant to measuring the excess water being injected into the formations through the help of tracers. The same procedure can then be performed with the remediation agent planned for use to reduce or prevent seepage. The Lugeon value can be determined from the equation below:

$$L_u = \frac{VP_s}{TP_iL} \qquad (1)$$

Where:

V = Volume of water injected

P_s = 981 kPa

T = Injection Time

P_i = Injection Pressure

L = Length of grout section

The grouting depth is typically determined based on the height of the water level and the depth of karst topography relevant to the area.

The injection pressure is an important aspect of the characteristics determined within the working area. The injection pressure is dependent upon the strength parameters, volume, and layout of the karst topography underlying the troubled area. Typically the injection pressure of the grout is held within the critical pressure that would cause hydrofracture of the formation. Within recent developments the hydrofracture pressure has been utilized to prevent the number of borings necessary to grout the cross sectional area [10, 11]. The hydrofracture limit can be used to fracture the formation further to gain access to adjacent cavities that would have required additional boring holes.

Each injection pressure and Lugeon values are based upon the material used for remediation techniques that serves its unique purpose in relationship to the site characteristics.

3. Current Techniques

When determining which material to inject into the underlying formations, there are a number of characteristics to look at. The cohesion and viscosity are the two main properties important in choosing the solution necessary for remediation [7, 10].

3.1. Injection Properties

The cohesion of the injected material is an important factor as it a measure of how far and how easily the material will flow through the porous channels of a given grain size of a certain pressure. The cohesion is also important when determining the hydrofracture pressure necessary as the cohesion can lead to a lower injection pressure at a higher cohesive strength of the solution injected [12]. The cohesion is also a requirement to have within the solution has it will help in the prevention of a "wash out" of the material. At high injection rates the solution has a tendency to wash out the fines from the solution leading to a lower strength of material or to completely wash out the material. The cohesion has to be decided upon so that it adapts to the rock properties and develop a bond rather than being completely washed through the system.

The viscosity of the material is an important aspect as it relates to the materials cohesion and its reaction to the injection pressure. The viscosity is dependent upon the inter-particle forces between solids which results in a yield stress that must be executed to induce flow. With more inter-particle reactions, the viscosity is much higher and will require more pressure to induce flow and leads to higher pressures experienced within the formations that can lead to hydrofracturing of the structures.

3.2. Grout and Asphalt Solutions

From common practice, grout or cement based solutions have been used to remediate cavities causing seepage or stability issues. More often over the past years the use of bitumen has yielded strong results for unique cases [13]. The development of additive and admixtures has also led to new techniques in grouting and a wider range of remediation techniques.

Bitumen remediation techniques have increased over the last 30 years as the technology has advanced enough to reduce the overall cost of the procedure [13]. There are a number of great properties of the bitumen mixture in the remediation of karst topography. Bitumen mixtures have great thermal shrinkage characteristics that lead to great injection properties in filling voids and cavities. Due to its high specific gravity it is less prone to creep unlike its counterpart grout. Due to the heating properties of the bitumen mixture, the material is great at filling very small voids on the scale of 0.002mm [14]. The only unknown aspect of the bitumen treatment is the long term accountability as there are no projects over 30 years of last being treated. The short term aspect of the solution proves too great and very useful where small voids are present. The small voids lead to very high flow rates within the voids and tend to wash out simple grout solutions and segregate them where the bitumen remains consistent and performs well.

Grout has a great deal of experience in the field and still remains to be the main solution for remediation of karst topography [4]. The grout should be mixed in accordance to the site properties determined in the investigation. Should the site contain large voids and cavities, it would be proper to apply a low mobility grout that contains a low slump to allow for the voids to be filled with a smaller amount of material. There are a number of additives and admixtures that can produce site specific properties that will benefit the site. There are a number of additives that can be added to the grout solution to create properties necessary to adapt to the site specific project.

Slag can be added to the solution to delay the initial set of the material to allow for great flow times. The addition of slag works well with ultra-fine grout solutions and reaches numerous small voids that it would not have been able to originally. The addition of the slag can yield higher strengths of the grout solution has it increases chemical resistance and lowers the matrix porosity of the solution.

Fly ash and silica fume are also another common additive used in grout remediation projects. They increase the strength of the grout material as it reacts with the free lime available. The uses of additives are common as it can also leach the free lime in the rock formations within the project if they are present. The use of fly ash also reduces the segregation of the grout once injected into the voids.

Natural pozzolans can be induced into the grouting solution to resistant to pressure filtration, reduces bleeding, and increases the cohesion and viscosity of the grout solution. The use of natural pozzolans is derived from clay products and come at a cheaper price than other additives. The natural pozzolans are typically used in projects where there are very large void spaces and the cost benefit analysis yields to the use of the pozzolans. Bentonite is the most common of this particular additive [10].

From the admixtures available for grout solutions the main ones utilized today are high range water reducers, super plasticizers, viscosity modifiers, and starch. Each have the ability to reduce the viscosity of the solution, reduce the segregation, and increase the cure time to allow for greater flow opportunities. The addition of starch can lead to shear thinning of the material to reduce the pressure necessary to obtain the flow necessary.

It is imperative that with the use of bentonite and starch that the materials are added first to the solution and prehydrated. Should they not be, the material properties expected with the implementation of them would lack and quite possible reduce certain aspects of the grout solution

4. Methods of Remediation

Upon determining which technique should be used to remediate the karst or voided underlying topography, one should begin assessing how to inject the solution [10, 12, 15]. Often these steps are performed a number of times over a span of years as new voids are created and the failure of underlying formations occur. Steps in assessing the situation typically follow in the following order:

1. Determine if the procedure will be top down or bottom up for injecting the grouting. This is typically based on the material selected as the void filler and upon the location of the voids in relationship to the bore hole.
2. Determine the grouting series by applying the spacing method. Start with primary holes and based on the Lugeon value and the range to which the filler can cover begin spacing your secondary holes. Secondary holes typically fall between your primary holes. This same method is followed with tertiary and quaternary holes. This method is based on the size of the boring holes, size of the voids, and location of voids.
3. Upon completion of the boring holes, the underlying topography is washed. Over time the voids are filled with fines and some may not have been completely

washed out due to prior seepage from the dam and reservoir. It is common practice for the washing pressure to be approximately two thirds that of the effective grouting pressure to not further disturb the formations.

4. Begin the grouting or injection of the filler material through the necessary method chosen. Injection of the grout varies with depth of the hole and location of voids and unknown areas. This is typically assessed by the Lugeon values obtained in site investigation procedures. Necessary changes in the grout or mixture can be made in accordance to the size of the voids [14].
5. Check of the grout holes are performed upon the necessary set time. This is performed by conducting more bore holes with core recovery.
6. Water tests are performed next to determine the percent of the voids filled and the amount of seepage being experienced upon completion of the remediation. This is similar to that of the Lugeon test discussed previously.

Each case is typically unique in its setting and different procedures can be implemented to assess the problem. In the case of very large voids, a large number of large diameter bore holes are developed over the cavity. Filler material with a proper gradation is typically placed through the borings to fill the large cavity. Only the top 10-15% of the cavity is capped with a cementations material to in essence plug the hole [16].

Should the underlying cavities and formations be to complex and too large for complete remediation, there has been the use of blanket grouting to be performed. This method can be implemented within the reservoir itself or within the downstream portion of the dam. This decision is typically financially justified based on overall amount of grouting necessary to be performed. The blanket grouting idea basically works as placing an impermeable or limited permeability layer of material down across the area necessary for treatment. This basically limits the water table from entering the karst topography [16, 17]. The risk with this method is that with the underlying karst topography, the blanket is prone to failing as the underlying materials break down further. This method typically only useful in regions where the underlying rock material is not prone to high weathering.

5. Case Studies

Due to the uniqueness of each project it is often best to learn by example. There are an endless number of projects that have implemented grouting techniques and the injection of materials to fill voids in material that causes problem in seepage and strength.

5.1. Great Falls Reservoirs US

This project was one of the first projects to implement the use of bitumen solutions into the underlying cavities to help in the reduction of water loss [14]. The dam is located on the Caney Fork River in Tennessee. The Tennessee area is famous for its karst topography and proves to be a major problem in the design and management of dams. Upon the completion of the dam in 1920's, the leakage within the dam was measured to be nearly 9.5 m^3/s and accounted for almost 10% of power loss for the reservoir. Dye tracing was performed in order to determine the flow paths and rates at which the water traveled during the Lugeon testing [9]. Flow rates were measured to be on average 60 cm/s and reached a maximum of nearly 180 cm/s. Due to the extremely high flow rates, it was found necessary to treat with bitumen material as it would prevent the wash out of the material and would reach a number of the small voids and cavities.

The initial grouting was performed with primary holes spaced at 12.2m and then followed up with secondary holes between with occasional tertiary holes. The bitumen material was used to essentially fill the major voids and reduce the flow of the water so that a grout mixture could be implemented thus providing a cheaper fix. In total the grout curtain stretched a distance of nearly 1,750m long and an average depth of 15.25m. 6,200 tons of bitumen was used and 9,884 tons of cement. Upon completion of the treatment the water loss was then reduced to essentially 2%.

5.2. Lar Dam Iran

The Lar Dam in Iran was a very interesting project as the volume of the voids experienced in the subsurface were extremely large and unique techniques had to be implemented [18]. The earth dam was 344 feet with a reservoir volume of 34 million cubic feet of water. The underlying conditions were very complex due to lava flow and limestone. An active tectonic fault lies within the vicinity of the dam splitting it into two blocks of troubled material. Upon the completion of the dam, the high rate of seepage caused a number of karst conduits to be developed deeper and deeper (Figure. 1). The depth of the ground water table was measured to be nearly 700ft below the dam site due to the large conduits. During the first attempt to fill the reservoir, leakage was measured to be anywhere from 280 to 390 ft^3/s with an inflow of nearly $500ft^3/s$.

Upon investigation of the underlying topography, cavities as large as 3.2 million cubic feet were discovered. The cavity required 49 bore holes alone to determine the total volume and characteristics of the cavity. The cavity was filled with gravel ¼ of the volume and 1/3 of the volume was filled with crushed rock. The remaining portion of the cavity was filled with a cement mortar to essentially cap the void. Grout consumption in other areas varied and ranged from 320 lb/ft to a maximum of nearly 300,000 lb/ft at deeper areas. Remediation procedures began in the summer of 1984 and as of 2004 are still experiencing very large losses of water [18]

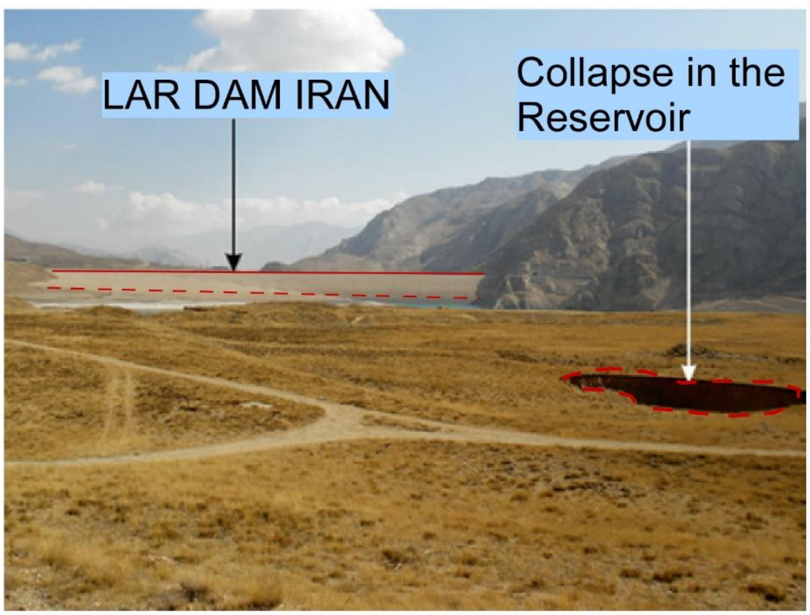


Figure 1. Location of Lar Dam and development of collapse in reservoir due to limestone karstification [modified after Kh. Feghhi [18]

5.3. Central Hill Dam US

The Center Hill Dam is located in Tennessee upon the troubled limestone karst area completed in the 1940s. The dam has experienced large amounts of seepage that creates a high rate of erosion and jeopardizes the 246ft high earthen embankment of the main dam and a 125ft high earthen saddle dam. A great deal of seepage was experienced between the earthen dam and the rock embankment. The high amount of seepage led to a great deal of erosion due to piping (Figure 2) [19].

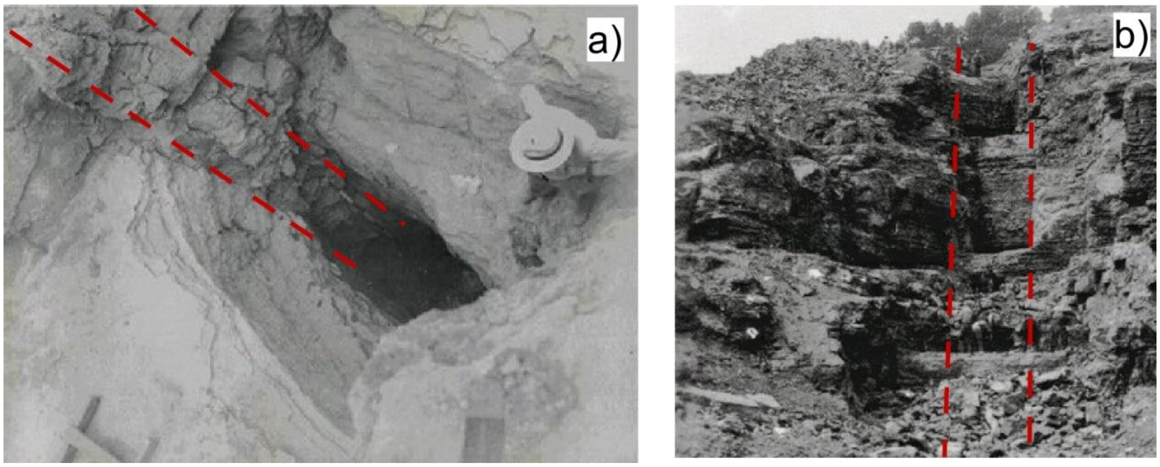


Figure 2. Location of the extensive seepage points in the Central Hill Dam, a) vertical joint, b) location of the damaged cutoff wall due to erosion, modified after L. Adcock [10].

Along the left rim of the embankment, treatment began in 1949 and the first phase of the treatment cost 2.2 million dollars then and treated a 3500ft grout line reducing the seepage from 38ft^3/s to 1ft^3/s. Due to a large flood in 1991, springs downstream from the dam discharged approximately 3823m^3 of chert and clay. Cavities were opened downstream of the dam with the largest being 200ft below the top of the ground and measured 80ft high by 15ft wide. In 1993 a second grout line was placed along the same alignment of the previously placed grout line. Since then, the seepage has increased to nearly 20ft^3/sec. Recently in 2007, a 260 million dollar contract was awarded to implement barrier walls and grouting techniques in order to control the seepage in the future years to follow.

6. Conclusions

There have been a number of cases across the globe and within our own back yard where a basic dam is placed and major problems with seepage occur due to the underlying karst environment. Due to the size and the unknown limits of the underlying topography, it becomes difficult to assess the situation. The projects can easily become very costly very quickly upon knowledge of the underlying setting. It is important for future projects to spend the initial money in determining the underlying topography of the site in order to begin treatment prior to any problems arising.

In the case that remediation techniques are imperative one should determine every aspect of the environment that will be a benefit to the remediation chosen. Whether bitumen or grouting techniques are chosen, additives and admixtures should be considered and implemented. At a certain point in determining which technique to implement it can soon be a decision based on the bottom dollar as the cavities and topography could be too complex for the budget available. Projects with karst geologic environments can easily become a geotechnical engineer's dream for a project with the large amount of work to be assessed. It is important however to involve hydrological engineers and geologists as the project can be sought after differently with a single overlooked property of the project.

References

[1] M.A. Knight, M.C. Harris, B.E. Van Cleave, A.N. Hockenberry, Seepage Remediation and Karst Fuondation Treatment at Clearwater Dam, Piedmont, Missouri, Environmental and Engineering Geosceince, XVI, No. 3 (2010) 195-210.

[2] J.A. Schaefer, Risk Evaluation of Dams on Karst Foundations, Managing our Water Retention Systems, 29th Annual USSD Conference Nashville, Tennessee, (2009) 541-579.

[3] R. Fell, M. Foster, J. Cyganiewicz, G. Sills, N. Vroman, R. Davidson, Risk Analysis for Dam Safety, "A Unified Method for Estimating Probabilities of Failure of Embankment Dams by Internal Erosion and Piping", Guidance Document, Version Delta, (2008).

[4] X. Ruichun, Y. Fuzhang Y, Karst geology and engineering treatment in the Geheyan projecton the Quingjiang River, China. Engineering Geology, 76(2004)155-164.

[5] S. Turkmen, Seepage problems in the karstic limestone foundation of the Kalecik Dam (south Turkery). Engineering Geology, 63 (2002) 247-257.

[6] B. Zhang, M. Wu, Seepage control treatment of Blind Valley Reservoir, Gao Yaoji, China, Hydroelectric Power Construction Engineering Consultant Company, Yunnan Province, (2000).

[7] L. Adock, A history of Karst seepage – Center Hill Dam rehab. www.waterpowermagazine.com/stroy.asp?sc=2049980 (accessed on June 18, 2013).

[8] S. Altug, Z. Saticioglu, Berke arch dam, Turkey: hydrogeology, karstification and treatment of limestone foundation. Present state and future trends of Karst studies. In: Proceedings of the 6th international symposium and field seminar. Marmaris, Turkey, (2000).

[9] P.F.F. Lancaster-Jones, The interpretation of the Lugeon water-test. Quarterly Journal of Engineering Geology and Hydrogeology, 8 No 2 (1975) 51-154.

[10] C.R. Donnelly, S. Hinchberger, E. Mohammadian,The Design of Foundation Treatment Measures for Dams on Karst Foundations, Hydrodivision Conference, (2000).

[12] P.T. Milanovic, Water Resources Engineering in Karst." CRC Press LLC, Florida, (2004).

[13] A. Naudts, S. Hooey, Hot Bitumen Grouting: The antidote for catastrophic inflows Grouting and Ground Treatment, (2003) 1293-1304 doi: 10.1061/40663(2003)76

[14] Corps of Engineers, Grout Materials' Engineering Manual EM 1110-2-3506 20 (1984) XP008137786.

[15] Y. Kang, B. Zhang, Karst and engineering handling to the karst in Wulichong Reservoir, Yunnan Province. Carsologica Sinica, Institute of Karst Geology, Guilin, China, 21 No 2(2002) 120-130.

[16] A. Naudts, Additives and Admixtures in Cement-based Grouts, Geotechnical Special Publication no. 120 II (2003) 1180 - 1191.

[17] G. Okay, B.A. Soidam, Experiences on two karstic dam sites. International commission on large dams (ICOLD), Antalia, (1999).

[18] K. Feghhi, Contribution of the Lar Dam-Polur Lineament in the Lar Dam Leakage. Dams and Reservoirs, Societies and Environment in the 21st Century (London: Taylor & Francis Group), 1(2006) 699–706. ISBN 9780203963555.

[19] L. Adcock, Center Hill Seepage Rehabilitation, Nashville District of the US Army Corps of Engineers, (2008).