GEOTECHNICAL ASPECTS OF DAM SAFETY AND FOUNDATION PROBLEMS

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ABSTRACT: The design, construction and maintenance of most dams around the world are under the control of various federal and/or state agencies. Experience has shown that most dam safety problems result from errors or oversights in the original design, and construction. Such mistakes become defects that remain hidden until reservoir impoundment develops these defects into a problem. Correction of major defects after the reservoir impoundment is often difficult and expensive. Therefore, emphasis must be placed on avoiding these errors during the design and construction phases. Most of the problems are common to both concrete and embankment dams and thus the prevention principles are generally applicable to both types of structures. The purpose of this lecture is to review the significant types of dam safety problems and how they can be prevented. A case study of failure of Titan Dam in USA is also discussed. This lecture is presented along with a film on the subject. Additional two case studies are presented and discussed to emphasize the importance of field studies and experience to avoid dam safety problems.

1. INTRODUCTION
Most dam safety problems can be grouped within five categories.

(a) Overtopping caused by inadequate spillway capacity.
(b) Structural failures of conduits and other appurtenances.
(c) Stability failures of abutments foundations or the dam itself.
(d) Cracking caused by differential movements and
(e) Seepage or seepage related problems

The first two of these have been solved by advanced technology. But the later three remain the most serious cause of Dam Safety problem. Overtopping can be prevented by proper hydrological predictions and design of spillway capacities adequate to peak reservoir level. Elevation of dam crest and spillway capacity must be designed to fit the specific needs and characteristics of each project. Spillway capacities and operating procedures must all have the common objective of passing the probable maximum flood without risk to the dam. Structural failure also can be prevented by adequate use of advanced techniques, prediction of static and dynamic loading and knowledge of construction materials. Concrete dams must be designed to withstand maximum reservoir loading with acceptable deformation. Structures and conduits associated with embankments must support the embankment and water loads of all possible load conditions. Conduits, sluices, intake and outlet structures, all must be designed and constructed to withstand forces of high velocity of water flow. Damage from erosion and cavitations must be prevented while safely dissipating the energy of discharging water. The majority of serious dam problems have been traced to generally interrelated categories of stability, cracking and seepage. These problems may occur singly or operate together in a progressing cascade of cause & effect and thus deserve the most careful attention in design and construction.

2. STABILITY AND CRACKING
Stability failure often is the result of inadequate shear strength in the foundation, the abutments or the embankment caused by adverse geological conditions, unsuitable materials or inadequate construction methods. These conditions become most serious when aggravated by unrelieved water forces, pressures or uncontrolled seepage. Cracking is generally caused by differential settlements or deformations in the foundation, abutments or adjacent materials within the embankment. Longitudinal cracking usually results from differential settlements between zones of varying compressibility within the embankment or foundation. Transverse cracking is caused by differential settlement along the length of the embankment usually related to compressibility of embankment or foundation at/or near the abutments. Internal cracking not usually visible to an observer can occur at abrupt changes in the geometry, configuration of foundations, abutments or internal structures. Load transfer forces due to differential settlement at these points create arching or internal cracking of the material. Cracking is a particularly serious problem if it disrupts the impervious zone and allows water to flow uncontrolled from upstream (U/s) to downstream (D/s). This could aggravate the problem of seepage which is the most significant threat to safe earth dam performance.

3. SEEPAGE
Seepage problems occur in a variety of circumstances but can be generalized in to two categories.

(a) The seepage that carries away the particles of embankment, abutment or foundation material resulting in internal erosion commonly known as piping. Since piping progresses in a U/s direction and accelerates as the
seepage flow is concentrated, it can result in a rapid failure.

(b) Another seepage problem is the creation of internal water pressure that decreases the shear strength and thus the stability of earth and rock materials. If not controlled or relieved, seepage of this nature can permeate the foundations, abutment, or embankment zones and can cause local sloughing, deep slides or large structural movements.

No dam is absolutely impervious. No rock foundation or abutment is free from joints, cracks or other discontinuities, which can carry water. Therefore, most dams seep to some extent. The problem depends whether or not the seepage is properly controlled to prevent erosion of material and adverse effect on stability. The danger inherited in all these safety problems is emphasized by failure of some dams in the years past such as Baldwin Hill reservoir in 1963, the Malt Se arch dam in 1959 and the Teton dam in 1976. Because Teton dam failure occurred during daylight hours and the photographs equipment was being used at the site, it provides the most dramatic documentation of the progressive nature of a dam collapse.

3.1 Case Study

Teton dam located in South Eastern Idaho, U.S.A., was to provide a multipurpose reservoir for irrigation, power generation, flood control and recreation. The project included a 305 ft. high and about 3100 ft. long zoned earth embankment, a gated spillway at the top of the right abutment and a powerhouse at the base of the left abutment. The site, which had been judged to be adequate for construction by an investigator panel, has a major bedrock formation of rhyolite characterized by open joints and fishers. The design foundation treatment includes a cut-off trench through the flood plain alluvium and up the abutments, a key trench below the cutoff in both abutments, a grout curtain the full length of the dam, and rock surface treatment under the core zone. The embankment zone included a central core of low plasticity silt, U/s and D/s zones and blanket drain of sand and gravel, a D/s zone of random fill and protective exterior zone of rock-fill, U/s and D/s.

The reservoir impoundment began in October, 1975. Heavy runoff from the spring snowmelt raised the reservoir to within 3 ft. of spillway by June 1976. On June 3rd, two small streams flowing clear water were found about 1300 and 1500 ft. D/s from the dam on the right abutment and on the morning of June 4th, a small clear seep was found about 200 ft. D/s from the dam on the right abutment. None of these flows were considered to be unusual. On June 5th, about 8.30 a.m., muddy flow of about 20 to 30 cfs was found exiting from the abutment near the D/s toe. Shortly thereafter about 9 a.m., seepage was observed about the right abutment contact. An hour later about 10 a.m., a leak appeared on the D/s face of the dam some 20 to 30 ft. off the right abutment and about 130 ft. below the crest. Beginning first as a wet spot, it soon became a flow; eroding embankment material and about 10.30 a.m. rupture with a load roar. Visual observation showed that the opening had become a tunnel about 6 ft. in diameter extending from 30 to 40 ft. into the embankment. About the same time, notification was given to evacuate the D/s areas. About 10.50 a.m., a whirlpool developed in the reservoir opposite the opening. By 11.30 a.m. the D/s hole was enlarging rapidly and shortly thereafter a sinkhole developed above the opening and minutes later the crest of the embankment collapsed. Dam was breached at 11.57 a.m. Subsequent detailed investigations, testing & analysis of dam site and construction events may never reveal the exact failure mechanism but do indicate that the most probable cause of the failure was the internal erosion by the piping. The fact that a modern dam could fail in a time frame of only a few hours (in this case, 3.5 hours) makes it imperative that renewed emphasis be placed on the principles and techniques employed in Site Selection, Design, Construction and Monitoring the performance of dams.

4. SITE SELECTION

The first major step in building a safe dam is the site selection process. Although this process includes social, political, economic and environmental factors; special consideration must be given to geotechnical, geological, hydrological and other engineering aspects of the location. With a few exceptions, a dam can be built at any location but to be a safe dam, specific characteristics of the site must be thoroughly understood. This requires that field site investigation be conducted by expert in Geotechnical filed using equipment and the technique which will develop the maximum amount of pertinent information. Each site will present special problems which must be identified to ensure that the dam will be safe. Primary emphasis is placed on geological features that may influence structural stability and seepage. Exploration includes analysis and testing of in situ earth, rock and potential construction materials to provide essential information for use in the design and construction phases. Investigation of foundation characteristics may sometimes appear to be an excessively expensive item but in perspective, it is a small percentage of the total project cost and is justified by minimizing costly modifications or changes later during construction. After completion of a site selection process, the second major phase is Dam Design.

5. DAM DESIGN

5.1 Site Conditions

Since conditions of each site are different, dams cannot be designed by standard cook-book approach but must be unique for specific conditions at that particular site. Design should take advantage of all advances in science and
technology including the computer applications which provides an opportunity to quickly examine wide range of assumptions and conditions for analysis of potential stability, cracking and seepage problems. The designer must confirm the validity of the assumptions and data employed and compare the theoretical analysis with insight of past performance. Dam Engineering is still an art and designer must have broad knowledge and experience in their field. During the design process, periodic reviews should be held in which specialists in different technical disciplines evaluate potential weakness. Evaluation of foundation, abutment and construction materials is difficult because these natural elements are variable and complex and often during construction are found to differ significantly from original assumptions and data. Good design will anticipate the differences that may occur and provide for necessary modifications to cope with such conditions. The contract documents, the budget and construction management must be flexible enough to accommodate the necessary changes. Every facet of the design process must consider the potential safety problems of stability, cracking and seepage and incorporate defensive measures to prevent or control them. It begins with sound design concepts tailor to its site and geological structure.

5.2 Impervious Zone

Basic to dam design is the impervious zone. In concrete dam, the structure itself serves this purpose. In an embankment dam, the preferred material for the impervious zone is the moderately plastic clay although silts can be used if properly protected against potential erosion. This zone should have firm bonding over the widest possible contact surface with the foundation, abutments and structures. Protection of the impervious zone is accomplished by additional zone of progressively coarser material. When properly designed, this transition zone provides control of seepage water, protection against erosion and structural support required for stability. The third function of transitions is to preclude movement of the small size impervious materials into the voids of adjacent larger size materials. These zones also provide the defense against transverse cracking. If the design so dictate, a cutoff trench excavated into the rock structure of the foundations and abutments is used to block the path of seepage. Cutoff trenches should have smoothly sloping sides and bases of sufficient widths to allow access of heavy rotary equipment for compaction.

5.3 Cut-off

The geological nature of the foundation and abutment rock may also require special treatment in cut-off to block or direct seepage flow. One form of treatment, a grout curtain, may be employed. But complete grout is often difficult to achieve and should not be relied upon as a singular feature to protect against seepage. Embankments, foundations and abutments must also be protected from instability aggravated from high seepage pressures. This is accomplished by internal drains, which may include chimney drain or blanket drains. The common purpose is to trap seepage and conduct to the safe exit path to the D/s foundation level. The same function in concrete dams is accomplished by galleries and drains built into the structures. Drainage zones must be of the proper gradation to prevent piping while providing adequate capacity to carry the anticipated seepage quantity within allowable pressure gradients. Use of the many available design features will vary widely with the local dam-site conditions. But the underlying philosophy should always be, first to minimize seepage and second, knowing that some seepage is inevitable, to effectively control it. Ultimately, the design process should develop definitive plans and specifications from which evolves the third major face, Dam construction.

6. DAM CONSTRUCTION

Close attention to the details of construction process is of paramount importance in assuring Dam’s safe operational performance. Plans and specifications must be adhered closely and construction procedures should use proven techniques and equipment. Also the construction must be supervised and inspected by qualified Geotechnical engineers and other personnel experienced in Dam construction who are familiar with the special problems and critical features pertaining to the project. Personnel must be alert to recognize any conditions encountered during construction, which differs from the assumptions and intend of the design. To support this endeavor, every project should have the on-site services of a qualified Geotechnical Engineer and a Geologist and other necessary specialists. The dam designers too, should visit the construction site at frequent intervals to ensure that actual site conditions are compatible with their design assumptions. If conditions differ, appropriate changes and modifications must be initiated.

6.1 Exposed Surfaces Treatment

he single most important phase of dam construction is when the foundation and abutments are exposed, shaped, cleaned and treated. As material is excavated, every exposed feature must be examined thoroughly to assure actual conditions are compatible with design assumptions. Excavation of cut-off should be to the competent rock or to an impervious layer whenever possible. Foundation and abutment trenches should be shaped to configuration avoiding near vertical or steep slopes and sharp changes. When the cut-off is to the bedrock, final shaping and cleaning of the foundation and abutments may be by use of heavy machinery, power tools or hand labour as needed to remove all unstable, highly fractured, weathered or untreatable rock. The result should yield the configuration of exposed treatable contact surfaces, which are accessible to machine compaction of embankment
material. Removal of overhang is particularly important. Overhangs prevent access to compaction and create areas of differential stress, which can lead to cracking of the impervious zone. Where blasting is required in preparing the foundation, small charge should be used to prevent opening fractures in the rock mass. Shaping should include filling all depressions, voids, irregular shapes and remaining overhangs with dental concrete to provide good surface for compaction. Once the shaping is finished, the exposed contact surfaces must be thoroughly cleaned with air and/or water jets to remove any remaining loose particles. Joints and fissures in the rock surface must be cleaned and filled with grout or concrete to prevent piping of material along or through these openings. Close supervision is essential to assure that all irregularities are removed, shaped, filled and treated before placement of embankment material. Oversights or omission at this stage of construction if not detected, are soon buried and become hidden defects. The process of foundation and abutment preparation for concrete dams is equally critical but with more emphasis on practice that could affect load bearing capacity or structural movement.

6.2 Placements and Bonding of Impervious Fill

Another construction phase of prime importance in preventing future performance problems is the placement and bonding of the initial lifts of the impervious material at the contact surfaces with the foundation, abutments and internal structures. Impervious fill should be compacted to achieve optimum density and bonding using rubber tyre equipment. The shape of structures within an embankment should present a surface on which embankment material can also be compacted with pneumatic equipment. Placement using hand operated power tamping should be avoided. Proper compaction and bonding at all contact surfaces is a key defense against seepage. Preparation of the embankment material is also a prime factor in preventing future problems. For economic reasons, embankment fill is obtained from excavation material or from selected nearby areas. All such materials must be segregated by type and composition and classified to the design requirements before placement. It is most important that proper material is used in different embankment zones and that each material has proper moisture content and is free of contaminating impurities. Thus each lift of materials must be processed to remove oversize particles and blended to achieve uniform moisture content.

For the embankment, materials are placed to specified lift thickness and compacted with the required number of passes of the compaction machinery. Compaction may be accomplished by using sheep-foot rollers, vibratory rollers or rubber-tired equipments as may be most suitable for a particular material. Compaction must achieve densities sufficient that compressibility, permeability and shear strength meet the design parameters. Successive lifts must be bonded together to avoid laminations with resulting planes of weakness. When a lift is to be placed over prior material that has become loose or desiccated, the existing surface must be reworked to ensure proper bonding. As the elevation of the embankment rises, the most critical placements are against the abutments and structural contacts were the bonds must prevent seepage along the contact plane. These are the most difficult because they are not in the regular placement compaction cycle applicable to the general portions of the embankment and must be accomplished by separate construction activity. This compaction can best be accomplished by rubber-tired equipments working directly against the contacts surfaces. An operation of power tamping is acceptable only in localized arrears inaccessible to heavy machinery, and when used must result in compaction densities equivalent to the machine compacted fill.

6.3 Filters

Placement of materials in filters and transition is of particular importance because of their function in controlling seepage, piping and transverse cracking. The placement activities must provide the proper materials that meet the specification requirements for particle size and are free from contamination. Contamination often results from surface runoffs or spillage from haul equipments. These should be avoided during construction by controlling both drainage patterns and routing the hauling machinery. If contamination does occur, the material must be removed and replaced. As construction work progresses, performance-monitoring devices placed in the dam must be observed periodically and the data timely evaluated. Throughout the entire construction process, supervision, inspection, testing and monitoring are essential to ensure the ultimate safe performance of the dam. Cooperation and co-ordination between designers and construction engineers and contract personnel is the key in achieving this goal. By utilizing the cumulative experience of all the technical disciplines involved, potential problems can be avoided or identified and corrected as they occur. The supervision and monitoring process does not end when the dam construction is completed.

7. MONITORING

Monitoring performance of the dam is the fourth major phase in safe dam operation. Continuing performance monitoring is essential to understand the dam’s behaviour and to detect any incipient problems before they become major difficulties. Monitoring is accomplished by variety of instruments and by visual observation. Internal measurements are obtained by various instruments placed at strategic points in the dam. The most frequently measured parameters are the internal water pressures and internal or external movements. External measurements using survey methods are referenced to bench marks located in stable materials at protective locations. Also visual observation of the structure by experienced engineers can provide additional performance information. This is essential to observe seepage outlets for signs of piping and to detect visible evidence of dam deterioration. Performance
monitoring data is recorded as a permanent record for future evaluation. As the data accumulates, the actual performance can be compared with the performance predicted by the design. Thus correlations are obtained that become valuable in the design and construction of future dams. In the performance monitoring process, if a problem is detected, timely corrective actions can be taken to limit its effects. Corrective actions may range from drilling of relief wells D/s to reduce water seepage pressures, to inserting a deep cut-off barrier into the embankment and/or foundation. Corrective action after completion and reservoir impoundment is usually a costly process and is not always completely successful.

8. ADDITIONAL CASE STUDIES

I will now discuss dam safety aspects by examples of case histories. These examples will illustrate what happens to dams that are established on what are supposed to be good foundation i.e. rock foundations. We often think that if we can establish a dam on rock, we will have a good foundation. Usually this is true, but only if we treat the rock properly and only if we design the dam properly at the interface with the rock. The kind of difficulties that we may get into depends to a considerable extent on the nature of foundation material. There are several types of foundation rock materials of which I will discuss the following.

(a) Jointed Rock
(b) Solutioned Rock

8.1 Jointed Rock

Jointed sound bedrock is rightfully considered to be a good foundation material and yet there have been failures or near failures on such materials. One of them is Sir Adam Beck No. 2 dike at Niagra Falls, Ontario, Canada.

Figure 1 shows cross-section of the dam, which was completed and filled with water for the first time in about 1957. The design is quite simple. It is a dumped and sluiced rock fill dam with a sloping clay core protected by filters. The foundation material is dolomite. The rock surface where the dam was located was covered with soil that formed natural blanket. Where this blanket was thin, it was reinforced to make it continuous with the core. Most of the joints in the rock seemed to be filled with silty or clayey material. In order to keep the filling in joints from eroding upward into the rock-fill of the dam under normal seepage, a filter was placed on the bedrock so that the upcoming water would not flush the material out of the rock joints and increases the permeability of rock thereby increasing the leakage.

A year after the dam was placed in service, the seepage increased from about 300 gpm to 3000 gpm overnight and the next day to 5000 gpm. During the next two days, the operators pulled the reservoir down. They found a sink hole about 9 ft. in diameter in the clay core with loose material and voids beneath it. When they explored the sink hole in more detail, they found a gap several hundred feet long parallel to the axis of dam beneath the core. Given little more time, the sinkhole might have reached to a size, which might have caused the dam failure. They also found that there was an open joint between points A and B (Fig. 1) and that the joint led directly to a small sink hole in the bottom (bed) of the reservoir. The sinkhole was at a place where during construction, a hole had been blasted to erect a light pole for night work on the project. The hole had been backfilled but obviously backfilling was not proper. What happened can be seen from Figure 2(a) and (b).

As shown in the Figure 2, on top of the rock was a rather thin base filter, 6 inch, of crushed dust, overlain by 6 inch of 3/8" to 3/4" material, designed to keep fine material from washing up out of the bedrock joints into the rock fill under normal seepage but not designed to keep water in an open joint from flushing the base filter material itself in to the voids of the rock fill. With considerable volume of water coming through the open joint, the water was literally funneled upward. It simply blew the base filter up into the rock fill, let the rocks fall down and develop a sinkhole. Thus it was a sort of built-in defect, which was activated by seepage after reservoir impoundment. The geological and construction coincidence was coupled with a filter that was not designed for what
really happened. A disaster was averted because it was possible to lower the reservoir level rapidly and because fortunately, the problem that developed gave a few days of time to handle it before it could turn in to a disaster.

This episode should remind us the importance of properly grouting the boreholes upon completion of drilling during subsurface investigation especially on U/s in reservoir bed. It not grouted, we are creating open wells for the water to flow. Just one such open ungrouted borehole connecting the underlying weak layer or open joint is enough to create a disaster. It should also be noted that relief wells reduce the internal foundation pressure but they also increase the quantity of seepage, increase the hydraulic gradient locally and therefore, tend to accelerate any deterioration that might have occurred due to other adverse conditions.

8.2 Solutioned Rock

The next type of foundation that certainly deserves attention is solutioned rock, usually limestone or dolomite. Wolf creek dam in Kentucky, USA holds back one of the largest man-made lakes. The dam was designed and contracted just before World War-II. The foundation work was almost complete when the war broke out. The contract was terminated. Later the construction started and the dam was completed.

As shown in Figure 3(a) and (b), the foundation was Limestone having two layers, the upper layer notoriously cavernous and the bottom one less solutioned. It was realized that the limestone had to be cut-off but instead of providing a cut-off wall or an impervious core trench through major part of solutioned rock, they decided to use an already existing large solutioned trench on U/s.

A grout curtain was constructed below the solution trench, the trench was thoroughly cleaned and was filled with clay to provide an impervious cut-off. The compacted clay was carried down to the bottom of the trench but the clay could not be compacted properly against the caverns U/s and D/s of the solutioned trench. This was because of overhangs and sharp edges in the geometry of the trench surface.

About 20 years after the dam was completed, sinkholes and wet sports began to appear on D/s. It was obvious, the foundation was deteriorating. The Corps of Engineers, who owned and operated the dam, recognized the sign of danger and inaugurated an extensive grouting programme. By this act, they most likely saved the dam from immediate failure but sinkholes continued to develop. The joints and solution features that were partly filled with soil by mother nature (geological time) and later partly filled with grout were gradually being washed out. As water leaked through the solution features, it removed the materials and made larger and larger openings until they developed in to pipes. These pipes led to the sinkholes and allowed materials to collapse. It reached to the point where it was questionable if grouting could keep up with the erosion. It became obvious that something more permanent was needed. In 1978, a concrete diaphragm wall was constructed to replace the original cut-off. The wall went as much as 40 ft. at some places into the bottom limestone formation.

Wolf Creek is not the only dam on limestone that has experienced troubles. Hales Bar Dam of TVA was abandoned and replaced because of deterioration of foundation.

The lessons that we need to learn from this case are basically two:

(i) The sides of the trench for impervious clay cut-off must not have overhangs or sharp edges because it is not possible to compact clay properly against such irregular surfaces and therefore proper seal is not formed against such surface which will allow the water to percolate and eventually to deteriorate the foundation. Such overhangs must be removed, surfaced properly and then clay material be completed to form proper seal. Also rubber tyred rollers should be used for compacting material against slopes.

(ii) The idea that one can solve foundation seepage problems by grouting is simply false. The old slang, “Grout in Doubt” and be worry free does not hold good at all. The new idea should be grout and then forget that the foundation is grouted, meaning that Do Not solely depend on grouting alone. It is not a Dependable measure. The foundation must have other protection against seepage along with grouting. This is because one can not hope to remove all the soil like filling that has accumulated in the solution features over a period of time. Therefore, even if the grout fills every open space, it fails to occupy many regions of erodible material. Sooner or later water will percolate through the
foundation and sooner or later it will remove some of the fillings and enlarge the channels. A foundation on cavernous/solutioned limestone or dolomite that has grouting as a Primary treatment must eventually deteriorate.

9. SUMMARY AND CONCLUSIONS

As you now know, dam safety problems can be avoided by proper attention to design and construction details. Dam safety begins with the site selection process giving proper attention to the finding the engineering and geological site characteristics. Design of a dam must be site specific and must be accomplished by qualified engineers having expert experience in his field. Construction techniques are also a key element in dam safety. Compliance with plans and specification requirements is essential with particular attention to the critical phases of shaping, cleaning and sealing foundation and abutments and placement of materials at these locations. Close inspection, supervision and performance monitoring are also essential to ensure that the dam fulfils the design intents. Dam’s safety depends most of all on designers and constructors working together to coordinate their expertise and judgment to achieve sound structures that reliably perform the project’s stated objectives. The cost of failure is too great to accept anything less.

For a safe dam, one must have detailed knowledge, more detailed than sometimes realized of the geology and the foundation materials of the site. Engineers dealing with dam foundations have to be well versed in soil mechanics, engineering geology and behaviour of materials.

A requisite for success is to design defense in depth. If we elect to install a grout curtain, fine, but then we should take care of the seeping water as if the grout curtain weren’t there. We might provide a drainage system that makes the seeping water harmless. We might place against the rock or any other surface where there is a possibility for the water to emerge into the body of the dam, materials as non-erodable as we can get. We have to recognize that design of a dam continues through construction and reservoir filling and perhaps a number of years thereafter.

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