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CRACKING OF DAMS

IN

ARIZONA

Report of the Crack Study Team

April 27, 1978

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Cracking of Earth Dams in Arizona

Report of SCS Study Team, April 1978

I. Authority and Charges

A team was appointed to investigate reported cracking of earth dams in the vicinity of Phoenix, Arizona. The distressed dams have been constructed since the early 1950's under the Pilot Watershed Program and the PL-566 watershed protection program.

The team members are:

C. E. Stearns, State Geologist, SCS, Davis, California
R. J. Smith, State Design Engineer, SCS, Bozeman, Montana
J. C. Stevenson, Construction Engineer, SCS, WTSC, Portland, Oregon

The team was specifically charged to conduct sufficient studies to determine the magnitude of the cracking problem, its probable effect on existing structures, repair needs and methods, and changes in procedures and criteria needed to eliminate or control the problem in future SCS work in the area.

This report completes the assignment of the study team. Contained in the report is an analysis of the cause of the problem, the likely consequences of the cracking and proposals for repair. The team also proposed changes for investigation, planning, design, and construction of new dams in the area.

II. Introduction

The history of SCS earth dam design and construction in Arizona is included in this study team's interim report, dated July 21, 1977. Also,

in that report and in the Engineering Testing Laboratories, Inc., report, dated July 1, 1977, are descriptions and photographs documenting the cracking. Subsequent to these reports, much excavating, sampling, testing, and field surveys have been made.

III. Summary of Conclusions and Recommendations

The Dam Cracking Team has concluded that the transverse cracks pose the greatest hazard to the dams. The transverse cracking problem is of a greater magnitude than originally recognized and poses a real hazard to the integrity of the structures.

The principal cause of transverse cracking is tension release associated with embankment drying. Secondary causes could have aggravated the cracking but cannot be verified.

A dust mulch does not prevent cracking. Natural self-healing of the cracks has not occurred and cannot be depended upon unless a filtered discharge face is provided.

It is recommended that all structures distressed by cracking be expeditiously identified and repaired. Repair by installing a graded sand and gravel filter in a trench parallel to the structure centerline is recommended.

It is recommended that all future designs of dams in hot arid areas incorporate features to eliminate or control transverse drying cracks.

IV. Effects of Regional Subsidence

A. General

In the Phoenix area (Salt River Valley), excessive groundwater use has caused widespread land subsidence. Groundwater, not unlike any other mineral, is being actively mined in this valley. More water is taken out of the basin each year than is being replaced by recharge. The net effect of this overdraft has been subsidence in the heavily overdrafted areas. The subsiding areas are well known locally and are listed below:

1. Between the White Tank Mountains and Sun City
2. Mesa-Queen Creek area to the Santan Mountains
3. Eloy-Picacho area
4. Miracopa-Stanfield area

Our dams are on the edge of the first two areas. The Buckeye dams and White Tanks 3 and 4 are on the south edge of area 1. Spook Hill (under construction), Queen Creek (in planning), Powerline, Vineyard, Rittenhouse, and Magma are on the east side of area 2.

What was said about subsidence in our Interim Report, dated July 21, 1977, is still valid. Since that time, more data has become available and more is rapidly being developed. A real effort is being made now to understand the mechanics of regional subsidence, the mechanics of the formation of earth fissures and, perhaps of more importance to the Service, where the fissures will next occur. The following brief discussion summarizes in more detail the current thinking on the subsidence problem, and in later sections, this committee's feelings on

the effect it will have on Service dams.

Overpumping in this groundwater basin has long been recognized as a problem, but initially the problems caused by the resulting subsidence affected only isolated areas. As the population grew, more people and projects were affected. As the population build-up continues, it's certain that more people and property will be affected in the future. One very large project that will be affected by subsidence problems is the Bureau's Central Arizona Project (CAP). This project seems to have brought all those working individually on the subsidence problem together.1/ Consequently, the most detailed information on subsidence is being developed along the Bureau's CAP canal alignment on the east side of the valley. The CAP centerline is immediately downstream of our east side dams, Powerline, Vineyard, Rittenhouse,Magma, and Spook Hill. The information and techniques developed should be applicable to other areas in the state as well. The information being developed is vitally important to the Service and will have to be used in planning future projects. Service people are keeping current on this developing information and,in fact,are sharing data with the four principal agencies listed in the footnote.

B. Earth Fissures

Earth fissures in basins like the Salt River are vertical cracks in the alluvium. Though not wide, they can be miles in length. Those

1/ Data is being generated principally by four groups: Bureau of Reclamation (USBR), Geological Survey (USGS), Arizona Transportation Department, Highways Division, Photogrammetry and Mapping Services (ATD) and Arizona State University, Dept. Geology (ASU).

that have been trenched are 1 inch or less in width and are partially filled with loose sediment washed in from above. They have not been seen deeper than can be easily trenched with a backhoe, so our observation is limited to 12-14 feet below the ground, at least at this time. The cracks have been described in various publications since they were first seen near Picacho in 1927. It is thought they propagate upward from depth, and may extend hundreds or perhaps thousands of feet into the alluvium. They first appear as hairline cracks on the surface. Subsequent erosion of the sides enlarges them into gullies as much as 20-feet-wide and 25-feet-deep. One crack has been probed to 60 feet.

Erosion of a fissure occurs either from sheet flow (runoff) or from irrigation. Since the fissures are parallel to the basin margins, they intercept sheet flow on the fans and shortly develop into gullies. The resulting gulley has been logically called a fissure gulley. Though commonly parallel to the basin margins, some fissures have other orientations. One on the north side of the Santan Mountains is normal to the basin. It has captured the nearby drainage and has been greatly enlarged by the stream flowing into it.

Differential movement is reported across some fissures. The down side typically is on the basin side of the crack. A famous fissure near Picacho has dropped Interstate Highway 10 about 1.5 feet. The section of highway is constantly being repaired as a result.

In summary, an earth fissure is the surface expression of tension cracks that form on the margins of subsiding basins. Some fissures have shown offset, but most do not. They form on the margins of the subsiding basins and are roughly parallel to the basins. The spectacular gullies frequently seen are the result of erosion. They are called fissure gullies.

C. Effect of Fissures on Dams

To date, no earth fissures are known to intersect any of the dams the team studied in the valley. The lineament seen in the Magma reservoir has not been verified as to its origin. This will be done shortly by USBR and USGS people. The team believes there is always a possibility a fissure could break the surface near or through one of the dams. The reasoning is that the fissures occur on the margins of the valley where the dams are located. Should this happen, the respective section of the dam will be unserviceable. The dam will automatically then have to be divided into two segments and the area of the fissure abandoned. The runoff from the affected watershed can be controlled by making wing dikes on either side of the breach. The above solution is relatively simple when the fissure is about at right angles to the dam.

A more serious case is one where a fissure occurs parallel to one of the dams. Should the fissure occur within about 500 feet up or downstream, the dam would be unserviceable. The reason is that the fissures and their resulting gullies are commonly in zones 100-200-feet-

wide with intersecting cracks and gullies criss-crossing the zone in an en-echalon pattern.

Therefore, the assumption is that the dam should be reasonably safe if the fissure zone is about 500 feet away from the dam. Should a parallel fissure zone develop near enough to jeopardize a dam, and a decision be made to destroy the dam because of it, a much greater reach of the dam would need to be breached. Although it is believed the likelihood of a parallel fissure occurring under the dams is low, the possibility exists. The consequences should be considered along with an appropriate course of action should the situation occur.

D. Subsidence

Subsidence can be most simply called a sinking or lowering of the land surface. As fluids are pumped out and the sediments permanently dewatered, the overlying column of soil is supported more and more by the soil grains rather than the buoyant effect of water. Settlement occurs as the individual grains adjust and re-orient themselves to the increased weight they now carry. The effect is cumulative over several hundred feet. The result is expressed on the surface as a lowering of the land surface. As much as 12 feet of lowering has occurred at Picacho. Since 1971, up to 1.2 feet of subsidence has occurred in the area of the Powerline Dam and about 0.5 feet near Rittenhouse. The attached profile shows the lowering of the ground surface, the lowering of the water table and the proximity of the east county dams to the subsidence area on the same plot. Data is from measurements on USBR benchmarks along the CAP centerline.

E. Effect of Subsidence on Dams

Dams constructed with SCS assistance in the Salt River Valley are on the margins of major subsidence areas. Consequently, they are away from centers of maximum settlement. Nevertheless, the areas are subsiding as the plotted USBR and later SCS survey data document. Nothing can be done to control or stop the subsidence short of stopping groundwater pumping in the areas, which is not practical at this time.

What can be done is to systematically and periodically monitor and document the subsidence. This aspect of data gathering is very important. Should a dam settle lower than the emergency spillway, for example, it would be overtopped in a design storm. This is a serious problem. Another possibility is that capacity of the reservoir may change as the reservoir tilts and have less capacity than designed. Either way, the subsidence must be monitored so corrective measures can be taken as needed. The monitoring should be done so that the elevation of the emergency spillway relative to the dam is always known. The only corrective measure considered is to raise the dams should they subside to the danger point.

V. Investigations Needed for Planning and Design in Subsidence Areas

Two major problems may be encountered at a dam built in areas undergoing regional subsidence:

A. An earth fissure can breach the dam

B. Differential movement due to subsidence can cause loss of storage capacity.

Because of the danger of breaching, dams should not be built across earth fissures. Known areas of earth fissures can be avoided. They are usually known locally and are documented in reports and maps. Even if not previously mapped, they can be found because they are exposed. Newly developing fissures are a different problem. In the past, fissures were ignored until found. In the future, it may be possible to predict the location of new fissures. Should this happen as is anticipated, such areas can be avoided at damsites. Costly repairs and potential disasters can thus be avoided.

In future investigations for dams, the committee recommends that a serious effort be made to locate existing earth fissures. The following suggestions are methods that could be used, state staff people probably have knowledge of others:

A. Research published maps and reports

B. Study existing aerial photos

C. Take special aerial photos for a given site using various means that will emphasize surface features. Low-sun angle photos are good for these purposes.

D. Fly over the area in a light plane or helicopter to check data gathered in the previous studies and to make a final check for features that may have been missed.

Different studies need to be made in order to predict locations of new earth fissures. Such technology is rapidly being developed mostly through the impetus of the Bureau's CAP. Work now in progress shows that reasonably valid predictions can be made. To do this, the following data needs

to be gathered and analyzed:

A. Depth and form of bedrock beneath the alluvium

B. Depth to water table and average rate of lowering

C. Historic rate of land subsidence

D. Nature of alluvium in the area of interest such as:

1. Location, extent, and depth of gravel beds

2. Location of major facies change from gravel to sand and clay.

The above information is important because current studies have documented that fissures occur on the margins of subsiding basins, on the margins of bedrock islands or hills, over buried bedrock ridges, knobs, or breaks in slope of the rock, and through changes in facies from gravel to sand and clay.

In the planning phase of Service work, the information can be obtained from gravity surveys, water well data, and land subsidence data. The USBR and USGS have recently had success using seismic refraction surveys in finding facies changes and predicting the nature of the underlying alluvium. Some deep borings may be necessary to verify assumptions.

The committee strongly believes that the studies outlined above are essential when planning dams in subsiding basins. The studies should be made a routine part of geologic investigations in such areas.

VI. Cracking Problems, Observations, and Testing

In 1970 similar investigations of cracking in the Vineyard Road dam were conducted by Arizona SCS personnel. There is considerable parallelism

in the condition found and documented in that study and the findings of the current effort. In fact, there is strong evidence that the cracking situation may not be significantly worse now than it was in 1970 in this dam.

At the time of 1977 Interim Report, it was thought that self-healing of some cracks was occurring by the formation of natural filter faces. It was also thought surface dragging at White Tanks No. 4 had either prevented cracking or had effectively sealed them. Those two conclusions were based on evidence observed on the surface of the dams. The Study Team recommended these two items be checked with test pits. These later investigations showed that both processes were too erratic to be reliable. The test pits showed that some cracks were sealed, some tightly and some loosely, or not at all. Therefore, the two processes are not dependable and must be disregarded in the repair of the dams. It is recommended that any dams having cracked zones have the entire zone repaired as recommended below.

Under the direction of the State Conservation Engineer, Ralph Arrington, the nature and extent of the apparent cracks in the Florence and Magma dams were investigated. This work was done in October 1977. Several cracks apparent on the surface of the dams were excavated and studied with somewhat erratic results. Some cracks were fairly well healed by washing in of materials and creation of natural filter faces. Some of the natural crack filling was dense and continuous. Other cracks were

erratically filled with loose to dense material, with some voids remaining. In at least one instance, an open 2" crack abruptly terminated in a very short distance. This crack could not be seen in a pit only 3 or 4 feet from its widest expression.

The results of this study certainly raise serious questions about the reality and predictability of natural self-healing processes in earth cracks.

In January 1978, county crews excavated pits to study cracks in the Buckeye No. 1 dam. At this time, they used a small trenching machine to explore the condition of the White Tanks No. 4 dam. Several open cracks were discovered in both dams. Open cracks were found and traced to depths of 11+ feet. At White Tanks No. 4, several cracks were traced that were well filled with dense material. Such fillings may have resulted from the dragging of the surface that was regularly done for many years. However, open cracks were traced that certainly compromise the safety of the dam.

In April 1978, additional excavations were made under direction of the study team at Buckeye No. 1, White Tank No. 3, Rittenhouse, and Vineyard Road dams. At Buckeye No. 1, pits were excavated near the upstream and downstream toes in the areas of severest embankment cracking. No cracks were found in the foundation. The pits verified cemented caliche

at shallow depths except near Palo Verde Road, where no cemented material was found to a depth of 10+ feet.

At White Tanks No. 3, pits were excavated in the embankment in two areas of suspected cracking. No cracks were located.

At Vineyard Road,pits were excavated in the dam to try to locate and observe cracks that were repaired in 1970. Two well filled cracks were located. It could not be determined whether these were a result of activities to fill cracks in 1970, or a result of natural filling. At Rittenhouse, several pits were excavated in the south part of the dam that is covered with a gravel facing. The gravel facing is about 8' thick. In all cases the lower part of the gravel was moist. The earth core was moist, though probably slightly drier than optimum, and looked very good. This verifies the effectiveness of a gravel surfacing to maintain moisture in an embankment even under hot, arid conditions. What is unknown, is the minimum effective thickness of gravel facing needed to break up capillarity and insulate against the hot conditions.

Trenches were excavated at the upstream and downstream toes at Sta. 130+12, very near to the deepest crack found by the consultant in 1977. Two cracks were discovered in a layer about 2' deep in the downstream pit. These cracks did not go to the surface nor penetrate into underlying material deeper than 3½ to 4'. These cracks would be cut off by the core trench. The backhoe operator told us such cracks were very common in the area. He regularly encounters them in excavating trenches and foundations. No cracks were found in the upstream pit. A 4-foot-deep pit was excavated

across a crack in the top of the dam at this station. The crack was open about 1/2 to 3/4 inches wide in both sides and in the bottom of the pit. The pit was near the downstream shoulder of the dam. The crack in the downstream face and the pit bottom was cleaned out. A probe wire would penetrate about 3' plus toward the downstream face. Water was pumped into the pit and it drained rapidly. After several minutes, water emerged on the upstream face about 10.5 feet below the top of the dam. An attempt was made to plug the crack in the bottom and upstream side of the pit, to see if water would follow an open crack to the downstream face of the dam. Water was again pumped in. After a few minutes the plug failed and water again emerged on the upstream face of the dam, about 3 feet higher than the previous time. No evidence of water moving toward the downstream face could be determined.

A pit was excavated across a longitudinal crack zone near Stations 201+46 on the north wing of the dam. This crack was 3 or 4 inches wide near the surface and penetrated to 11'+. The crack zone appeared to be about 150-200 feet long. The crack was cleaned and water was pumped into the crack a few feet east from the pit. Water followed the crack into the pit and after several minutes of pumping did not erode deeper. Part of the water followed the crack away from the pit. Water was pumped into a crack a few feet west of the pit. No water flowed into the pit. No water surfaced anyplace after several minutes of pumping at a rate estimated to exceed 25 gpm.

A feature resembling a subsidence fissure was seen in the reservoir of Magma Dam. The feature was a shallow crack in one spot, but its principal feature was an alignment of small sinkholes 12 inches or less in diameter. The total length of string of sinkholes was about 200 feet. It is parallel to the dam and about 50 feet upstream. The feature has the appearance of a subsidence crack. Another similar feature was reported by county flood control inspectors on Vineyard Road on December 8, 1977. We looked for it and couldn't find it, so the sinkholes may have been covered up with sediment by runoff from the 1978 storms. If this happened, it is unlikely the Vineyard feature was a subsidence fissure.

VII. Causes of Cracking

Analysis of observations made and data collected indicates the majority of the transverse cracking is a result of tension zones because of drying of embankment materials. No direct evidence of dessication cracking of high-shrink-potential soils was observed. At the worst, some of the soils in the embankment might have moderate shrinkage potential. Most of the soils have low shrinkage potential. The mode of cracking suggests that relatively minor volume changes occur as the material slowly dries, the dams untimately become essentially large adobe bricks. During the baking-drying process, cracks form when shrinkage stresses exceed the tensile strength of the soil. These cracks are then aggravated by volume changes due to temperature changes. The evidence collected and studied certainly supports the above mode of cracking, particularly for the transverse cracks in the White Tanks No. 4, Rittenhouse, Vineyard Road, and Magma dams. It is the opinion of the Study Team that most of the trans-

verse cracks occur because the tensile strength of the soil is exceeded by the capillary stresses of drying.

Certainly, the movement associated with subsidence as a result of groundwater removal may well have aggravated the cracking in some areas. No evidence has been collected to indicate that subsidence cracks occur in any of the dams' foundations.

Equally certain is the fact that shallow foundation compression can cause cracking by differential settlement. This potential cause has not been verified for any transverse cracks. This mode of cracking is quite likely the cause of many of the longitudinal cracks observed.

The Team recognizes that tremors or shocks from earthquakes would likely contribute to the cracking of these dried, brittle embankments; no evidence to verify this as a primary cause has been documented.

The Team's studies have not verified that any of the cracks are a direct result of different materials being placed adjacently, or because of different degrees of compaction or moisture in the fills. It is believed, however, that such conditions may well have added to the magnitude of the problem. The Team's studies pretty much verify that the magnitude of the cracking is greater where materials have been placed at moisture contents greater than optimum. !!

II. Summary of Findings

A. The principal cause of the transverse cracking is tension release because of shrinkage as the embankments dry from placement moisture content

in the severely hot, arid climatic conditions in the area.

B. Secondary causes of cracking are:

1. Tension zones resulting from differential settlement because of shallow foundation compression. This is the primary cause of the longitudinal cracks investigated.

2. Tension zones resulting from stress differences caused by regional subsidence associated with groundwater withdrawal.

3. Tension zones caused by stress differences resulting from variations in type of material, degree of compaction or moisture content in fill materials as placed.

4. Stresses induced by tremors and earthquakes.

C. As a result of recent storms, Rittenhouse and Magma had up to 11.5 feet of water in their flood pools. The foundationsdidn't leak, so it is believed this has verified that cracking does not completely traverse the lower portions of these embankments or disrupt their foundations.

D. Cracking is sufficiently severe in the upper zones of essentially all the embankments studied to require repairs.

E. Studies have not located any cracks penetrating through the foundation. No cracks have been identified in any of the dam foundations that are clearly associated with the embankment cracking.

F. The studies made have verified that natural self-healing processes cannot be depended upon, unless a filtered discharge face is present.

G. The safety of all the dams studied can be assured with properly applied repairs.

H. Gravel (shells) or thick facings on embankments effectively control cracking caused by drying in this hot, arid area.

I. Although the design and construction of the dams was commensurate with the state of the art at the time, methods of analysis, investigation, and construction procedures used by the industry in the past have been proven to be inadequate to assure safe dams with reasonable maintenance requirements.

Consequently, a change in the philosophy of earth dam design and construction is necessary to assure safe and proper functioning of earth embankments to be constructed in the future in this area.

J. Significant regional subsidence has occurred at the east county dams (See plate No. 1).

IX. Monumenting and Monitoring Future Structures

In a subsiding basin continued monitoring of all earth embankment structures is necessary to insure long-term safe operation. It is essential to install a system of measuring points so that movements of each structure relative to its elements as well as absolute movements with respect to a fixed datum can be determined and evaluated. The measuring point system should be spaced and referenced to provide sufficient detail to determine regional as well as highly localized movements. Generally, of principal concern are vertical movements; however, longitudinal shortening or lengthening along the centerline of the dam, as well as movements at the embankment toes with respect to the centerline are also needed.

Significant examining of the structure should be done at regular intervals and after significant storm events or other natural happenings that indicate

the need, i.e., newly developed earth fissures in the general area, seismic disturbances, etc. Overall conditions, any apparent movements, cracking, erosion, etc., should be recorded and measuring points established as necessary to monitor further action. A well planned and executed photo documentation of events and observations would be very valuable.

While the 500 feet apart monuments established on several of the dams are producing good results indicating the magnitude of general subsidence, they are inadequate to permit evaluation of differential movements that may occur in short distances.

It is recommended that settlement and ℄ of dam horizontal monitoring monuments be installed at intervals of 100 feet along the top of all newly constructed embankments. Also, measuring points to establish cross-section movements should be established at each shoulder of the dam and each toe at approximate 1,000-foot intervals.

These points should be measured at least annually until pattern of movement or lack of movement has been established. The measuring period can then be extended commensurate with conditions as they develop.

X. Recommendations for Repair

A. Possible Methods of Repair

Several methods of repair have been considered by the Study Team; several have been suggested by other parties. All methods have been considered, studied and discussed in detail by the Team.

The alternative methods of repair are:

1. A graded sand and gravel filter installed in a trench parallel to the centerline.

2. A narrow reworked compacted earth core installed parallel to the centerline.

3. A narrow soil cement core parallel to the centerline.

4. A program of periodic repair by water cleaning and mud grouting all cracks.

5. A granular filter in a filter cloth envelope installed in the lower portion of a narrow trench parallel to the centerline. The upper portion of the trench backfilled with excavated material compacted at a moisture content dry of optimum.

6. A filter cloth filter installed along the upstream face of a narrow trench parallel to the centerline. The trench to be backfilled with excavated material compacted to a moisture content dry of optimum.

7. Lower the emergency spillways and decrease detention capacity to an elevation at or below that of the average maximum depth of cracking.

8. Lower the spillways as in No. 7 above and construct floodgates in the spillways. Should leakage or piping start,the floodgates could be opened to increase the rate of drawdown and decrease the extent of damage to the dam.

9. Segment the detention storage within the reservoir by installing dikes perpendicular to the dams to limit the volume released by failure of a cracked section.

10. Install a graded sand and gravel filter on the existing downstream face of the dams and cover with additional embankment section from material excavated for the Central Arizona Project (CAP) canal. This would be a method limited to structures adjacent to the CAP canal alignment.

B. Discussion of Methods of Repair

1. General. Since subsequent investigations have revealed cracking in areas not previously located, a detailed inspection will be required to identify all areas needing treatment. On dams with known cracking problems, all reaches not already identified as having cracks should be investigated. Investigation by means of flooding a 6-inch-wide by 2-foot-deep, "Ditch Witch," trench has proven to be a good method to locate areas of cracking. Backhoe pits are then required to investigate and determine the depth of cracking.

On dams with no known or visual evidence of cracking, a random selection of areas should be investigated by the Ditch Witch method to check for cracks.

2. Method No. 1. Sand and Gravel filter.

The committee recommends repair by this method, as discussed and also recommended in our interim report of July 1977 (see interim report). The sand and gravel filter should be installed to a depth of 12+ feet, adjusted to deeper depths where inspection indicates the existence of cracks deeper than 9 feet. Careful inspection during repair will be required to determine the full depth of cracking.

Initial investigations indicated many cracks were partially filled with loose material and some were partially filled with dense material. Later investigations have shown many areas where the loose materials are actually packed into the crack during the excavation process and was only surficial filling adjacent to the pit walls. Some locations were found where the excavation process packed material into the crack so tightly that all evidence of the crack was obliterated. In such instances, careful inspection and probing is required to continue tracing the crack.

Probing with a thin wire cannot determine the total extent of cracking. Although probing proves the existence of an open crack, resistance to probing can be caused by irregularities in crack alignment. Cracks thinner than the probe wire cannot be successfully probed.

A two-step inspection process is recommended to verify a trench depth 3 feet deeper than any existing cracks. The first step is an in-trench inspection and probing at selected locations of extensive cracking. In-trench inspection and probing with an ice pick or similar tool and a probe wire to determine the maximum depth of the larger and generally deeper cracks. Shoring or portable shielding will be required to protect personnel during in-trench inspections. The second step should be washing (hosing) down the trench sidewalls to identify all cracks. Any crack appearing to be deeper than those found by the in-trench probing should be further inspected.

Any locations where the trench does not exceed the maximum crack depth in that area by 3 feet will require additional trench excavation to deepen the trench. The trench bottom should be graded to drain to an outlet.

This method will control seepage quantities by flow resistance so that water quantities will not create a piping problem in cracks downstream from the filter. It will also provide limited protection to piping of undetected cracks that may not be intercepted by the filter.

A graded filter of concrete aggregate will have a satisfactory gradation and is readily available. A mixture of 45% fine aggregate and 55% size (1½" minus) in accordance with ASTM-C33 appears to be adequate for most of the needed repairs.

3. Method No. 2. A narrow reworked compact earth core.
This method was described in the interim report. It is not considered a viable alternative because of the rapid development of drying cracks.

4. Method No. 3. A narrow soil cement core.
This method was also described in the interim report. It is not recommended as a viable alternative because of its rigid brittle nature and associated problems noted in the interim report.

5. Method No. 4. A continuing program of cleaning and mud grouting cracks. This is not considered a viable solution for the following reasons: First, it provides no protection against failure through newly developed cracks; second, to be successful, every individual crack needs to be located, cleaned, and grouted - logistically impossible; third, unconfined cracks cannot be completely filled; fourth, mud grout will shrink and recrack as it dries. A variation of this method where mud grouting should be done along with installing a vertical filter was discussed. The same basic uncertainties are common to this possibility.

6. Methods 5 and 6. Using cloth filter.

These alternatives were identified by ETL (consultant engineer) in the crack evaluation report for FCDMC. The committee cannot recommend these alternatives because of the nearly total reliance on an unproven material (filter cloth). We question any filter cloth's ability to resist tearing if subjected to crack development of the magnitudes encountered in the dams investigated. If the filter cloth did not tear, the stretching across a crack could significantly alter its filtering ability.

Although Alternate No. 5, the cloth enveloped granular filter, could be designed to function satisfactorily should the cloth tear, it would have no advantage over Alternate No. 1, and would be more difficult and expensive to install. The filter cloth would partially prevent filter material from filling voids that may develop under the filter.

7. Methods 7 and 8. Lowering emergency spillways and installing floodgates. These are also alternatives identified by ETL in their report to FCDMC. The committee does not consider these as viable repair alternatives because they change the scope of the original project.

8. Method No. 9. Segmenting the detention area with dikes.

This method was suggested by ETL and others as a means of decreasing the extent of damages caused by a failure. Although it is not a repair measure, it does have merit when considered in conjunction with other repair methods.

The detention basin could be divided into several basins by constructing dikes (embankments) perpendicular to the main dam. The smaller basins would need to be interconnected by conduits through the dividing dikes.

9. Method No. 10. Combining repair with construction of the CAP. This is not considered a viable alternative because:

a. It would delay needed emergency repairs for an unknown period.

b. It has not been determined at this time when the CAP will be completed.

C. Conclusions and Recommendations for Repair

The Team has concluded the cracking problem is of greater magnitude than originally recognized. Investigations subsequent to our interim report of July 1977, have revealed areas of cracking not previously identified in dams, with little or no surface evidence of cracking. Cracks have been found to extend to greater depths than previously encountered. Any one of these deep cracks could endander the structure if it extends through or nearly through the embankment.

The Team has concluded the cracks pose a real hazard to the integrity of the structures. We recommend that steps be taken to identify all dams with cracking problems, to identify the extent of the cracking in each dam, to repair the cracked dams and to incorporate design methods to eliminate or control drying cracks in future structures.

Priority of repair should be based on a combination of factors. These include the hazard and damage potential from failure, the severity and depth of cracking and a hydrologic evaluation of the probability of significant runoff producing events. All structures distressed by cracking should be repaired expeditiously. Structures should be repaired by installing a sand and gravel filter in a trench parallel to the ℄ (Method No. 1).

XI. Design Concepts to Control Cracking

A. Alternate Methods

Several alternatives are available to design for control of cracking problems. Some are intended to prevent cracking, others to control the effects of cracking. These alternatives are:

1. A granular filter zone within the embankment. This design feature is similar to the recommended method of treatment proposed for the existing cracked structure. In new construction, the filter zone could be either sloped or vertical. It would also extend down to or into the embankment foundation.

1a. Placing and compacting the embankment dry of optimum combined with a granular filter zone. The compaction of fill materials dry of optimum is supplemental to Alternative No. 1.

2. Granular embankment shells. A gravel shell can be used to prevent cracking of the core zone of embankments provided it has adequate thickness.

3. Install a sand wick and drip irrigation system in the top of the dam. This alternative would prevent crack development by replacing moisture lost from the fill.

4. Install a vapor barrier over and around a core section of the embankment. This is a new concept and is intended to prevent moisture loss by using a vapor barrier of plastic or rubber sheeting or other similar material.

B. Discussion of Alternatives

1. Granular filter zone within the embankment.

This method will not prevent the formation of drying cracks within the embankment. A filter will control the problems associated with cracking and prevent breaching of the embankment by internal erosion and piping. It provides a filter face to stop migration of fines and promotes self healing of the crack. A filter zone will also provide protection to the embankment from cracking caused by differential movements. The single-grained granular material will readily readjust without rupturing.

In dry dams, the filter zone can be relatively thin since hydraulic conductivity is not of paramount importance. The rapid development of a filter face within a crack will quickly restrict water movement into the filter zone. For downstream toe stability, the embankment should be designed to be structurally stable with the filter zone fully saturated.

This will require the filter zone to be placed near the center of the embankment. For upstream toe stability and full drawdown, the filter zone can be considered as drained.

1a. Compacting the embankment dry of optimum combined with a granular filter zone. This alternative is a modification of Alternative No. 1. By compacting the embankment dry of optimum, shrinkage from drying will be decreased. Cracking will still occur, but the width of each crack should be smaller than for the same material compacted at or above

optimum moisture content. The embankment will be more brittle and susceptible to cracking from differential movements. However, the filter zone will adequately control problems associated with cracking. At the filter face, the narrower cracks will heal faster than wider cracks.

2. Granular embankment shells.

Where large quantities of granular materials are readily available, drying cracking can be prevented by gravel shells. Adequate thickness is required for insulation as well as breaking capillary rise. The thickness of gravel shell that prevented drying cracks is 8 feet. It is believed that a thickness of 5 feet may be adequate. However, verification is needed.

A gravel shell helps prevent surface rilling. However, vegetation on the embankment will need to be controlled.

3. Sand wick and irrigation system.

This method relies on supplemental moisture, supplied by a drip irrigation system, to replace soil moisture lost by drying. It would consist of a shallow 2-foot-deep trapezoidal sand wick with drip irrigation installed in the top of the dam. The sand would be a small reservoir and would provide uniform distribution of water. The object is to keep the core of the embankment at or above field capacity and prevent the buildup of high capillary stresses. Instrumentation could be used to determine the need for the timing of irrigation.

This alternative requires continued operation and maintenance. It will have a relatively high first cost and annual operating cost. However, it

may be viable alternative where granular filter materials are limited and expensive. Some vegetation control would be required.

4. Install a vapor barrier over and around a core section of the embankment. This is a new concept in embankment design to prevent crack formation with drying. It is intended to prevent moisture loss during hot periods. The Team believes it holds promise as a possible design solution in specific instances. This alternative would require stage construction. The first stage would be to construct and trim a narrow core section with steep side slopes. Something like a 5-foot-top with 1/2:1 side slopes. The core would then be covered with a continuous vapor barrier of 12 mill, or thicker plastic, rubber sheeting, or other long-life watertight material. Remaining sections of the embankment would then be constructed around the core. Care would be required to prevent puncturing the vapor barrier.

Each of the outer sections of the embankment would be designed as independently stable structures.

Unless properly installed, the vapor barrier could be subject to tearing as the outer portions of the embankment crack. A thin sand section next to the barrier would provide protection from tearing.

Poorly graded sand unsuitable for use in a filter would be adequate to protect the vapor barrier.

Unless the vapor barrier is of a tough durable material, it could be punctured by plant roots. Some vegetation control may be required.

Although the vapor barrier will also function as a diaphram in the embankment, that is not its principal purpose.

C. Design Conclusions and Recommendations

Deep cracking in dry dams in hot, arid areas presents a greater problem than previously considered. Dust mulch covers, which break the capillary rise do not effectively prevent drying cracks. It is also our opinion that thin granular blankets are also inadequate. To be effective, the gravel blanket should be thick enough to be called a shell, or gravel zone. To be effective, the shell must be thick enough to provide insulation from heat buildup within the embankment and to break up the capillary rise.

The design of future dams, in hot, arid areas where past experience has indicated cracking problems, should include features to effectively eliminate or control cracking problems.

The Arizona Engineering staff and Design Unit have already adopted improved design procedure in their current design. They are providing filter drains as an integral part of structure designs.

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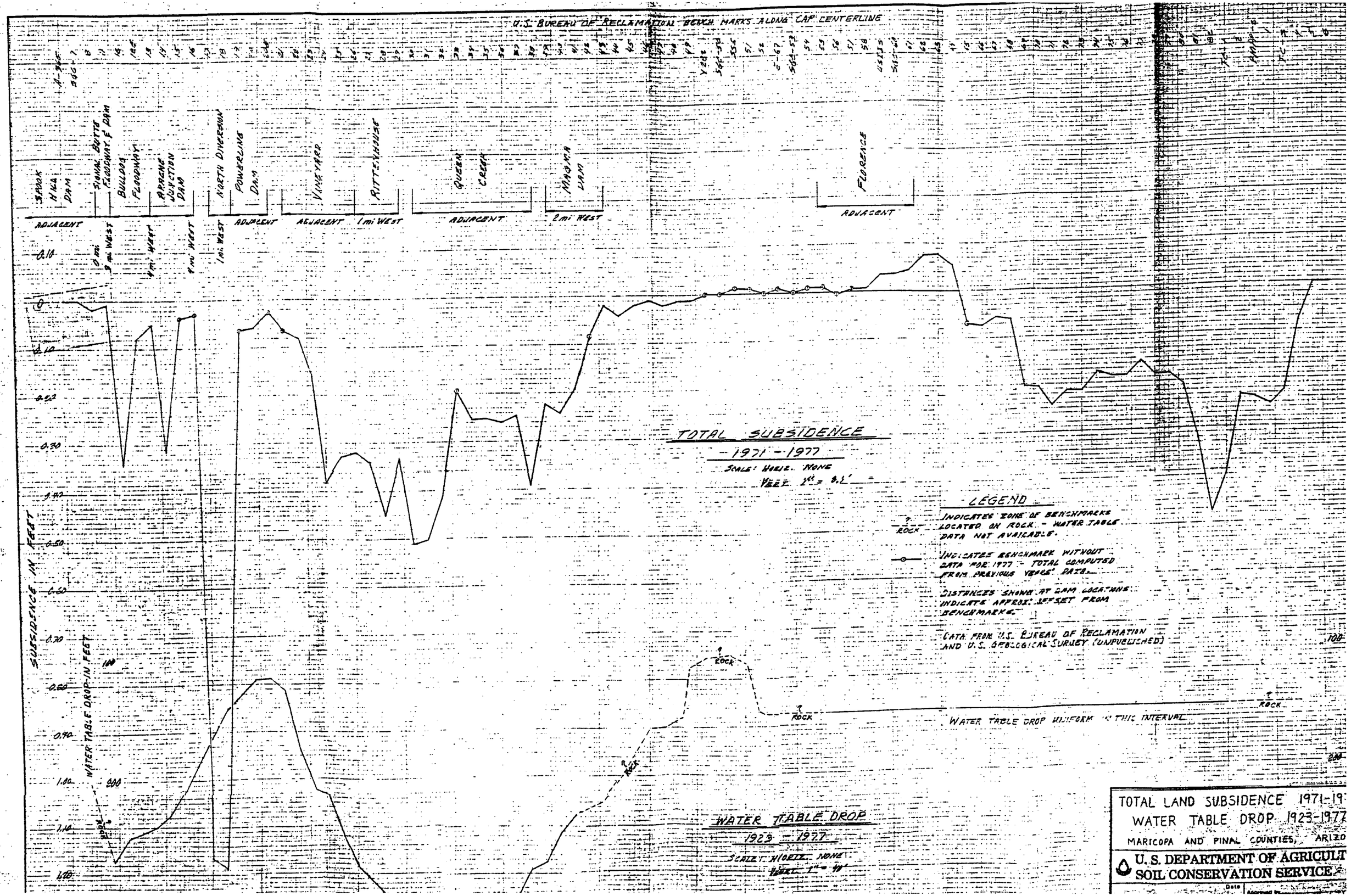
Ray Smith

Ed Stearns


U.S. BUREAU OF RECLAMATION BENCH MARKS ALONG CAP CENTERLINE
SPOOK HILL DAM
SIONN. BUTTE FLOODWAY DAM
BULLDOG FLOODWAY
APACHE JUNCTION DAM
NORTH DIVERSION
POWERLINE DAM
VINEYARD
RITTENHOUSE
QUEEN CREEK
MAGMA DAM
FLORENCE
ADJACENT
0 mi. WEST
3 mi. WEST
4 mi. WEST
6 mi. WEST
1 mi. WEST
ADJACENT
ADJACENT
1 mi WEST
ADJACENT
2 mi WEST
ADJACENT
SUBSIDENCE IN FEET
WATER TABLE DROP-IN FEET
TOTAL SUBSIDENCE
1971 - 1977
SCALE: HORIZ. NONE
VERT. 1" = 0.1'
LEGEND
ROCK
INDICATES ZONE OF BENCHMARKS LOCATED ON ROCK - WATER TABLE DATA NOT AVAILABLE.
INDICATES BENCHMARK WITHOUT DATA FOR 1977 - TOTAL COMPUTED FROM PREVIOUS YEARS' DATA.
DISTANCES SHOWN AT DAM LOCATIONS INDICATE APPROX. OFFSET FROM BENCHMARKS.
DATA FROM U.S. BUREAU OF RECLAMATION AND U.S. GEOLOGICAL SURVEY (UNPUBLISHED)
WATER TABLE DROP UNIFORM IN THIS INTERVAL
WATER TABLE DROP
1923 - 1977
SCALE: HORIZ. NONE
VERT. 1" = 10'
TOTAL LAND SUBSIDENCE 1971-19
WATER TABLE DROP 1923-1977
MARICOPA AND PINAL COUNTIES, ARIZO
U.S. DEPARTMENT OF AGRICULT
SOIL CONSERVATION SERVICE