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INVESTIGATION OF CRACKED FLOODWATER RETARDING EARTH FILL DAMS

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by

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INTRODUCTION

Earth fill dams have been constructed in the vicinity of Phoenix Arizona since the early 1950's under federal watershed programs. These structures are classified as dry dams because they retain water only for short periods following rainfall. They are also designated as Flood Retarding Structures (FRS).

Cracking had been reported a short time following construction. Inspection of these dams by the Soil Conservation Service (SCS) in 1977 revealed the existence of extensive transverse and longitudinal cracks which could pose a hazard to the integrity of the structures (SCS, 1978). Subsequent to the SCS studies, Fugro investigated five of the most severely affected structures to document the locations and characterize the depth and extent of cracking that may affect stability of the embankments. Services were also contracted for construction inspection of an embankment drain in a previously investigated FRS to provide protection against possible failure caused by piping through the structure.

The primary purpose of the crack location investigation was to provide sufficient data for engineering design of remedial measures, not to specifically determined the cause(s) of cracking. The data obtained should assist, however, in evaluating and identifying cracking processes. Degree of cracking maps were developed to assist in prioritization of corrective action at each of the five structures. Several possible mechanisms for cracking include desiccation and differential settlement induced by hydrocompaction, subsidence and/or consolidation.

The crack location investigation encompassed a total of 109,349 linear feet of structures in Maricopa and Pinal Counties, Arizona (figure 1). This

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included Magma FRS (28,750 feet); Vineyard FRS (28,400 feet); Buckeye FRS (37,400 feet); White Tanks No. 3 FRS (7,920 feet); and White Tanks No. 4 FRS (6,389 feet). Remedial actions were applied to Rittenhouse FRS which required 13,500 feet of trench excavation and backfilling with engineered drain fill.

The work performed during the crack location investigations included:

- Review and analysis of studies previously conducted by the SCS and other related maps and reports concerning the site area.
- Detailed mapping of features along the crest of the 109,349 feet of structures.
- Excavation and flooding of 402 shallow trenches totalling 26,635 linear feet.
- Excavation and detailed logging of 71 backhoe trenches.
- Collection and classification of soil samples obtained from exploratory trenches.
- Photographic documentation of field activities and selected features identified during the detailed mapping and subsurface exploration.
- Detailed logging of the centerline remedial drain trench excavated at the Rittenhouse FRS.
- Analysis of the collected data to prepare appropriate plans, profiles, and a final report for each structure.

GEOLOGIC SETTING

The study area is situated in the northcentral part of the Sonoran Desert subprovince of the Basin and Range Physiographic Province (figure 2).

Stratigraphically the generalized sequence includes (1) the basement complex consisting of Precambrian, Laramide and granite, gneiss, volcanic and minor sedimentary rock, and (2) Tertiary through Quaternary valley fill consisting of a volcano-sedimentary unit, a thick (10,000 $\pm$ ft.) essentially fine-grained deposit and thin heterogeneous unconsolidated alluvium.

Groundwater extraction induced subsidence and associated earth fissuring is occurring within and at the margins of the deep basin deposits.

CLIMATE

The area has essentially a dry climate with most precipitation resulting from summer thunderstorms or winter Pacific storms. Annual precipitation averages

from 7 to 10 inches whereas average evaporation rates range from 68 to 73 inches per year. The temperature range is also extreme with summer highs exceeding 100°F and winter highs averaging 50°F. Diurnal temperature changes exceeding 40° are not uncommon.

EMBANKMENT CHARACTERISTICS

All of the embankment structures investigated are similar in profile with 2:1 or 3:1 (horizontal to vertical) upstream slope inclinations, and 2:1 downstream slope (figure 3). As-built construction plans indicate over excavation of foundation soils was performed to varying depths depending on soil conditions. The structures vary in height from grade to about 43 feet. All are homogeneous earth fill dams with no internal drainage systems. Drainage from the structures is controlled primarily via vegetation gates of low discharge capacity. During periods of high volume runoff, discharge is provided by an emergency spillway. The structures are constructed on or downstream from the lower slopes of alluvial fans in nearly flat but rolling terrain.

CRACK LOCATION FIELD PROCEDURES

Detailed Surficial Mapping

The detailed mapping emphasized features occurring along and near the crest of the structure where they were not obscured by slopewash and vegetation. Cracks, pipes, anomalous depressions and animal burrows were described and mapped at a scale of one inch to 20 feet along the entire length of each structure (figure 4). Many features occurring on the slopes of the structures were also mapped. During the field mapping, flexible wire probes were used to ascertain the apparent depth and continuity of the features as well as shallow hand-dug pits.

Shallow Trenching and Flooding

Following completion and analysis of the detailed mapping, shallow trenches, one-half foot wide by two feet deep were excavated with a Ditch Witch-type trencher along the crest centerline in representative cracked and uncracked segments of the structure ranging from 25 feet to 100 feet in length (figure 5). A total of 26,635 linear feet or 24 % of the structure was trenched in this manner. These trenches were flooded to determine the relative extent of cracking by noting the volume of water required to fill the trenches. Records of trench dimensions, water used, time required to fill each trench segment,

and water loss (due to trench leakage) were used to calculate a rough index number, called the flooding ratio, to rank the apparent internal extent of cracking. Flooding ration (F.R.) is defined as

$$F.R = \frac{\text{volume of water required to fill trench}}{\text{volume of trench}}$$

The flooding ratio is a useful indicator of cracked areas because as the flooding ratio increases it signifies an increasing amount of leakage into cracked areas. Ratios between 1.0 and 1.2 indicate no water loss into the embankment.

A total of 402 trenches were tested in this manner. Of these, 195 had no detectable leakage and 81 had leakage so severe that the trenches could not be filled at the maximum pumping rate of about 240 gal/min. It would appear that the trenches intercepted a major conduit connected to a complex network of transverse and/or longitudinal cracks. Leakage from down slope conduit outlets induced by artificial flooding was observed in only a few of the flooded areas which would indicate that most of the water losses were internal.

Deep Trenching and Subsurface Investigation

Portions of each structure were excavated with a backhoe to allow for subsurface inspection of crack features (figure 6). Seventy-one backhoe trenches, 1.5 feet wide and ranging in depth from 3.3 to 17 feet were excavated. Detailed trench logs of each excavation were drawn at a scale of one inch equals two feet.

The embankment soil types of the structures range from clay to gravelly sand USCS nomenclature) and are commonly dry to moist. The dominant soil type encountered were silty clay and clayey sand. The cracks most commonly encountered in the trenches were of the transverse type because of the orientation of the trench and narrowness of the crest; however, longitudinal cracks and cracks oblique to the centerline of the structures were also trenched.

CHARACTER OF CRACKING

Cracking patterns observed in this study (similar to those described by Sherard, (1973)), include transverse - normal to the embankment axis, longitudinal - parallel to the axis, and oblique - intermediate to the transverse and longitudinal (figure 7). Cracks are well developed along and across the crest of the structures yet many may be found on both upstream and downstream slopes. There appears to be no preferred clustering or dominance of crack type.

Transverse, longitudinal, and oblique cracks are easily identified at the surface by the alignment of the vertical to near-vertical conduits or pipe-shaped circular features (figure 8). The conduits range in size from one to three inches in diameter and a few inches to two feet in depth. Conduits up to 12 inches in diameter were observed where localized erosion or collapse had occurred. These pipe-like features were also observed on the upstream and downstream slope as much as 20 feet below crest grade. The features appear to be identical in character to vertical erosion tunnels described by Sherard, 1977, that affected the Wister Dam in southeastern Oklahoma. It is suspected that the tunnels developed from rainfall or slope wash entering desiccation cracks. Where open cracks were observed, they were at least 1/16 inch to three inches wide. Incipient cracks less than 1/16 inch wide occur both transversely and logitudinally to the centerline. Surifical "healing" or infilling has occurred in some cracks. This sediment filling was much more loose and coarse-grained than the adjacent undisturbed fill of the structure.

The maximum depth of cracking ranged from 8.6 feet below the crest grade at the White Tanks No. 4 structure to 21.9 feet at White Tanks No. 3. Most were vertical or slightly inclined from vertical. The average opening of the cracks were about one-half inch and terminated at depth as a hairline crack (figure 9). Where the cracks were open, the crack face was usually irregular and rough but smooth portions were observed locally. Some cracks were characterized by sediment-filled intervals containing loose, poorly graded sand. These filled intervals, where they occurred, were discontinuous along the lengths of the cracks. Commonly, horizontal pipe-like structures were also located along the cracks. Their origin is unclear but they appear to represent conduits through which water escaped during induced flooding.

DEGREE OF CRACKING

A map depicting the apparent degree of cracking affecting each structure was developed from the field data (figure 10). The highest degree, moderate to severe, was defined where significant cracks or related features were indentified. Distances between features were less than 60 feet and the features were primarily open cracks, large conduits and clusters of small conduits. Crack or conduit outlets were identified from the induced flooding and the flooding ratio exceeded 1.3. The next degree was defined as low where some cracks were identified (primarily short incipient cracks and small conduits).

The distance between features was generally less than 100 linear feet or where a particular reach of the structure was bounded by moderate to severe areas. The flooding ratio was also less than 1.2. No cracking was defined where no cracks or related features were identified on a reach of the structure for at least 150 linear feet or 50 feet where the crest height was less than five feet. Also, the flooding ratio for the reach was less than 1.2.

REMEDIAL MEASURES

As a result of this investigation several remedial measures were suggested. These measures do not represent a permanent cure to the cracking problems but represent interim corrective action to minimize existing hazards. The use of these measures is dependent on problems that may be unique to the particular structure; upstream and downstream developments; design capacity; geologic, hydrologic and soil parameters; ease of construction and economics.

The proposed alternative remedial measures include:

1. Excavation of a centerline trench and backfill with an engineered drain fill aggregate.
2. Placement of an engineered earth fill buttress on the upstream slope.
3. Installation of a downstream toe drain and graded filter blanket.
4. Channelize runoff to reduce impoundment.
5. Modify retention capacity of structure.
6. Breach the structure to eliminate dam break hazard.
7. Raze and reconstruct structure using current state-of-the-arts designs.
8. Utilize combination of measures for the most effective mitigation of potential problems.

One of the remedial actions was applied to the Rittenhouse FRS (figure 1). The action involved the excavation of a centerline trench with outlets to the downstream toe. The main trench was approximately 13,000 linear feet in length. The nominal width of the trench was about 2.6 feet with depths ranging from about 13 feet to about 15.8 feet. A total of 40 outlet drain trenches were excavated at the locations specified on construction drawings and as required by the Resident Engineer. These drains were excavated to a

depth sufficient to maintain trench drainage. The drain fill was placed in 2 to 3 feet lifts. No water was used during placement and no compactive effort was applied. Trenches were excavated with a Parsons 250 bucket trencher and an American 35 backhoe. Equipment used in placing the fill consisted of a Link Belt LS 118 track-mounted crane with a bottom dump bucket and tremmie.

Continuous geologic inspection of the upstream face of the trench was performed during construction to provide assurances that all cracks were adequately intercepted by the drain trench. Cracking intensity was about 7 to 8 cracks per 100 linear feet of embankment. Ninety percent of the cracks observed were transverse to the centerline of the dam. The remaining 10% are longitudinal or oblique. These percentages are probably biased because of the orientation of the interceptor and outlet trenches. The deepest observed crack was about 16 feet below the top of embankment. The maximum width and probed length of the cracks was 0.4 feet and 2.8 feet, respectively. They were generally hairline and generally vertical or near-vertical. Crack surfaces were generally irregular but planar surfaces were observed locally. Loose infilling with coarser soil was common.

CONCLUSIONS

Cracking of earth fill embankment dams has been recognized and reported as affecting many structures, particularly after dam failures have occurred. Few detailed investigations have been performed on smaller dry dams because the potential hazards are not readily apparent. This false sense of security could be devastating. More work is required on small structures of this type to determine the severity of the problem and expand the data base whereby the cause(s) can be determined and existing designs modified to eliminate or minimize the problems.

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