Evaluation of Seepage from an Embankment Dam Retaining Fly Ash

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Abstract: Observations, data, and analyses used to investigate the cause of fly ash-laden seepage from the right abutment of an earthen dam are presented herein. The investigation shows that the sediment-laden seepage occurred through permeable/jointed bedrock in the right abutment that was exposed by a landslide prior to construction of the dam. When the level of the impounded fly ash reached the level of the prior landslide, the fly ash-laden seepage migrated through the jointed bedrock of the abutment and exited on the downstream right abutment. The joint bedrock was exposed to the fly ash reservoir because the landslide removed the clayey colluvium and/or residual soil overlying the jointed bedrock that formed a natural impervious barrier to seepage. This sediment-laden seepage initially was a great concern because of the potential for erosion and piping in earth dams. However, the rapid investigation into and subsequent monitoring of the seepage revealed that accumulation of fly ash and other coarser particles created a filter cake that reduced the seepage and eventually sealed the joints and fractures in the sandstone abutment. No fly ash-laden seepage has been observed on the downstream abutment since April 2004 after first appearing on February 16, 2004. This filter cake development and self-healing process averted additional seepage and illustrates the beneficial effects of fly ash-laden seepage in controlling reservoir leakage.

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CE Database subject headings: Dams, embankment; Fly ash; Filters; Drainage; Tailings; Seepage.

Introduction

Sediment-laden seepage and subsequent piping is one of the most common and catastrophic failure modes of an earthen dam (Sherard et al. 1963). The seminal example of the rapid and catastrophic consequences of uncontrolled piping is the failure of Teton Dam in 1976 (Independent Panel 1976). Teton Dam is a 93 m (305 ft) high central-core zoned earth fill dam located in Idaho. Teton Dam failed during the initial reservoir filling with the reservoir about 1 m (3 ft) below the spillway sill. In a similar manner to Teton Dam, Cardinal Fly Ash Dam 2 (FAD2) initially and historically showed clear downstream seepage as did Teton Dam early in the filling process. However on February 16, 2004, sediment-laden seepage was observed at the right downstream toe of Cardinal FAD2 by the Cardinal Power Plant personnel. This sediment-laden seepage did not lead to a catastrophic piping of Cardinal FAD2 as occurred at Teton Dam. The cause of the fly ash-laden seepage, the techniques for assessing and monitoring the seepage, and the remedial measures are discussed herein. This is an important case history because of the instrumentation monitorin, and investigation that was quickly conducted to assess the situation and the beneficial effects of the fly ash-laden seepage in remediating the reservoir seepage by creating a filter cake that eventually stopped the leakage.

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Description of Fly Ash Management Complex

Fly ash is a combustion by-product produced from coal-fired power plants that has small enough particle size which rises instead of falling after combustion. Thus, it is referred to as fly ash. Bottom ash is also a coal combustion by-product with large enough particle size that falls to the bottom of the combustion chamber.

The coal-fired power plant that is the focus of this investigation is located near Brilliant, Ohio. The fly ash is sluiced from the power units to an impoundment Fly Ash Dam No. 2 (FAD2) that was originally constructed in 1986–1987 and raised in 1997–1998. When the fly ash reservoir is filled it will cover approximately 560 km^2 (139 acres) at elevation 293 m (960 ft), the maximum operating pool elevation, or approximately 18% of the eastern branch of Blockhouse Run. There are no other dams located downstream of FAD2 that could be operated during an emergency to store flood flow and/or fly ash if it was released from FAD2. In addition, there are residences and commercial and industrial establishments located below FAD2 in the town of Brilliant, OH that would be adversely affected by the failure of FAD2 and the subsequent flooding. Fig. 1 is an aerial photograph that shows FAD2 upslope of the power plant which is located at the bottom of Blockhouse Run by an arrow. FAD2 is located at an elevation that is about 82 m (270 ft) above the town of Brilliant, OH and the power generation complex. Fig. 1 also shows the location of the fly ash seepage on the right abutment downstream of FAD2.

Fly Ash Dam No. 1 (FAD1) is located upstream of FAD2 (see

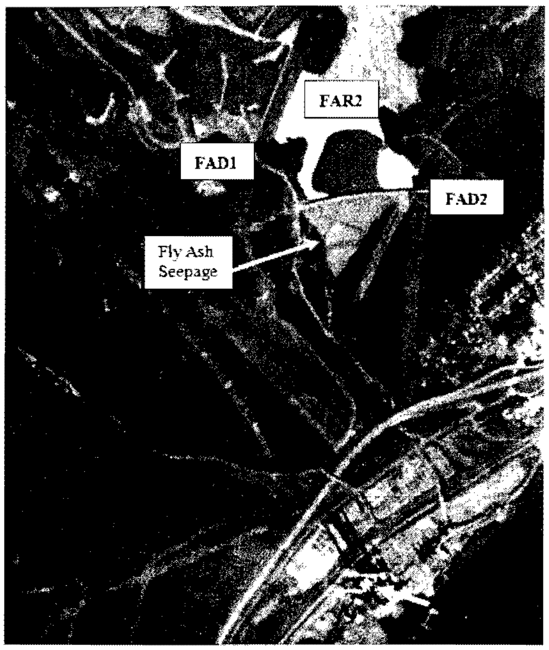

Fig. 1. Aerial view showing power plant at bottom of valley (see arrow), FAD1, and FAD2

Fig. 1) and is located in the west branch of Blockhouse Run but no longer impounds water because the storage capacity has been fully used. Thus, FAD1 probably would not have been affected by a failure of FAD2.

FAD2 consists of a 67 m (220 ft) high arched embankment with a roller-compacted concrete (RCC) upstream face and emergency spillway channel. The spillway channel is located in a cut through rock of the left abutment. The dam has a crest elevation of 296 m (970 ft), a crest width of 10 m (30 ft), and is 427 m (1,400 ft) long. The RCC upstream face has a $0.83H:1V$ slope and is constructed in 0.3 m (1 ft) stair-stepped lifts above elevation 279 m $\pm$ 1.5 m (915 $\pm$ 5 ft). The upstream slope below the RCC slope is $2.5H:1V$ and consists of soil. A central clay core and 3 m (10 ft) of bottom ash (sandlike) material chimney drain provides seepage control through the dam. The downstream slope of FAD2 is $2.5H:1V$ and is protected from surface erosion with a vegetative cover. A general cross section of FAD2 showing the final dam raising is presented in Fig. 2.

The reservoir is used for the storage of fly ash that is discharged in slurry form at the back of the reservoir. The fly ash settles to the bottom of the reservoir as the water flows toward FAD2 where the excess effluent is discharged through a drop inlet structure. Thus, the finest gradation of fly ash is deposited in the vicinity of FAD2. Flow restrictors are placed in the drop inlet structure as necessary to maintain settling action and to control the discharge. The dam is normally unattended and the discharge structure has no remote control system to regulate the flow. The nature of the pond, the design of the dam, and the capacity of the outlet works provide sufficient freeboard to mitigate concerns of overtopping during a rainfall event. Plant personnel routinely monitor FAD2 and conduct a detailed inspection of FAD2 to comply with Ohio Revised Code Section 1521.062 and the owner performs instrumentation data review annually. In addition, the Ohio Department of Natural Resources Dam Safety Inspection Program visits the dam every 5 years. The Ohio Environmental Protection Agency also monitors water quality issues for the FAD2 and the fly ash reservoir. The owner's personnel collects piezometer data and conducts movement surveys every 6 months and visually monitors the performance of FAD2 and searches for any anomalous condition on a weekly basis. For dams that have been successfully operating for a period of time, the key to inspection and maintenance is to observe any change in the condition of a dam.

Description of Sediment-Laden Seepage

During a routine weekly inspection, the plant personnel observed fly ash sediment-laden seepage through the right downstream abutment of FAD2 that was not present in prior inspections. Five major fly ash sediment releases occurred in an irregular episodic manner from the right abutment of FAD2 over the course of several months from February to April 2004. Historical observation of seepage over the past 19 years from both abutments was clear. Visual examination of the fly ash sediment-laden seepage in each of the five events consists of light gray sediment exiting from fractures and bedding plane joints. No fly ash sediment seepage was observed at any time from the left abutment. Several aspects of the seepage, the subsequent investigation, and the causation discussed subsequently make this case noteworthy.

Fig. 3 shows a partial view of the downstream slope of FAD2 near the right abutment. At the right of the photo is Drain Pipe

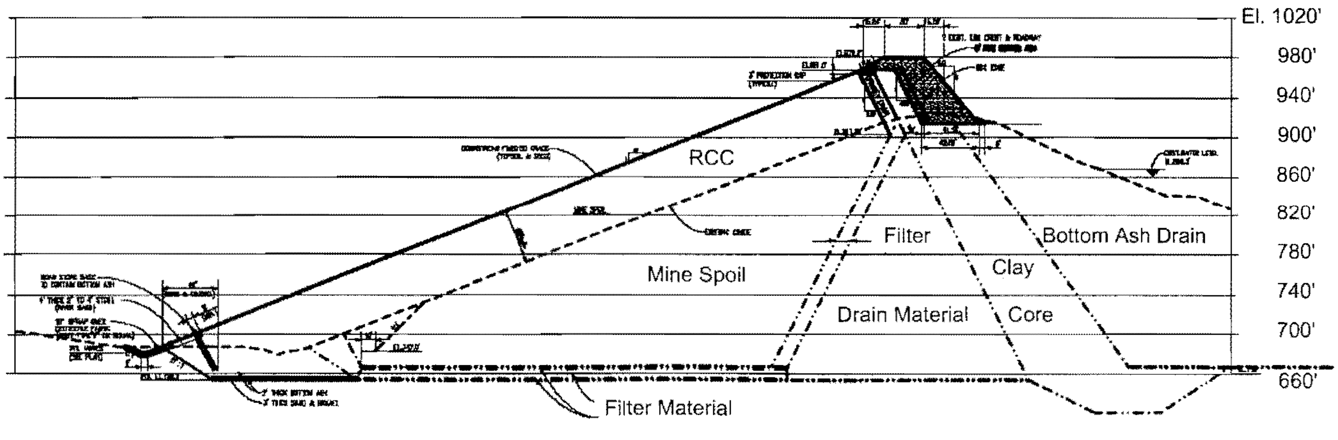

Fig. 2. Cross section of FAD2

Fig. 3. Photograph of right groin ditch formed by the right abutment and downstream slope of the dam and large drain pipe in right abutment that discharges into groin ditch

Fig. 5. Photograph of anomalous seepage emanating from sandstone outcrop on right downstream abutment

No. 7, which consists of a 0.15 m (0.5 ft) diameter corrugated high-density polyethylene (HDPE) pipe. This drain pipe discharged clear water on February 16, 2004 and continued to discharge clear water during the four subsequent fly ash sediment-laden discharge events. This drainage pipe drains the upper portion of the jointed rock that forms the right abutment of FAD2. Also shown in Fig. 3 is the right downstream groin ditch which is the area at the interface between the right abutment and the downstream slope of the dam. In other words, the groin is located at the connection between the right abutment and the downstream slope of the dam. The contact between the right abutment and the downstream slope of the dam forms a ditch. The wooded area near the bottom of Fig. 3 is the location of the sandstone outcrop that is shown in more detail in Fig. 4 as well another HDPE drain pipe that drains the middle portion of the jointed rock formation of the right abutment of FAD2.

Fig. 4 shows the sandstone outcrop where the sediment-laden seepage was observed on February 16, 2004. A second light gray discharge occurred on February 19, 2004 from the right downstream abutment. Just upslope of the sandstone outcrop that is indicated by a dashed arrow is another HDPE drainage pipe. Fig. 5 shows the right groin ditch with light gray sediment-laden seepage exiting the abutment near the sandstone outcrop and flowing down into the groin ditch. The fly ash seepage then continued down the downstream slope of FAD2 in the groin ditch to the toe of the dam.

Fig. 6 shows three HDPE drainage pipes located at the toe of the downstream slope of FAD2. From left to right in the photograph are Drain Pipe Nos. 2 (left), 3 (center low), and 4 (right). Drain Pipe No. 2, which collects abutment seepage that enters the right side of the drainage blanket immediately below the right groin ditch, is shown discharging a similar light gray liquid as observed exiting the sandstone outcrop on the right abutment. Drain Pipe No. 3 collects seepage from the drainage blanket immediately downstream of the clay core and Drain Pipe No. 4 collects seepage from a central trench constructed below the slag buttress.

Drain Pipe Nos. 3 and 4 did not discharge any light gray sediment. Drain Pipe No. 3 had to be carefully inspected and monitored to ensure that it was not discharging the observed light

Fig. 4. Photograph of drainage pipe near midpoint of downstream slope in right abutment (see dashed arrow) and sandstone outcrop downslope of pipe where spring flow occurs (see solid arrow)

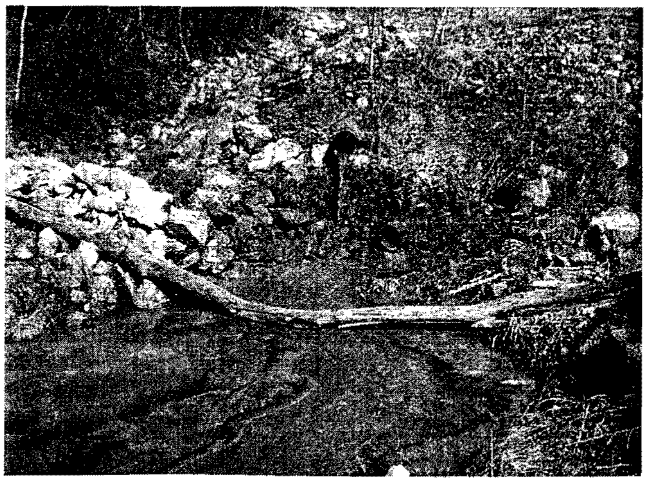

Fig. 6. Photograph of three drains at bottom of right downstream abutment with anomalous seepage

Fig. 7. Photograph of fly ash sediment in downstream creek from five major fly ash discharges

gray sediment because the discharge from Drain Pipe No. 2 sprayed liquid on the drain pipe and the area surrounding the drain pipe, as shown in Fig. 6. This gave the impression that Drain Pipe No. 3 had discharged fly ash-laden sediment. Drain Pipe No. 4, which is normally without a flow, did not show any discharge during the five anomalous seepage events. Drain Pipe No. 4 has experienced intermittent flow in the past and thus is assumed not to be clogged or broken.

Fig. 7 shows the stream channel downstream of FAD2 with an accumulation of fly ash. Approximately 703,000 kg (775 t) of fly ash sediment had to be excavated from the stream channel as a result of the five fly ash discharges. Fig. 8 shows a partial view of the fly ash reservoir impounded by FAD2 and the slope immediately upstream of the right abutment which is adjacent to the RCC crest of FAD2. At the time of the photo, February 2004, the reservoir pool was frozen.

Potential Seepage Mechanisms

The two seepage mechanisms initially investigated in response to the appearance of the light gray sediment-laden seepage on the right downstream abutment are: (1) piping of the clay core and/or shell fill material that could lead to failure of the dam as occurred at Teton Dam and (2) clogging of the chimney and drainage blankets that could lead to instability of FAD2 due to a buildup of pore water pressures. To investigate the seepage mechanism and to predict the future performance of FAD2, several independent methods of investigation were immediately undertaken. The frequency of monitoring program for FAD2 was increased over a 3-month period and was supplemented by additional field and laboratory investigations. The monitoring program for FAD2 consists of pneumatic and standpipe piezometers, slope inclinometers, survey settlement monuments, and seepage measurements at various points. The piezometers, slope inclinometers, and survey monuments did not show any significant change before, during, or after the fly ash seepage was observed so this data are not included in this paper. This lack of change in the data helped focus the investigation on the right abutment.

Fig. 8. Photograph of native slope just upstream of right abutment

Bathymetric surveys were conducted at 2-week intervals to map the submerged topography of the upstream dam face and right abutment area. A bathymetric survey is the measurement of the depth of a water body from the water surface. With the depth of water known, the surface of the fly ash below the water can be determined. Bathymetric surveys are generally conducted with a transducer which both transmits a sound pulse from the water surface (usually attached to a boat) and records that same signal when it bounces from the bottom of the water body. An echosounder attached to the transducer filters and records the travel time of the pulse. At the same time that the pulse occurs, a Global Positioning System (GPS) unit records the location of the reading. After many of these readings are taken, corrections are made based on fluctuations in the water surface elevation that may have occurred during the survey. The individual points are then mapped using a geographical information system.

The bathymetric surveys were used to create a contour map of the upper surface of the impounded fly ash. The resulting contour map was used to determine if any large sinkhole had developed in the reservoir that would indicate an area of significant material loss from the reservoir. Two new borings were drilled for the installation of monitoring wells with one monitoring well screened across an open joint upstream of FAD2 at the suspected point of entry into the bedrock formation. The second well was screened across several closely spaced fractures downstream of FAD2 along the suspected flow path within the formation. Laboratory testing of the fly ash discharge sediment consists of grain size analysis, elemental analysis, and mineralogical analysis. Seismicity and precipitation records were also reviewed to ascertain if a release coincided with either type of event.

Determination of Seepage Material and Seepage Pattern

Even though the seepage event from the sandstone outcrop appeared to be the gray fly ash, laboratory testing was conducted to confirm that the sediment was the impounded fly ash and not the shell fill or clay core which would indicate erosion of the embankment materials. Samples of the fly ash-laden sediment were collected from the sandstone outcrop on the downstream right abutment and analyzed for grain-size distribution, major and minor elemental analyses, and mineralogical analyses from the February 16, 2004 discharge event. Samples of the upstream and downstream fill materials and a sample of the clay core from a previously constructed test pad were also analyzed for compara-

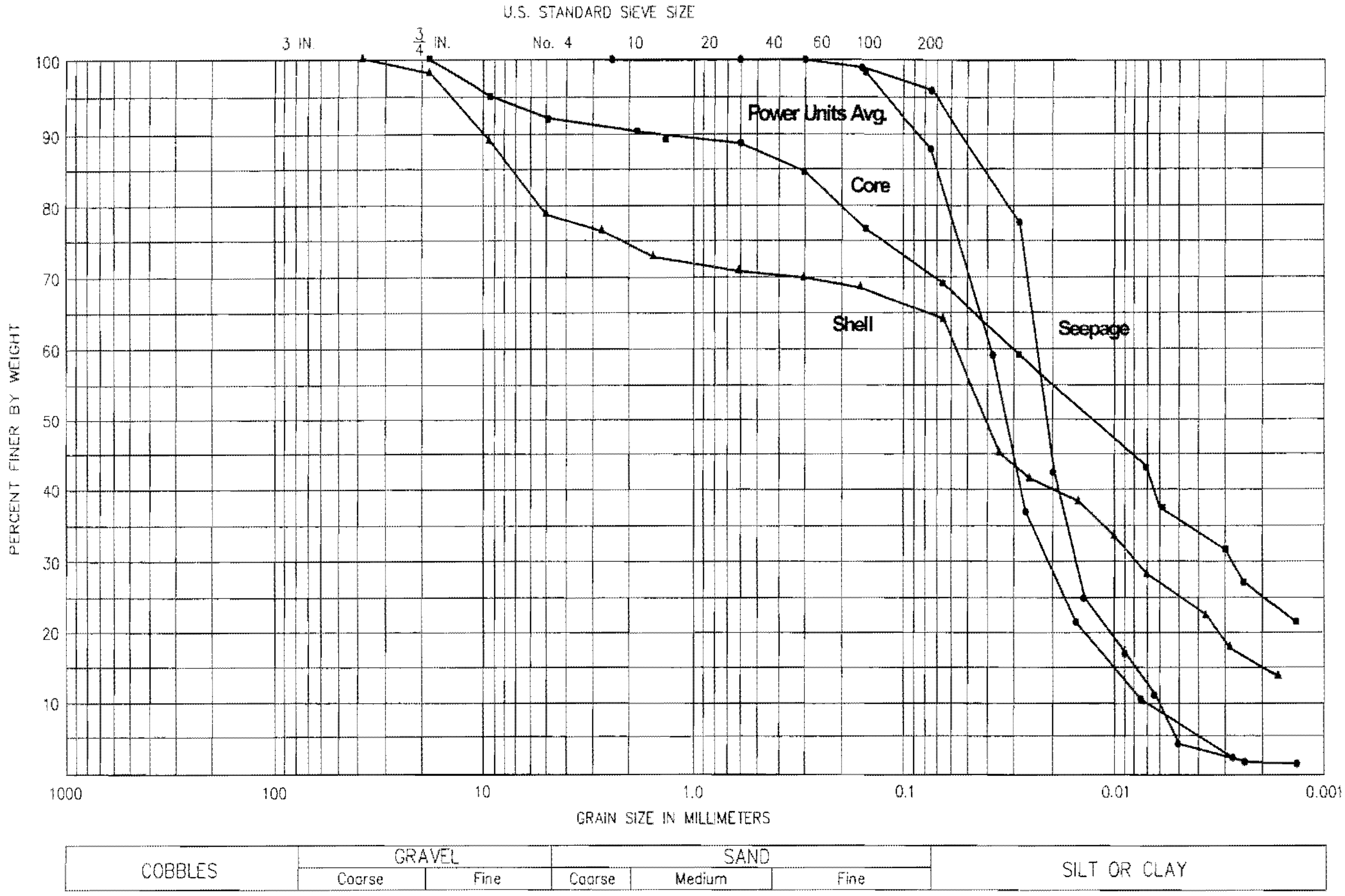

Fig. 9. Comparison of soil gradation relationships for clay core and shell material of the dam and fly ash seepage

tive purposes. Samples of the fly ash were also collected from the slurry line for each of the three power units to compare to the sediment obtained from the sandstone outcrop.

Fig. 9 illustrates the disparity between the particle size gradations of the fly ash seepage, clay core, and shell fill materials. Also shown in Fig. 9 is the average gradation obtained from fly ash samples collected from the slurry lines that transport fly ash from the three power units to the FAD2 reservoir. Fig. 10 shows the particle size gradations of the fly ash collected from the slurry line for Power Unit Nos. 1, 2, and 3. The three gradations shown in Fig. 10 were used to develop the average of the fly ash generated by Power Unit Nos. 1, 2, and 3 shown in Fig. 9 and labeled Power Unit Avg.

Fig. 9 shows agreement between the gradations of the fly ash seepage and the average of the fly ash generated by Power Unit Nos. 1, 2, and 3. However, there is a lack of matching of the grain size distributions between the clay core, shell materials, and the fly ash gradations. This indicates that the sediment in the observed seepage was not embankment dam material but fly ash material. Fig. 10 also shows the similarity in particle size gradation of the sediment-laden seepage and the fly ash collected from the slurry lines for Power Unit Nos. 1, 2, and 3 that would be deposited in the reservoir of FAD2.

The mineralogical analysis of the right abutment seepage sediment yielded the presence of mullite. Mullite is a high-temperature aluminum silicate formed at elevated temperatures of inorganic minerals present as trace impurities in the coal as it is combusted in the plant boiler. In addition, only a small amount of quartz is present in the seepage sediment and the majority of the material is amorphous. Overall, the mineralogy of the sediment discharged through the right abutment is typical of fly ash mineralogy. The mineralogical analyses of the clay core and shell fill material consist largely of chlorite and quartz with trace amounts of gypsum and calcite. This mineralogy is significantly different than the seepage sediment discharged through the right abutment. This analysis also indicates that no loss of material occurred from either the clay core or shell materials.

In a similar manner, the elemental analysis of the major and minor elements confirms that the right abutment seepage consists of fly ash because the constituents by weight are similar in abundance to fly ash. Table 1 shows the sample from the fly ash slurry line from power generation Unit #1 has similar elemental constituents as the sediment sampled from the stream channel downstream of FAD2. The elements shown in Table 1 are not dangerous. The sediment samples from an upstream monitoring well (FA-7 samples 1 and 2) and from the downstream monitoring well (FA-8 samples 1 and 2) show a greater similarity to the host lithology than the fly ash and are believed to be reflective of the filter cake around the monitoring well despite efforts to collect representative samples after extensive well development. This is especially apparent for the aluminum oxide element. The elemental analysis of the clay core soils strongly resembles the wellbore filter cake because these soils are inherently derived from the weathering of the local bedrock. Hence, a greater reliance was placed upon the X-ray diffraction mineralogical analysis to provide a definitive identification of the sediment-laden discharge.

The results of the particle size gradation, mineralogy, and elemental analyses confirm that the seepage was primarily fly ash and did not contain clay core or upstream/downstream shell material. Thus, the initial seepage mechanism was deemed to be

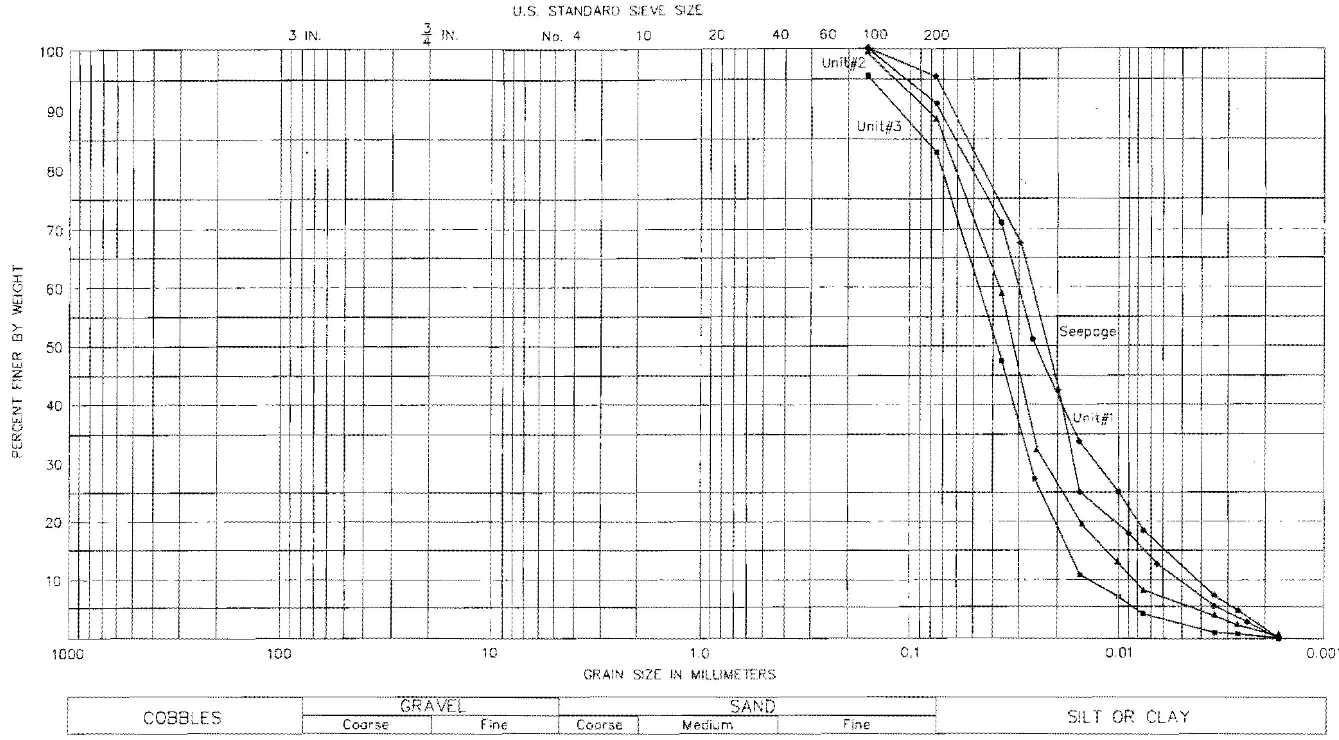

Fig. 10. Comparison of soil gradation relationships for fly ash seepage and new fly ash from Power Unit Nos. 1, 2, and 3

incorrect. The second seepage mechanism considered initially—clogging of the chimney drain and drainage blankets—was also dismissed because instability did not occur in the downstream slope and seepage from the drainage blankets did not change during or after the observed fly ash seepage. As a result, other seepage mechanisms were sought to explain the observed fly ash-laden seepage.

No earthquake occurred in 6 months prior to the anomalous seepage in the vicinity of FAD2 and thus seismicity was determined to not be a cause. Above normal precipitation had been recorded at the plant rain gauge in the preceding month of January but no discernable correlation between the five major sediment releases and precipitation events was obtained. In fact, Hurricane Frances and Hurricane Ivan yielded 0.17 and 0.25 m (6.5 and 9.75 in.), respectively, without inducing any type of release. (The dam is routinely inspected after such severe storm events and no adverse conditions or anomalous seepage conditions were observed.) Approximately 2.2 m (88 in.) of rainfall were recorded for the 2004 calendar year at the plant and is well above the normal 1.1 m (40 in.) per year.

Causation of Fly Ash Seepage

An important fact in determining the cause of the fly ash seepage is the seepage stopped in April 2004, about 2 months after the initial release, even though the reservoir continued to rise as a result of continued fly ash disposal. The groundwater and dam monitoring programs have previously observed clear seepage from the impoundment through the jointed sandstone layer. This layer is called the Morgantown Sandstone. This jointed sandstone showed seepage into the valley prior to construction of FAD2 and reflects a degraded water quality from overlying unreclaimed

Table 1. Elemental Analysis of Fly Ash and Monitoring Well Samples with Significant Results Reported by Percentage Weight

Significant constituents by percentage weight	Power unit 1: fly ash slurry line	Sediment from drainage ditch	Monitoring Well FA-7 Sample 2	Monitoring Well FA-8 Sample 2	Monitoring Well FA-7 Sample 1	Monitoring Well FA-8 Sample 1
Silica	51.8	55.8	54.9	59.2	49.9	49.1
Aluminum oxide	27.5	28.3	17.3	16.8	11.6	10.8
Iron oxide	11.5	4.0	5.6	4.6	6.9	6.5
Calcium oxide	1.0	1.0	3.1	3.4	8.2	8.7
Manganese oxide	0.7	0.7	2.0	1.8	6.1	5.3
Sodium oxide	0.3	0.3	0.2	0.4	0.6	0.6
Potassium oxide	2.1	2.1	2.4	2.5	1.8	1.8
Titanium oxide	1.5	1.5	0.9	0.7	0.6	0.7
Total carbon	2.1	5.7	0.8	1.3	3.8	4.2

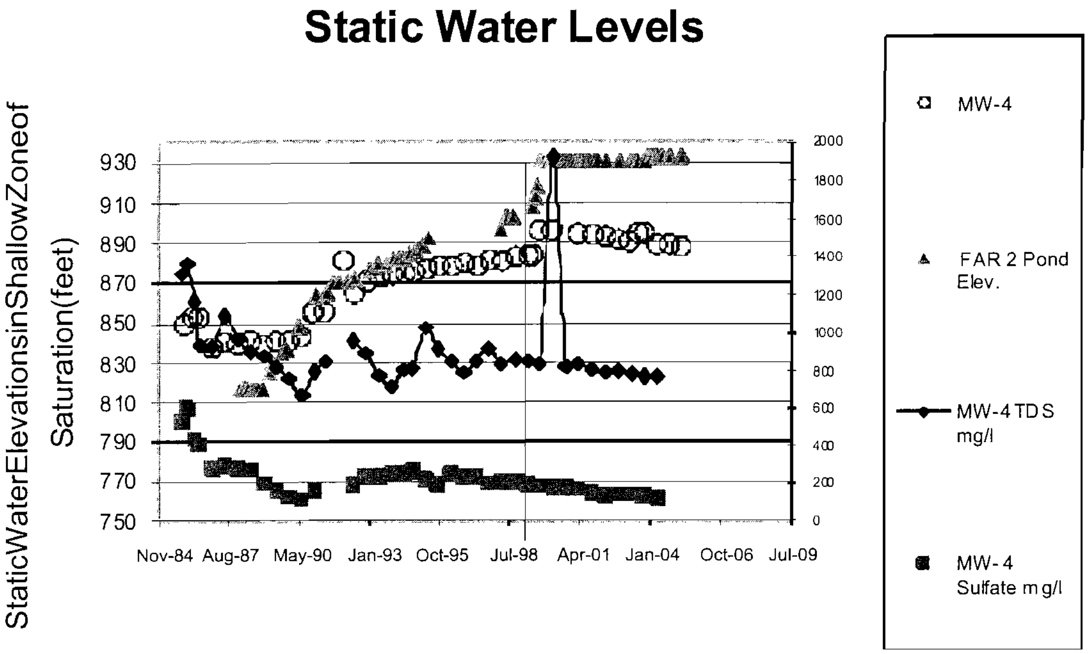

Fig. 11. Data from Monitoring Well No. 4 and FAD2 reservoir level

abandoned strip mines during the baseline monitoring period. Subsequent filling of the FAD2 reservoir resulted in a rise in groundwater levels which eventually reversed the hydraulic gradient within the Morgantown Sandstone such that the fly ash reservoir is able to recharge the jointed sandstone. This is evident from the observed environmental ground water monitoring program that shows sulfate concentrations and total dissolved solids (TDS) in nearby monitoring wells experiencing improved water quality as the fly ash reservoir recharges the bedrock formation, as shown in Fig. 11, which shows the decrease in TDS over time except for one anomalous point around 2000 that is included for completeness. For comparison purposes, Fig. 11 shows the level of Fly Ash Reservoir No. 2, i.e., FAR2, that is impounded by FAD2. The reservoir increased with time because of fly ash disposal but the TDS decreased over this time period. The water level in Monitoring Well No. 4 (MW-4) shows an increase with time which reflects the increasing level of FAR2 with time. In April 2001, ground water levels in the bedrock formation began to decline in several monitoring wells as the fly ash delta began to cover the formation and reduce the amount of flow. Covering of the formation provided a seal for the sandstone and also allowed recharge of the formation (see Fig. 11). This seal helps explain the decrease in sulfate in MW-4 with time, also shown in Fig. 11.

Potential Seepage Modes

FAD2 was constructed in 1986–1987 and no fly ash-laden seepage was observed until February 16, 2004. The Teton Dam experience shows that the first time geologic material is subjected to a hydraulic gradient is the critical time in terms of seepage and subsequent piping. When the fly ash reservoir reached an elevation of 268.5 m (880 ft) in the vicinity of the right upstream abutment, the abutment materials at this elevation were finally being subjected to a hydraulic gradient. Thus, it is not unusual that the seepage condition in the right or even left abutment would change as a new hydraulic gradient was experienced. However, this does not explain why no fly ash-laden seepage had been observed during reservoir filling from about elevation 241.0–268.5 m (790–880 ft).

Coincidentally in 1984, prior to construction of FAD2, a small landslide occurred in the right abutment just upstream of FAD2. The toe of the landslide is in the vicinity of elevation 268.5 m (880 ft). Construction photographs show that the landslide displaced all of the clayey colluvium and/or residual soil that formed a natural impervious barrier to reservoir seepage in the vicinity of the right abutment immediately upstream of the dam. Thus, the fly ash did not have to permeate the colluvium and/or residual soil in this area to enter the right abutment as it did from elevation 241.0–268.5 m (798–880 ft). This landslide was discovered prior to construction and was photographed during construction. However, no provisions were installed to cut off the potential fly ash seepage probably because it was not anticipated that fly ash-laden seepage would occur through the right abutment.

If the fly ash did enter the right abutment, it was anticipated that there might be some depression in the surface of fly ash reservoir. To investigate this possibility, a bathymetric survey of the fly ash reservoir surface in the vicinity of the upstream right abutment was conducted. The bathymetric survey shows a well-defined depression at elevation 272.6 m (893.8 ft) near the right abutment and a smaller depression in the fly ash surface at an elevation of 270.4 m (886.6 ft). Thus, it is possible that fly ash was leaving the reservoir and seeping into the jointed sandstone in the vicinity of the 1984 landslide. This seepage probably resulted in the depressions in the reservoir surface and the fly ash-laden sediment exiting on the downstream right abutment. The surface of the reservoir should be somewhat uniform due to the hydraulic filling of the reservoir and the subsequent flow of the fly ash over the surface of the reservoir.

Remedial Measure and Future Monitoring

After weighing a number of remedial measures, including applying bentonite to the 1984 landslide area to reduce the hydraulic conductivity of the jointed bedrock, and based on the cessation of fly ash-laden sediment exiting the right downstream abutment in April 2004, it was decided to allow the fly ash to "self-heal" the jointed sandstone. The self-healing process involves the creation of a plug and/or filter cake in the joints of the bedrock that reduces and/or eliminates seepage. The development of a plug involves the sediment-laden seepage depositing finer particles in the voids of the material that it passes through. Eventually the buildup of particles from the seepage reduces the void space in which seepage can occur. As the void space decreases, the rate and quantity of seepage decreases which facilitates additional particle buildup. After a plug is formed, a filter cake can develop, which traps fly ash particles while allowing clean water to pass. Thus, a filter cake will allow subsequent seepage to occur without carrying sediment.

In this case, the self-healing process involves a filter cake developing from the fly ash sediment that is present in the reservoir. As the reservoir level increases, the hydrostatic pressure forces the fly ash slurry into the exposed bedrock joints of the right abutment. As the fly ash slurry seeps into and through the abutment joints, fly ash sediment attaches to the surfaces of the joint and/or is deposited in the joints. The flow through a joint is initially slow because the reservoir level rises slowly. Thus, when the reservoir level reaches the height of an open joint, the fly ash slurry flows slowly through the open joints and may stop partway through the joint which results in deposition of all of the fly ash sediment in the joint. As the reservoir level increases, the hydraulic head and gradient increase in the joint which increases the flow rate through the joints and the distance over which the fly ash sediment can travel. This eventually allows seepage to occur along the full length of the joint. As flow is occurring along the full length of the joint, fly ash particles are bonding to the surfaces of the joints and/or being deposited in the joint, both of which reduces the available void space for flow. Before the joint is sealed up, the fly ash can flow the full length of the joint and exits on the downstream right abutment and downstream toe drain.

The fly ash particles are very fine/small (about 90% passing U.S. Sieve No. 200 or 0.074 mm) because they rose from the coal combustion process instead of falling to the bottom of the combustion chamber as bottom ash. These fine particles have a high surface area and can bond to each other creating a plug and/or filter cake. In addition, in small void spaces the fly ash particles can span or partially span the void space which blocks the flow of subsequent fly ash particles. In this case, the subsequent fly ash particles create a plug and/or filter cake behind the first particle that blocked or partially blocked the void space resulting in a seal of the joint.

If the joints are extremely large, the fine fly ash particles may not be able to seal the joint and prevent further fly ash-laden seepage from occurring because the flow velocity is too high and the void too large. If the fly ash slurry will be placed in contact with jointed or coarse material, an erosion test (Sherard and Dunnigan 1989) should be conducted to determine if the fly ash slurry will be able to seal the joint or void space of the coarse material. In this case described herein, the joints were obviously small enough to permit the fly ash to seal the jointed bedrock of the right abutment even though prior testing was not conducted. Another reason why the fly ash might not be able to seal up open joints or coarse material is that the hydraulic head and gradient are too high, which creates a high velocity that does not allow for sufficient deposition and/or bonding of the fly ash particles in the joints. This can occur because the flow velocity is calculated by multiplying the permeability of the porous media through which seepage is occurring by the hydraulic gradient. As a result, the greater the hydraulic gradient, i.e., the change in total hydraulic head divided by the seepage length, the greater the flow velocity and the less likely that fly ash particles will be deposited.

In summary, fly ash-laden seepage may not result in the development of plug and/or filter cake and a decrease in seepage quantity in all cases so it should not be assumed that the positive result experienced in this project and at Connor Run Dam described below (Leonards et al. 1991) will occur at all sites.

The self-healing nature of the fly ash also has been reported by Leonards et al. (1991) for Conner Run Dam which is approximately 50 km (30 mi) south of FAD2. Pinhole tests (Sherard and Dunnigan 1989) with fly ash placed upstream of the clay blanket material show no seepage under a water pressure of 550 kPa (11,490 psf) while similar pinhole tests without fly ash showed a flow rate of 30 mL/s. To confirm this no seepage condition in the field, a boring was drilled in the upstream clay blanket material at Conner Run Dam about 30 cm above the water line. The boring revealed the clay blanket to be completely dry for the entire length of the boring (11 m) through the clay blanket (Leonards et al. 1991). In addition, the water content of Shelby tube samples taken from this boring are in agreement with the compaction water contents and not subsequent wetting. This field data support the laboratory results which show that the fly ash clogged the pores of the compacted clay blanket and significantly reduced the hydraulic gradient of the clay blanket.

Leonards et al. (1991) also presented reservoir level and seepage losses and rates from the foundation drainage blanket in Fly Ash Dam 1 (FAD1) at the same site as FAD2. The erratic fluctuation in seepage losses and rates indicate that the FAD1 seepage is not controlled by the total head imposed by the reservoir because the reservoir level increased continuously with time. Leonards et al. (1991) explained this anomaly by the fly ash effectively clogging open joints and other defects in the rock formation along the periphery of the reservoir created by FAD1. Leonards et al. (1991) also presented the following information to reinforce their explanation of the seepage behavior. A stratum of fractured strata is located between elevations 292.8 and 293.4 m (960 and 962 ft) at FAD1. As the fly ash reservoir reached elevation 292.8 m (960 ft), a dramatic increase in flow rate was observed. However, when the reservoir reached elevation 298.9 m (980 ft), about 6 ft higher, a dramatic reduction in flow rate occurred which suggests clogging of the fractured stratum between elevations 292.8 and 293.4 m (960 and 962 ft).

This self-healing process also appears to have been successful at FAD2 because no fly ash-laden sediment has occurred from the right abutment since April 2004. However, it is possible that future fly ash-laden seepage could occur as the reservoir continues to fill and thus the hydraulic gradient induced by the reservoir increases. This increase in hydraulic gradient may continue to be resisted by the self-healing nature of the fly ash.

It is not anticipated that the prior landslide mass on the upstream right abutment will move again because it is buttressed by the fly ash in the reservoir. However, in another situation slope movement could occur and disrupt the filter cake that has developed on and in the right abutment. If the filter cake was disrupted in this case, it is anticipated that the fly ash-laden seepage would occur but it would not occur indefinitely because the joints in the right abutment of FAD2 and the hydraulic gradient are small enough to allow self-healing to occur.

In the interim, the facility continues to conduct weekly inspections of the dam and instrumentation of FAD2. The reviews continue to show that the dam is performing safely and as designed.

While the discharge of fly ash on the downstream abutment is still a concern and a subject of careful monitoring, it is anticipated that FAD2 will continue to perform as designed because of the self-healing properties of fly ash on jointed bedrock.

Conclusions

Observations, data, and analyses used to investigate the cause of fly ash-laden seepage on the right downstream abutment of a significant fly ash dam are presented. The only mechanism that explains all of the observed features is that the fly ash-laden seepage occurred through the jointed right abutment and exited on the downstream abutment. The investigation shows the seepage is probably caused by permeable/jointed bedrock in the right abutment that was exposed by a landslide that occurred prior to construction of the dam and removed the layer of low hydraulic conductivity colluvium/residual soil that covers the majority of the upstream right abutment. When the level of the impounded fly ash reached the level of the prior landslide, the seepage was able to migrate into the jointed right abutment and exit on the downstream right abutment and downstream slope of the dam. However, the previously observed self-healing nature of fly ash eventually sealed the jointed abutment which stopped the sediment-laden seepage. No fly ash-laden seepage has been observed on the downstream slope since April 2004 after first appearing on February 16, 2004 even though the reservoir continues to fill to higher elevations. This self-healing process was also observed at FAD1 and was reported by Leonards et al. (1991).

Thus, the two seepage mechanisms initially investigated in response to the appearance of the light gray sediment-laden seepage on the right downstream abutment are (1) piping of the clay core and/or shell fill material that could lead to failure of the dam and (2) clogging of the chimney drain and drainage blankets that could lead to instability of FAD2 due to the buildup of pore water pressures were dismissed. The piping of the clay core and shell fill material was dismissed because Fig. 9 shows that the gradation of the observed seepage does not match the gradation of the clay core or downstream shell materials. The clogging of the chimney drain and drainage blankets was dismissed because instability has not occurred in the downstream slope and seepage from the drainage blankets did not change during or after the observed fly ash seepage.

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