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BIG BRANCH SLURRY IMPOUNDMENT BREAKTHROUGH: WHY IT HAPPENED AND LESSONS-LEARNED

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Background

The Big Branch Slurry Impoundment in Martin County, Kentucky, broke into an underground coal mine in the Coalburg seam on 11 October 2000. Volume estimates of the water and fine coal refuse (slurry) spill range from 250 to 300 million gallons. The impact of the release on the environment was severe. Due primarily to the Herculean efforts of the owner, the spill was cleaned up and there were no fatalities and no injuries. Government officials commissioned studies to identify the cause of the spill and evaluate the practice of coal processing waste disposal in slurry impoundments to reduce the potential for breakthroughs at other sites.[1, 2]

What caused the spill? What is the potential risk for an event like this to be repeated at other sites? What lessons can be learned from the Martin County spill by owners, designers, and government agencies to reduce the potential for spills in the future? Results of engineering analyses, performed using data generated from the government-commissioned studies, and opinions are presented as answers to these questions.

What Caused the Spill?

General

An investigation report prepared by the Mine Safety and Health Administration (MSHA) contains a detailed description of the subsurface conditions and history of coal refuse disposal at the site.[1] Generally, a relatively small spill occurred in 1994 when primarily water from the impoundment broke into mine works of the Coalburg coal seam. To reduce the potential for future breakthroughs, a "seepage barrier" of well-graded mine spoil (i.e. silty, sandy, rockfill) was placed around the perimeter of the impoundment. The spoil embankment extended from about elevation 970 feet (i.e. top of the 10-foot thick Coalburg coal seam) to elevation 1080 feet. The spill in October 2000 occurred when the slurry impoundment had achieved an elevation of 1060 feet and the level of the settled fine coal refuse was at elevation 1058 feet. At the breakthrough point, about 15 feet of unmined, unweathered coal and 55 feet of very stiff, natural cohesive soil overburden separated the deep mine from the slurry impoundment as measured along a horizontal projection of the mine floor.

The Big Branch Slurry Impoundment breakthrough was a seepage problem, yet after a year of study with millions of taxpayer dollars spent in the development of reports, none of the reports included results of engineering seepage analyses.[1, 2] Because the government-commissioned reports do not include the results of seepage analyses, a finite element model of the Big Branch site was developed as shown in Figure 1 using field and laboratory data contained in the government-commissioned studies. Table 1 summarizes coefficients of permeability used in the modeling.

Table 1. Coefficients of Permeability (k) Input Data for Finite Element Modeling

Material	k_v saturated, ft/min	k_v at -500 psf hydrostatic pressure, ft/min	k_h/k_v
Spoil Fill	1E-04	1E-05	9
Coal	1E-05	1E-06	9
Bedrock	5E-06	5E-07	9
Fine Refuse	1E-06	1E-07	100
Natural Cohesive Soil Overburden	5E-07	5E-08	9

Results of Failure Analysis

A seepage analysis was performed using the parameters shown in Table 1 to analyze for conditions that existed before the October 2000 breakthrough. Results included in Figure 2 predict that the maximum hydrostatic pressure on the natural outcrop barrier prior to the breakthrough was approximately 4000 psf.

Results of an electrical geophysical study, performed as part of the government-commissioned investigation at Big Branch, show ridges of high voltage running along bearings of approximately N65W, N10E, and N88E as shown in Figure 3. These high-voltage ridges could be near-vertical tension joints (i.e. N10E and N88E running into the natural outcrop barrier) and a near-vertical "hillseam" (i.e. N65W running roughly parallel to the natural topography/outcrop barrier). The tension joints at N10E and N88E were confirmed by field measurements in outcrops located above the spoil embankment.

Hillseams are weathered joints in shallow overburden in Eastern Kentucky that are formed by stress relief and tend to parallel topographic contours. An MSHA investigation report for a previous accident site in Martin County, Kentucky, summarizes a highwall collapse caused by a near-vertical hillseam, running parallel to the highwall at an average strike of N60W, and near-vertical tension joints at an average strike of N20E. The near-vertical hillseam and tension joints allowed a block to fall out of the highwall.[3]

If the near-vertical joint weaknesses at Big Branch created a block that had little or no side friction, then the failure block can be represented by a free-body pressure diagram as shown in Figure 4. Being isolated from the surrounding ground by the near-vertical hillseam, tension joints, and the mine void, the block could move inward whereas the ground on the opposite sides of the block could not. If the block started to move, then arching from the surrounding soil could reduce the earth pressures on the block to near zero. The only force acting to cause further movement would then be the hydrostatic pressure of 4000 psf as predicted in Figure 2.

Data in an MSHA-commissioned engineering report from Big Branch suggest shear strengths (i.e. cohesion values) of about 4000 psf for the cohesive overburden soil and about 56,000 psf for the coal. Using these values, a factor of safety much greater than 10 would be expected and no breakthrough would have occurred. The reported cohesion value for the cohesive soil (i.e. along L_1) is probably a valid estimation of the shearing resistance above the coal seam because the shearing orientation in this zone is about the angle one would expect in a laboratory shear test.

The shear planes along L_2 and L_3 are through the coal seam, or the residual soil of the coal seam, and the angles of shearing are much flatter than one would expect in a laboratory shear test. As shown in core logs from the drilling at Big Branch, the Coalburg seam is composed of interbedded layers of clayshale and coal. Even the residual soil that weathers from the Coalburg seam has the same relic weaknesses that were present before the coal weathered to soil (i.e. near-vertical joints and coal/clay bedding planes). The shearing resistance on a relatively flat angle between coal and cohesive soil is better defined by adhesion rather than cohesion. Geotechnical literature list the average adhesion between concrete and very stiff cohesive soil as being 1125 psf.[4] This value appears reasonable for the adhesion between coal and cohesive soil considering that the area was disturbed by near-vertical joints. The calculated factor of safety against sliding of the block is 0.98.

The failure analysis and site observations indicate that the natural outcrop barrier broke instantaneously and without warning. When it broke, it was like pulling the plug out of a bathtub or flushing a toilet. Water that had accumulated in the pore space of the pervious "seepage barrier" prior to the breakthrough continued the flushing of fine refuse solids into the mine long after water had drained off the impoundment. The flushing of solids into the mine did not stop until the owner used bulldozers to push spoil into the breach.

What Lessons Can Be Learned from the Martin County Spill?

General

Valuable lessons can be learned from the Big Branch breakthrough that will reduce, but not eliminate, the potential for future breakthroughs. Specifically, construction of the mine spoil embankment at Big Branch in 1994 was one of the first attempts to reduce the potential of a future breakthrough for an entire site. No references were available for design and no performance data were available to judge the effectiveness of an earthen embankment built in 1994 to reduce the potential for a future breakthrough. In 1996, two slurry impoundments in Virginia experienced breakthroughs into abandoned mine works.[5] MSHA issued Program Information Bulletin (PIB) No. P97-4 in 1997 which raised awareness of the potential for breakthroughs. Improvements were made in barrier design and construction methods. Internal drains were installed in 1997 in the mine barriers built in Virginia to reduce the potential for buildup of hydrostatic pressures during later stages of construction.

Drained Perimeter Embankment

Although internal drains in perimeter embankments were not in use prior to 1997, they are now.[6] Important lessons can be learned using the Big Branch seepage model if the practice of installing man-made internal drains in perimeter embankments had been in use in 1994. Based on the results of the finite element seepage analysis shown in Figure 5, a maximum hydrostatic pressure of 2000 psf (i.e. 50% reduction) is predicted in the natural overburden portion of the outcrop barrier if internal drains had been in use in 1994 when the spoil embankment at Big Branch was built. A factor of safety of 2.0 is calculated based on the predicted actual hydrostatic pressure of 4000 psf at failure from Figure 2.

No Perimeter Embankment

Another important lesson can be learned using the Big Branch seepage model if no spoil embankment had been built in 1994. Based on the results of the seepage analysis shown in Figure 6, a maximum hydrostatic pressure of 400 psf (i.e. 90% reduction) is predicted in the natural overburden portion of the outcrop barrier for conditions that existed before 11 October 2000 if no "seepage barrier" had been built at Big Branch in 1994. At such a low hydrostatic pressure, no breakthrough is predicted.

Low hydrostatic pressures, similar to those predicted in Figure 6, have been measured at other sites. At the Steer Branch Slurry Impoundment in Virginia, the Taggart coal seam was deep mined, stripped, and augered creating a thin coal barrier. The Steer Branch Slurry Impoundment reached the level of the Taggart outcrop in the 1970's. Now the impoundment is about 160 feet in elevation above the level of the Taggart seam. Last year, a coarse coal refuse drill pad was pushed about 300 feet into the impoundment to allow drilling through fine refuse down to the elevation of the coal seam outcrop.

As shown in Figure 7, a pneumatic piezometer was installed in the fine refuse adjacent to the coal outcrop at Steer Branch, 155 feet below the elevation of the impoundment pool. Full hydrostatic pressure for 155 feet of water and no flow is 9672 psf. The actual hydrostatic pressure measured in the fine refuse at the coal outcrop level was 1750 psf, an 82% reduction in hydrostatic pressure caused by energy loss during flow through the fine refuse. This 82% reduction in hydrostatic pressure at Steer Branch compares well with the 90% reduction predicted in the model for Big Branch in Figure 6. The unconfined compressive strength of the fine refuse at Steer Branch increases with depth as shown in Figure 8. Near the level of the mine, the fine refuse has an unconfined compressive strength of about 3500 psf, indicating that consolidated, drained fine refuse makes an effective barrier.

Partial-Height, Drained Perimeter Embankment

Another important lesson can be learned using the Big Branch seepage model if a partial-height, drained perimeter embankment had been built before the fine refuse reached the level of the Coalburg coal seam. Based on the results of the seepage analysis in Figure 9, a maximum hydrostatic pressure of 1000 psf (i.e. a 75% reduction) is predicted in the natural overburden portion of the outcrop barrier for conditions that would have existed after October 2000 if a partial-height, drained perimeter embankment had been built before the fine refuse reached the level of the Coalburg coal seam.

A partial-height, drained perimeter embankment provides protection when the pool level is near the mine. After the fine refuse rises above the elevation where an uncontrolled release can occur from "sinkhole-type" subsidence, the fine refuse can be allowed to fill above the drained perimeter embankment and thereby create an added barrier. In this manner, concerns about long-term performance of internal drains in perimeter embankments are reduced. If a drain loses capacity with time, due to iron precipitate or gypsum build-up, then it can still keep the embankment dewatered because of its lower flow-handling requirements. Specifically, comparison of the seepage rates in the drains in Figure 5 (i.e. 0.0027 cubic feet per minute per foot of embankment length) and Figure 9 (i.e. 0.00028 cubic feet per minute per foot of embankment length) shows a 90% reduction in the needed long-term flow carrying capacity by using a partial-height, drained perimeter embankment.

Likelihood of the Martin County Spill to be Repeated at Other Sites

The modeling results for Big Branch and the monitoring data from Steer Branch offer explanations as to why: 1) the Big Branch release on 11 October 2000 was the largest of its kind in history; and 2) another release of this magnitude is not likely at other slurry impoundments unless they have a saturated, pervious, "seepage barrier" that extends above the fine refuse level in the impoundment. Prior to the release at Big Branch in 1994, several other slurry impoundments experienced releases into underground mine works. Prior to 1994, the industry practice was to shove rockfill back into exposed mine voids and place spoil or coarse refuse between the filled openings and the impoundment as shown in Figure 7. Fine refuse eventually deposited above the level of the filled openings to serve as a barrier. Fine refuse contains clay. Clay has low hydraulic conductivity and makes good barriers. Other than fine refuse, clay is scarce in most parts of the Appalachian coal fields.

No plan approvals were required for such work because breakthroughs into underground mine works were considered by regulatory agencies as an operational problem not related to the dam. Besides, impacts from the breakthroughs had never been significant. Breakthroughs were treated like flat tires. Flat tires are impractical to predict. The practical approach to flat tire problems has always been, "you can't fix one until you get one".

The first recorded breakthrough of a slurry impoundment into underground mine works occurred in 1956 in Virginia. The 1956 breakthrough was repaired as described previously and the facility operated uninterrupted (i.e. no additional breakthroughs) for 30 years until the site was abandoned. The traditional approach to fixing breakthroughs using the "flat tire repair method" was crude but effective as illustrated by the low hydrostatic pressures predicted in Figure 6 for the Big Branch model and as measured at the Steer Branch site. All previous breakthroughs of slurry impoundments into underground mine works were small in comparison to the October 2000 Big Branch release because they occurred when the pool was near the level of the mine and hydrostatic pressures were low. At the pre-1994 breakthrough repair sites, the fine refuse served as the barrier between the impoundment pool and the mine after the fine refuse level increased in elevation. The deeper the fine refuse, the thicker the barrier.

The spoil embankment at Big Branch was built in 1994 because, unlike most previous breakthroughs that occurred into abandoned mines, the underground mine at Big Branch was connected to an active section used as access for an underground conveyor. Unlike pre-1994 breakthrough repair sites where an increase in fine refuse/pool levels resulted in thicker fine refuse barriers and lower hydrostatic pressures, an increase in fine refuse/pool levels at Big Branch resulted in an increase in hydrostatic pressures as the spoil continued to saturate at higher levels. The spoil embankment allowed water to accumulate adjacent to the natural hillside and prevented the fine refuse from creating a seal between the impoundment pool and the natural mine outcrop barrier. Whether or not clarified water was on top of the fine refuse at Big Branch was irrelevant. The models show that water seeped through the fine refuse and into the coarse-grained spoil at Big Branch faster than it could drain through the natural outcrop barrier. The pervious spoil at Big Branch did not perform as a "seepage barrier" but as a recharge zone allowing relatively high hydrostatic pressures to be generated directly against the natural overburden portion of the outcrop barrier.

Data and analysis of the Martin County spill indicate that in low cover, thin natural outcrop barrier conditions where an earthfill embankment is warranted, internal drainage provisions are needed to reduce the potential for a buildup of hydrostatic pressures during later stages of construction. Drained perimeter embankments are already being built at many sites and can be built at all sites where the fine refuse has not achieved mine level. Furthermore, for those many cases where no undrained, pervious "seepage barrier" has been built and the fine refuse is well above low cover areas, a breakthrough is unlikely provided that actual measurements show that the hydrostatic pressures are comparatively low, such as at the Steer Branch facility. MSHA reviewers are already requiring operators to install instrumentation and gather measurements of hydrostatic pressures in the fine refuse adjacent to underground mines at existing sites.

Retaining Wall Analogy

An analogy is offered for illustration purposes. Compare a natural outcrop barrier between a slurry impoundment and an underground mine to a retaining wall. When Man started building walls, water collected behind some of them and the walls failed. Man learned to put pervious backfill behind the walls for drainage. For some walls, water that collected in the pervious backfill had no place to drain. Water built up in the pervious backfill and again some walls failed. Man then learned to put perforated pipes at the base of the pervious backfill and to extend the perforated pipes so drainage could be maintained. Surface runoff sometimes washed in at the top of the pervious backfill, exceeding the capacity of the perforated pipes. Water built up behind the walls and some walls failed. Man finally learned to place impervious soil backfill above the pervious backfill at the top of walls to reduce infiltration. With all these advances, walls still fail. Man's latest challenge deals with terrorists flying hijacked airliners into walls causing failure and death. Man is now working feverishly on this latest wall problem. At no time in history has Man considered banning wall construction or airliners as a means to keep walls from failing.

Minimum Natural Outcrop Barrier Widths and Hydraulic Bulkheads

The National Research Council of the National Academies of Science and Engineering (NASE) published a report and a press release which recommend that federal agencies promulgate minimum coal outcrop barrier widths for slurry impoundments underlain by underground coal mines to help prevent breakthroughs.[2, 7] No explanation is given as to how NASE could offer recommendations for prevention without first performing engineering analyses to evaluate the cause of breakthroughs. Nevertheless, to test this NASE recommendation, a seepage analysis model was developed for Big Branch if the entire coal outcrop barrier had been removed by contour surface mining and replaced with drained engineered fill before the pool had reached the Coalburg coal seam level.

As shown by the results in Figure 10, a maximum hydrostatic pressure of only 60 psf is predicted if the coal outcrop barrier and areas of low cover had been removed by surface mining and replaced with a partial-height, drained perimeter embankment. Piezometers can be installed in the drained engineered fill to verify performance of the drain and the system. The results shown in Figure 10 suggest that if minimum coal outcrop barrier widths are promulgated, then the minimum widths should be "zero".

The NASE report also recommends that "MSHA develop guidelines for the design of bulkheads to withstand hydraulic heads associated with slurry impoundments...pressure grouting may be needed". Unfortunately, hydraulic bulkheads and pressure grouting reduce drainage, resulting in increased hydrostatic pressures. Higher hydrostatic pressures present greater risk and more severe consequences of breakthroughs. Coal miners know that if you want to reduce the risk of failure from water building up behind a wall or barrier, the prudent approach is to drill weep holes through the wall to let it relieve itself. Figure 11 shows the results of a finite element seepage analysis if relief wells had been drilled at the Big Branch site before 11 October 2000. A maximum hydrostatic pressure of 2000 psf (i.e. 50% reduction) is predicted using drainage wells to relieve hydrostatic pressures. Relief wells offer a means to reduce breakthrough potential at existing sites with undrained pervious perimeter embankments built adjacent to thin natural outcrop barriers.

Conclusions

Engineering is a humbling profession for practicing engineers. No matter how smart we get or how many tools we invent, practicing engineers realize that the best for which Man can aspire is to tie Mother Nature. In the end, Mother Nature always wins. The greatest engineering achievements of Man will all some day lie in ruin. It's inevitable. Despite these odds, practicing engineers labor to stay tied with Mother Nature for as long as we can. Why do practicing engineers even bother to play the game when we know we must lose? During the time when the score is tied with Mother Nature, Man enjoys a quality of life that would be the envy of all past generations of life on Earth.

Like any good parent, Mother Nature is a strict parent. She makes Man learn lessons the hard way at the school of hard knocks. She gives us hints, but she never tells us the answer to our problems. Like any wise parent, Mother Nature knows that what doesn't kill Man, makes Man stronger. Man fails only if Man ignores, denies, or puts the wrong "spin" on the lessons that Mother Nature tries to teach us.

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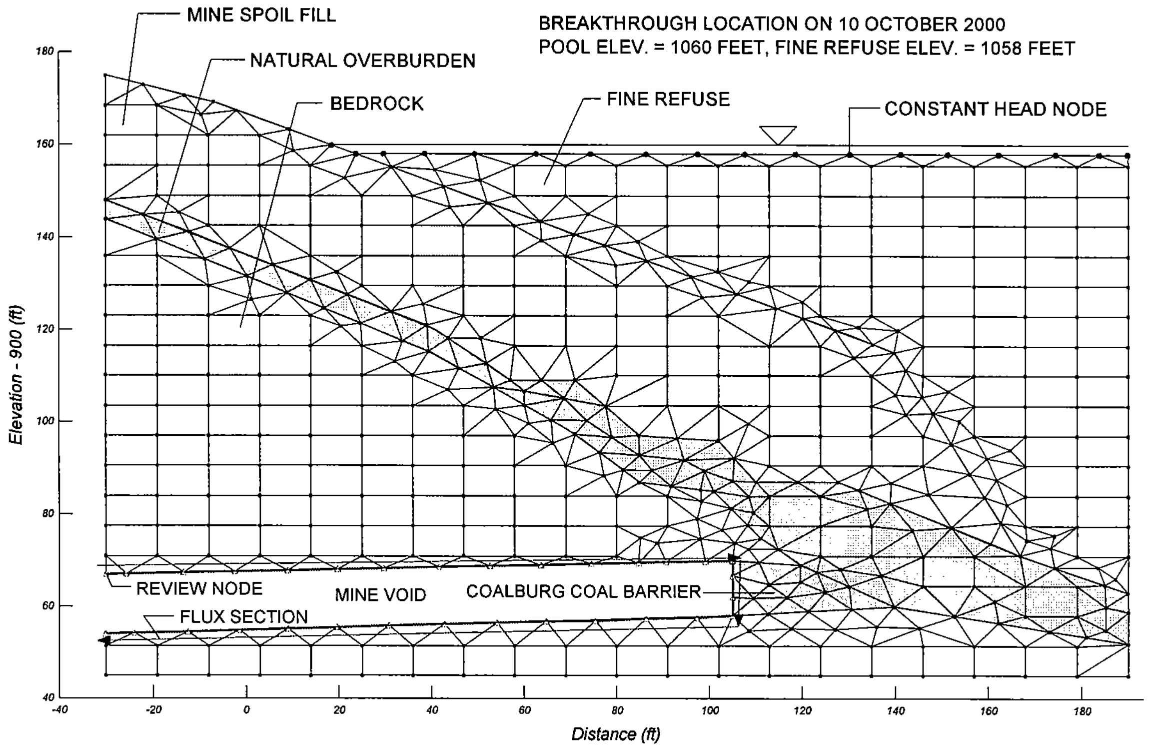


Figure 1. Finite Element Seepage Analysis Grid used to Model the Big Branch Slurry Impoundment Breakthrough Location

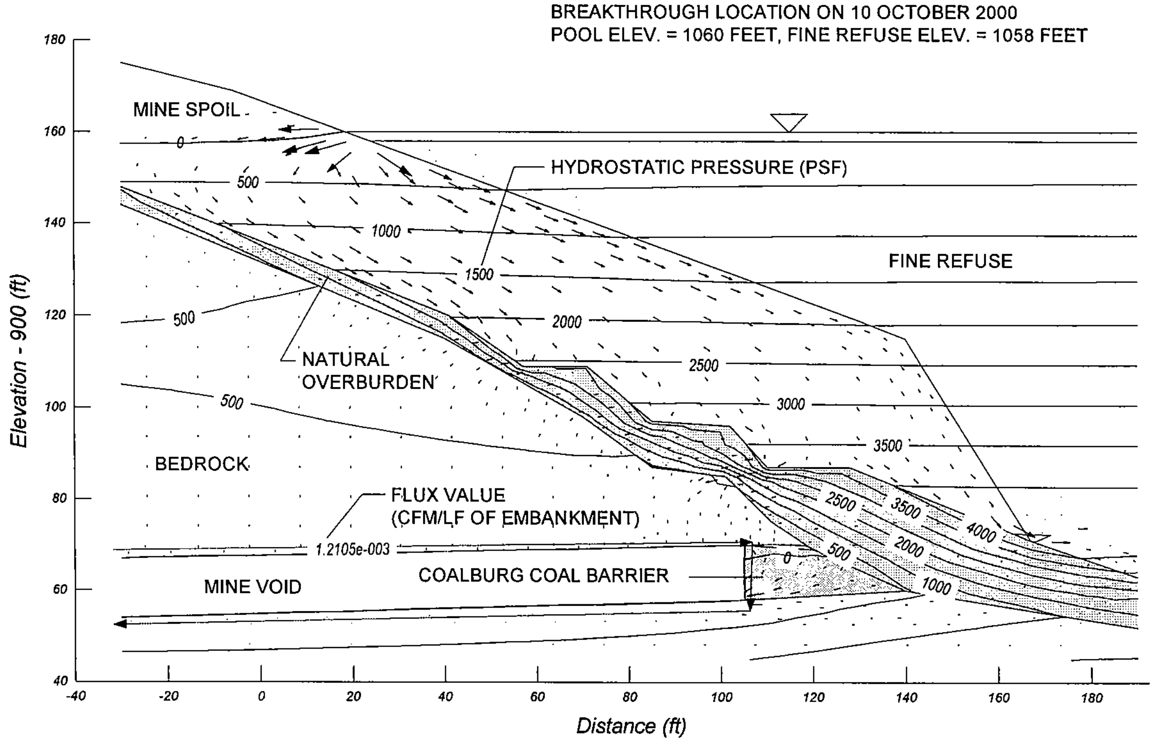


Figure 2. Results of Seepage Analysis using Data from the MSHA Study (Maximum Hydrostatic Pressure = 4000 psf in the Natural Outcrop Barrier)

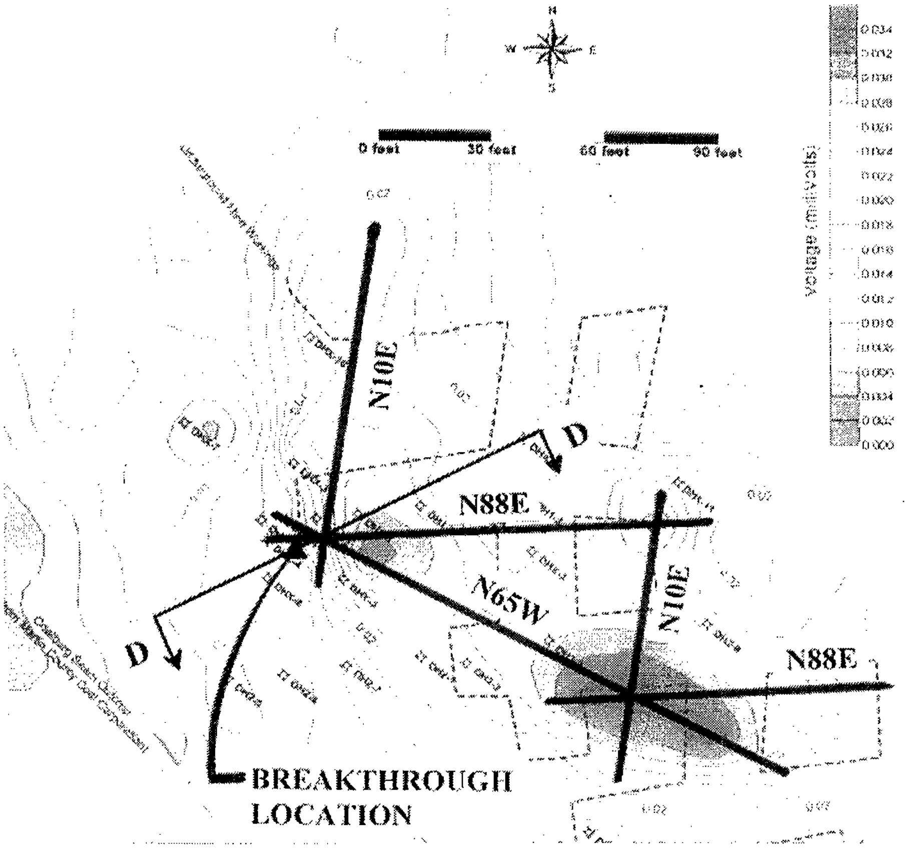
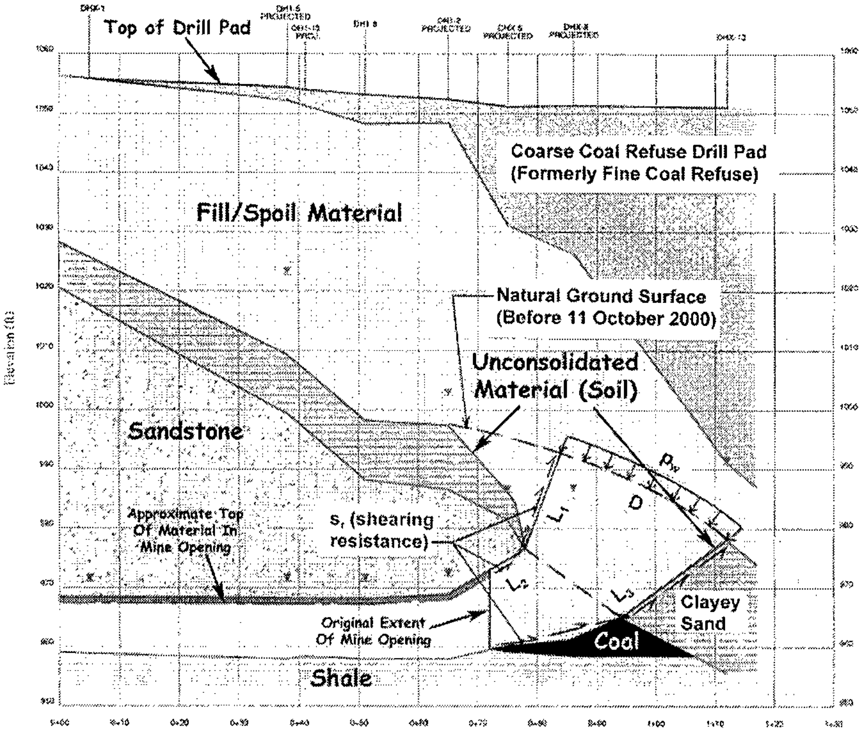


Figure 3. Results of MSHA Electrical Geophysical Study at Big Branch Showing Ridges of High Voltage Along Bearings of N65W, N10E, and N88E



$D = 32'$

$L_1 = 17'$

$L_2 = 7'$

$L_3 = 44'$

$s_{r1} = 4000$ psf

$s_{r2} = 1125$ psf

$s_{r3} = 1125$ psf

$p_w = 4000$ psf (hydrostatic pressure)

$$FS = \frac{(4000*17)+(1125*51)}{(4000*32)}$$

$$FS = 0.98$$

Figure 4. Free-body Pressure Diagram and Blow-in Calculations at Breakthrough Location Section D-D (Adapted From Figure 36 of MSHA Big Branch Report of Investigation)

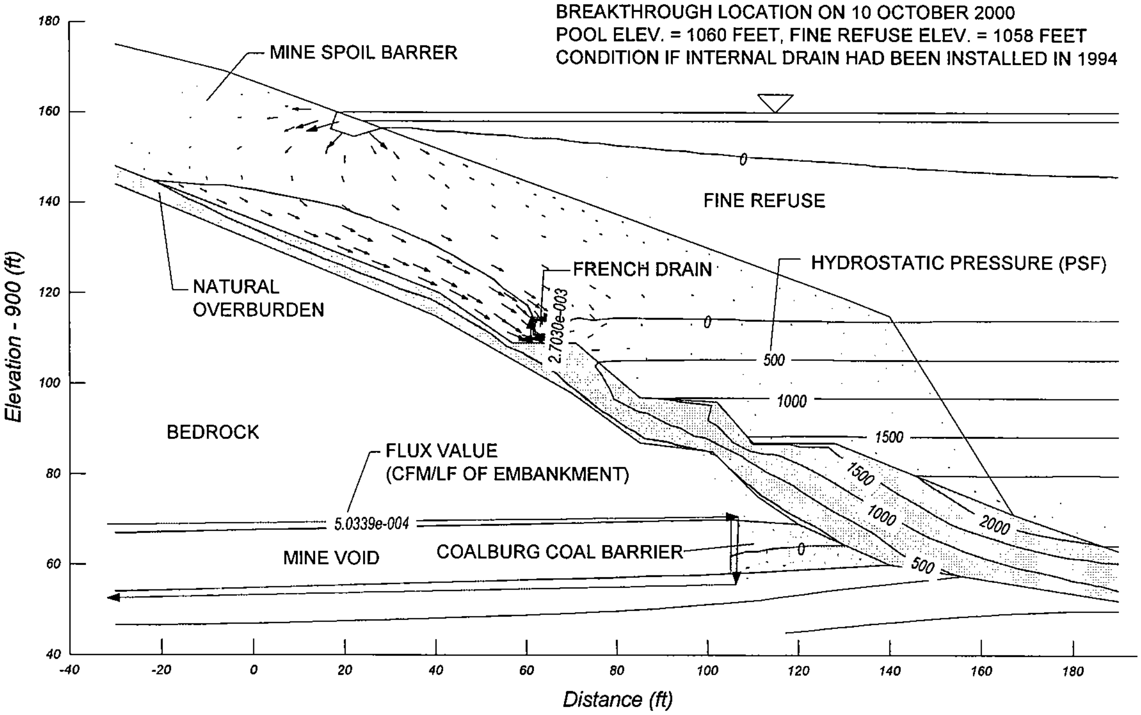


Figure 5. Results of Seepage Analysis for Drained Perimeter Embankment (Maximum Hydrostatic Pressure = 2000 psf)

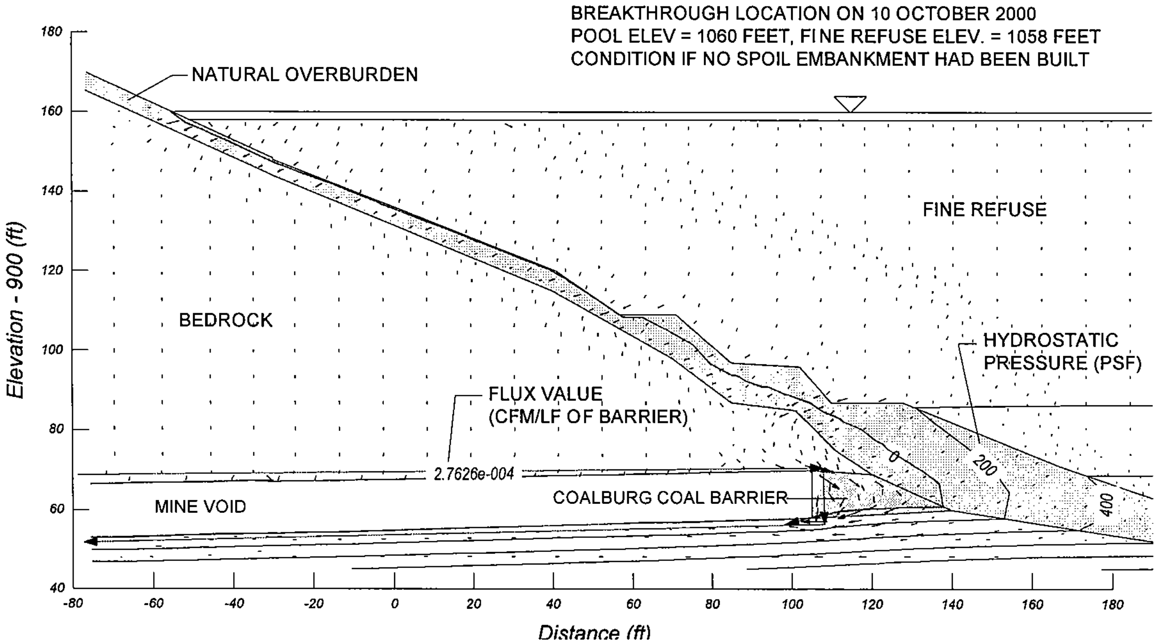


Figure 6. Results of Seepage Analysis for No Spoil Embankment (Maximum Hydrostatic Pressure = 400 psf)

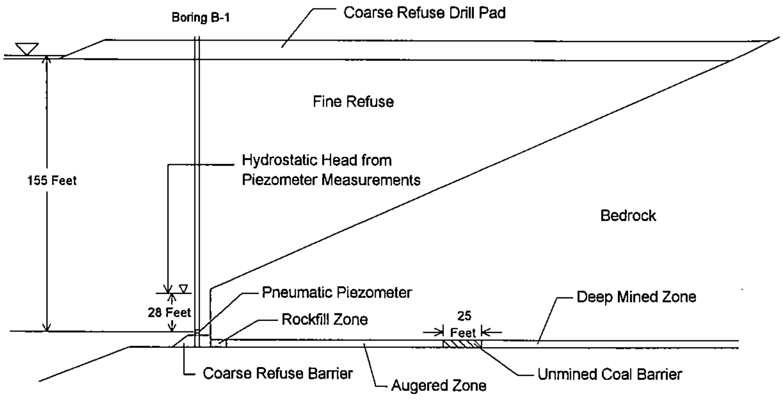


Figure 7. Sketch of Drilling and Instrumentation at Steer Branch Slurry Impoundment

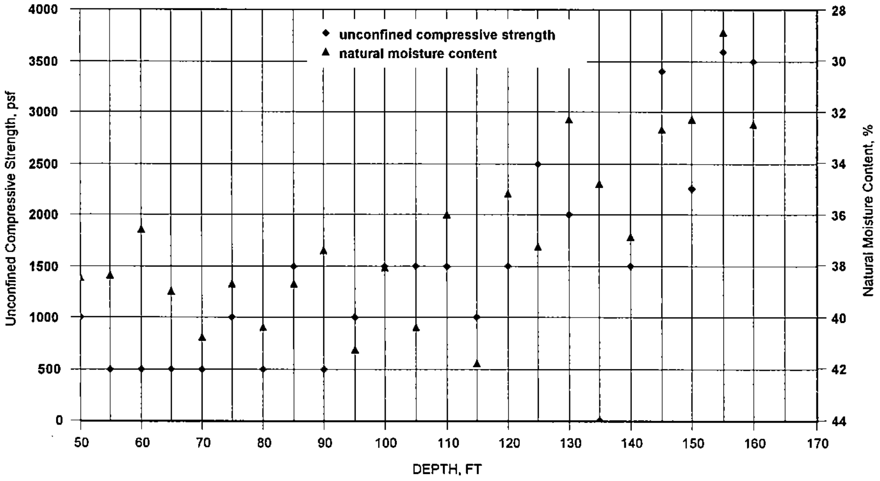


Figure 8. Comparison of Unconfined Compressive Strength and Natural Moisture Content with Depth for Fine Refuse at Steer Branch Slurry Impoundment

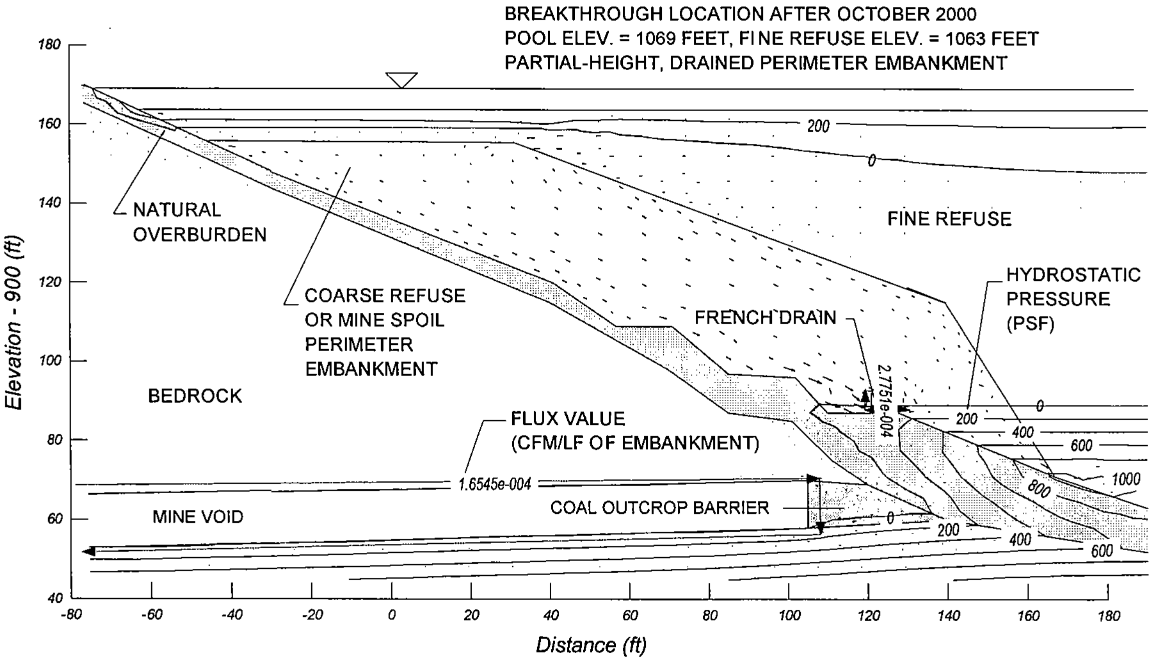


Figure 9. Results of Seepage Analysis for a Partial-Height, Drained Perimeter Embankment (Maximum Hydrostatic Pressure = 1000 psf)

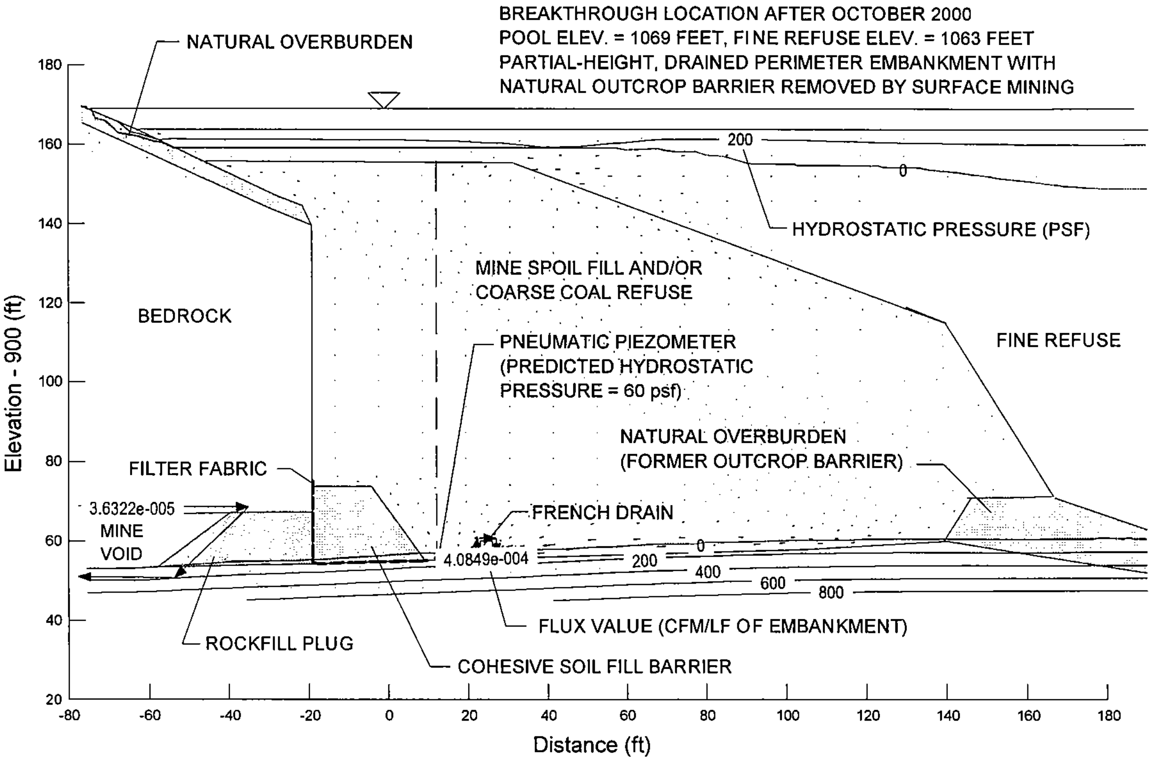


Figure 10. Results of Seepage Analysis to Test NASE Minimum Coal Outcrop Barrier Width Recommendation (Maximum Hydrostatic Pressure = 60 psf with a Partial-Height, Drained Perimeter Embankment and No Coal Outcrop Barrier)

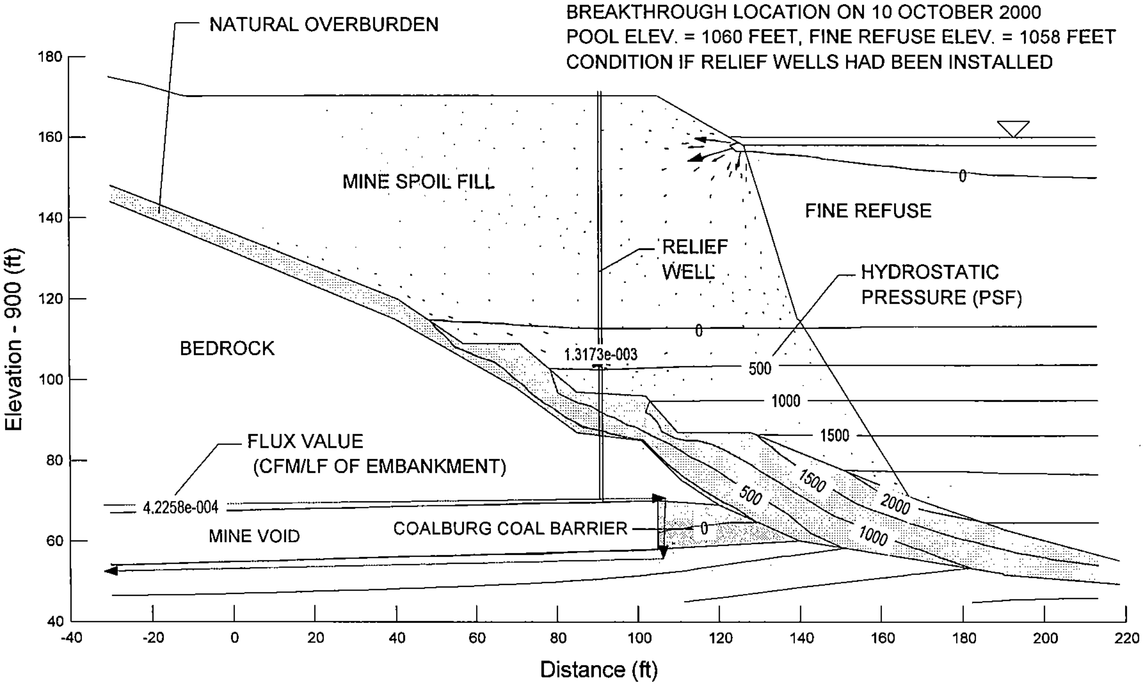


Figure 11. Results of Seepage Analysis for Relief Wells used as Drainage (Maximum Hydrostatic Pressure = 2000 psf)