

TECHNICAL POSITION PAPER

**POTENTIAL OF IMPOUNDED-COAL-WASTE-SLURRY BREAKTHROUGHS INTO
UNDERGROUND MINES**

ISSUES AND ANSWERS



**U.S. Department of the Interior
Office of Surface Mining Reclamation and Enforcement
Appalachian Region**

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POTENTIAL OF IMPOUNDED-FINE-COAL-WASTE BREAKTHROUGHS INTO UNDERGROUND MINES

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INTRODUCTION

Most underground and some surface mines in the Appalachian Region produce coal that must be processed prior to sale. The processing typically involves removing inert, non-coal (rock fragments) material from the raw mine output. Fine material is first washed from the coarser fraction. Both coarse and fine fractions undergo processes to separate coal from inert materials. Together, the coarse and fine inert materials are referred to as coal mine waste. Separately, they are commonly referred to as coarse and fine coal refuse. Coarse refuse is transported to a disposal facility by truck or belt line. Fine refuse is typically pumped in slurry form through a pipeline to a coal waste impoundment. This practice is authorized under the Surface Mining Control and Reclamation Act (SMCRA) (Sections 102, 201, 501, 503, 504, 507(b), 508(a), 510(b), 515, and 517) .

Most coal waste impoundments in Appalachia use the natural topography to form the storage basin containing the fine coal waste slurry. This is accomplished by constructing an embankment made of coarse coal refuse at the mouth of a valley and then pumping the slurry into the basin. A concern shared by many engineers, geologists, and mine inspectors familiar with coal waste slurry impoundments is related to the common occurrence of underground mine workings adjacent to or beneath the impoundments (Figures 1 and 2): the potential for slurry breakthroughs into mine works and subsequent breakouts into the surface waterways. Events of this nature can endanger underground mine workers and the downstream inhabitants; and negatively impact local ground-water resources and stream and river eco-systems.

There are four potential failure modes pertinent to breakthrough of impounded slurry into underground mines:

- Breakthrough at an unsealed underground mine opening: Slurry flows into a mine opening that has not been sealed. These openings may be covered, but only with colluvial soil or debris. Underground mine openings include, but are not limited to, “punchouts”, (i.e., intentional or unintentional voids or tunnel-like connections of the underground mine to the surface), portals, horizontal drainage and ventilation borings, adits, and auger holes that connect with underground mines.
- Failure of a sealed underground mine opening: The opening seal (made of rock, soil, or other material) fails, thus allowing slurry to flow into the underground works.
- Breakthrough at coal barriers: A coal barrier may be a natural outcrop barrier, a barrier between contour and underground mines; a barrier between auger holes and an underground mine; or barrier between small drift mines or house coal adits. Pressure resulting from build-up of water, slurry, and other materials may cause a failure of the coal barrier and allow slurry and water to enter the mine.

- Failure of strata overlying a coal mine: Slurry flows into a mine through natural fractures and joints or mine-subsidence induced fractures and sink holes.

The potential for fine coal waste slurry stored in impoundments to break through into underground mine workings and subsequently impact the environment became a significant concern after the Martin County Coal Corporation breakthrough near Inez, Martin County, Kentucky, on October 11, 2000. On that date, a combination of fine coal refuse slurry and water from the Big Branch Impoundment broke through into an underground mine and subsequently discharged into local streams. An estimated 306 million gallons of water and coal waste slurry drained from the impoundment into the adjacent underground mine. Approximately 230 million gallons subsequently discharged from the underground mine at two portals. This was the second breakthrough event at this impoundment, the first having occurred in May 1994. The breakthrough in 2000 differed from the 1994 breakthrough in that it resulted in severe stream degradation and property damage. Fortunately, no personal injuries were reported as a result of the 2000 breakthrough. However, the water-slurry mixture affected over 75 miles of stream in Kentucky and West Virginia. At some locations, the water-slurry mixture spilled over the banks and deposited slime onto adjacent property. Six public water intakes were adversely affected and alternative water supplies had to be arranged. It was reported that the cost to clean up the waterways and affected lands exceeded 56 million dollars.

As a result of this and several breakthroughs in Virginia in 1996, the U.S. Office of Surface Mining Reclamation and Enforcement (OSM) and other government agencies launched investigations to assess the causes of the events, the potential for additional breakthroughs in the future, and available methods for preventing them. In 2001, OSM's Appalachian Office also initiated an oversight review of how well States were implementing the requirements of SMCRA in relation to determinations for potential breakthrough into underground works. Oversight and technical assistance efforts in this area have been ongoing at various levels of detail in each State. In 2009, each OSM office was asked again to review its actions of the past and determine if the agency was being consistent in its overview of each State. Oversight activities in West Virginia has led to discussions among the OSM offices and staff about the degree of documentation necessary to demonstrate that the States have done a sufficient review of information provided by permit applicants pertaining to breakthrough potential. The purpose of this paper is to address the following issues concerning current permit-review procedures:

- (a) Is there a sufficient accounting for all minable coal seams cropping out within and underlying slurry impoundments?
- (b) Is there an over reliance on the existence and accuracy of mine maps when determining whether minable coal seams have been mined and the thickness of barriers between underground mines and the impoundment footprint¹?

¹ Over reliance on mine maps occurs when the absence of a map leads to the assumption that a certain coal seam has not been mined or when an existing map is assumed to be accurate, especially with respect to a mine's position relative to an impoundment. An adequate investigation into the presence of underground mine workings proximate to an impoundment entails taking additional measures to verify the presence or absence of mines or the accuracy of available mine maps. Methods of verification are discussed under Issue 3, starting on page 9.

(c) Is sufficient information being obtained to determine fine-refuse flowability when impoundments are either expanded in size or “eliminated,” i.e. capped, and no longer considered to be impoundments²?



Figure 1: Photo of active coal waste slurry impoundment.

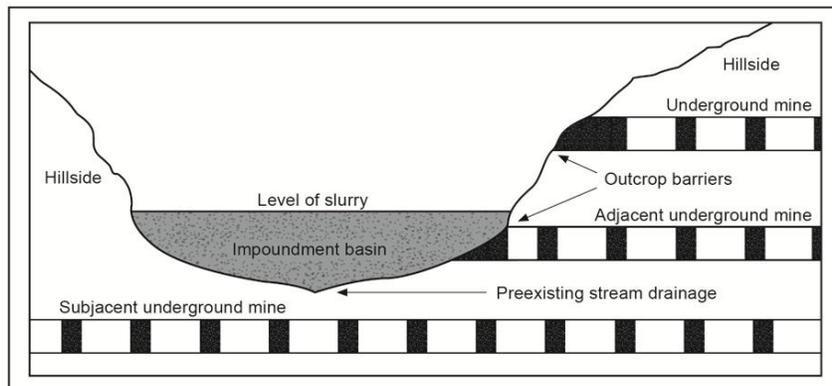


Figure 2: Schematic cross-section of impoundment basin and proximate underground mines. (Diagram modified from NRC, 2002)

As a result of the discussions, the authors³ of this report have identified the following seven questions regarding risk of breakthrough and severity of breakthrough impact:

² In many cases, slurry cells, i.e. smaller impoundments separated by compacted coarse refuse barriers, are built on top of an original impoundment after its “elimination.” The potential for a breakthrough from impounded fine refuse underlying slurry cells into an underground mine is discussed under Issue 4 on page 11.

³ The authors are identified on page 25 of this report.

- (1) What is a minable seam?
- (2) Can we trust mine maps to give us all the mining-related information we need?
- (3) How can we determine whether minable seams have been mined?
- (4) What do we know about the flowability of fine refuse slurry in active, inactive, and capped impoundments; and capped impoundments below multiple layers of slurry cells?
- (5) How can we test the impounded slurry for its flow characteristics?
- (6) What precautions and restrictions should we recommend to prevent breakthroughs?
- (7) If an underground mine that intersects or lies below an impoundment is below drainage,⁴ should we still be concerned about breakthrough potential?

An explanation of the issues and the authors' findings pertaining to them follows. The text and illustrations include modifications in response to some of the solicited peer review comments on the first draft that was completed in June 2010. The 26 reviewers included geotechnical engineers, engineering geologists, and mine inspectors familiar with slurry impoundments and similar structures from academic institutions and state and federal agencies (including OSM offices in the Appalachian Region).

THE QUESTIONS

(1) What is a minable seam?

The first step in accounting for all underground mines horizontally and vertically proximate to a proposed impoundment should be to identify all the minable seams that crop out within and beneath the impoundment's footprint. Once all the minable coal seams are known, the actual occurrence of underground mines and their location nearest the impoundment can be investigated. Following this procedure requires a working definition of a minable coal seam.

Reports of coal seam thickness in economic resource evaluations have either included or excluded the partings, i.e. thin layers of non-coal rock within the seam. For the purposes of breakthrough analysis, the thickness of the entire coal seam, including all partings, should be reported in a proposal to construct or enlarge an impoundment. This is necessary because the height of any mine void would be at least equal to the total seam thickness.

The SME Mining Engineering Handbook 2nd Edition, page 1557, states that seam heights as thin as 26 to 30 inches can be mined (Hartman, 1992). When the demand is high, top quality coal, including metallurgical coal, in seams as thin as 24 inches is mined by extracting additional rock above the coal. For example, it is common knowledge in the mining industry that the Alma, Sewell, and Eagle seams in West Virginia and the Blue Gem seam in Kentucky (with minimum thicknesses of 24 inches) are mined by mining the roof rock. Figure 3 shows a highwall miner that is capable of mining seams 24 inches thick up to 1,000 feet into a hill from the highwall.

⁴ Mines described as "below drainage" occur in coal seams that do not crop out at the surface.



Figure 3: Highwall miner capable of mining a 24-inch coal seam.

To be certain that all seams in the vicinity of major impoundments have been included in a breakthrough analysis, all coal seams with a reported or known thickness 24 inches or greater should be identified and investigated.

(2) Can we trust mine maps to give us all the mining related information we need?

Mine maps can be employed as a first step to estimate distances between the boundary of an impoundment and the boundaries of the mines (Figure 4). However, there is an unknown number of (especially older) mines without maps; or with maps that are inaccurate or not current. The information and data of existing maps can only be relied upon after their accuracy have been independently verified.

The accuracy of available underground mine maps is limited by a number of factors; some are common to all types of mapping, and some are unique to the underground environment. Numerous cases are on record of mine voids being discovered significant distances from where they were believed to be. Noteworthy examples include the following:

- An investigation into the 2000 Martin County Coal Corporation breakthrough by a consultant to the U.S. Mine Safety and Health Administration (MSHA) concluded that several of the entries near the breakthrough point had been advanced further toward the outcrop than was depicted on the mine map (Triad, Inc., 2001). The mine map also misrepresented the competence of the barrier in the area of the breakthrough. The width within the barrier of solid coal, shown on the mine map to be approximately 70 feet thick, was in fact, 15 to 18 feet thick. Investigative reports on the event are also provided by MSHA (2001) and OSM (2002).

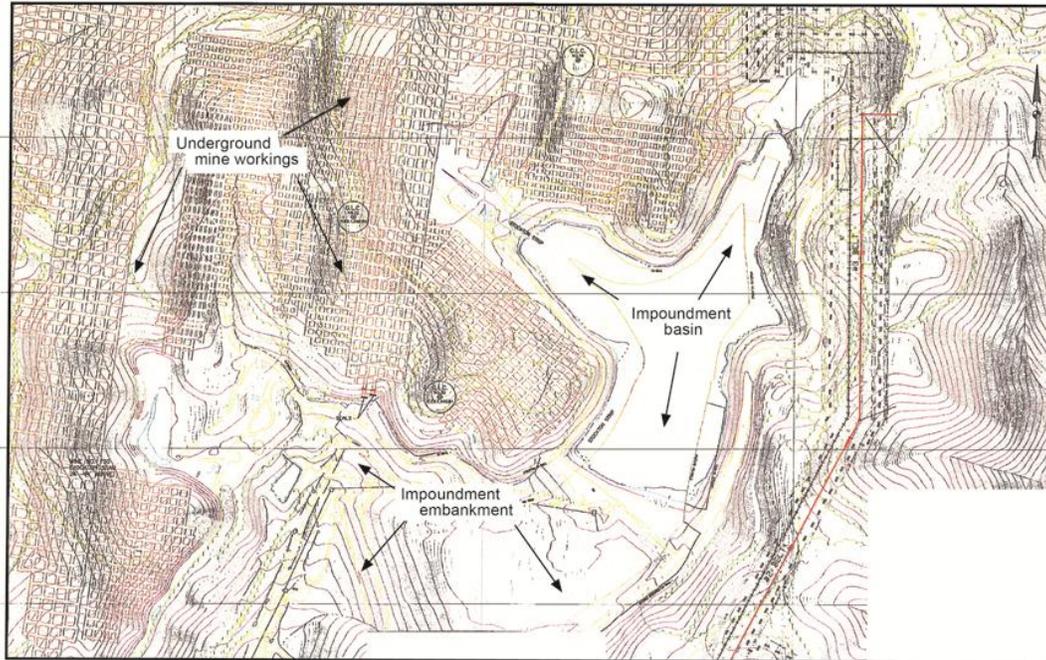


Figure 4: Example permit mine map of room-and-pillar underground mine workings adjacent to a coal waste slurry impoundment.

- On July 24, 2002, miners at the Quecreek mine in Somerset County, Pennsylvania, accidentally mined into the abandoned and flooded Saxman Coal, Harrison #2 mine. Nine miners were trapped when the Quecreek mine flooded with approximately 50 million gallons of water. Investigators subsequently concluded that the primary cause of the incident was the use of an uncertified and out-of-date mine map of the Harrison #2 workings. The mine map led the miners to incorrectly believe that the Quecreek works were at least 300 feet from the abandoned mine where the breakthrough occurred. This incident was not a result of inaccurate mapping, but of reliance on an older map that did not depict all mining. A final investigative report on the incident is provided by the Pennsylvania Department of Environmental Protection (Pauley et al., 2003).
- In 2009, OSM personnel investigating the elevation of a mine pool at the Bakerstown Mine in Grant County, West Virginia, discovered that the locations of recently mined areas, verified relative to surface features, did not correlate with positions of the same areas on the permit-application mine maps. When this was investigated, it was discovered that the mined areas on the mine maps were incorrectly located by as much as 800 feet (Figure 5). The information was provided to personnel at the West Virginia Department of Environmental Protection (WVDEP) who required the operator to correct the maps. Fortunately, this error was discovered before an incident could occur.

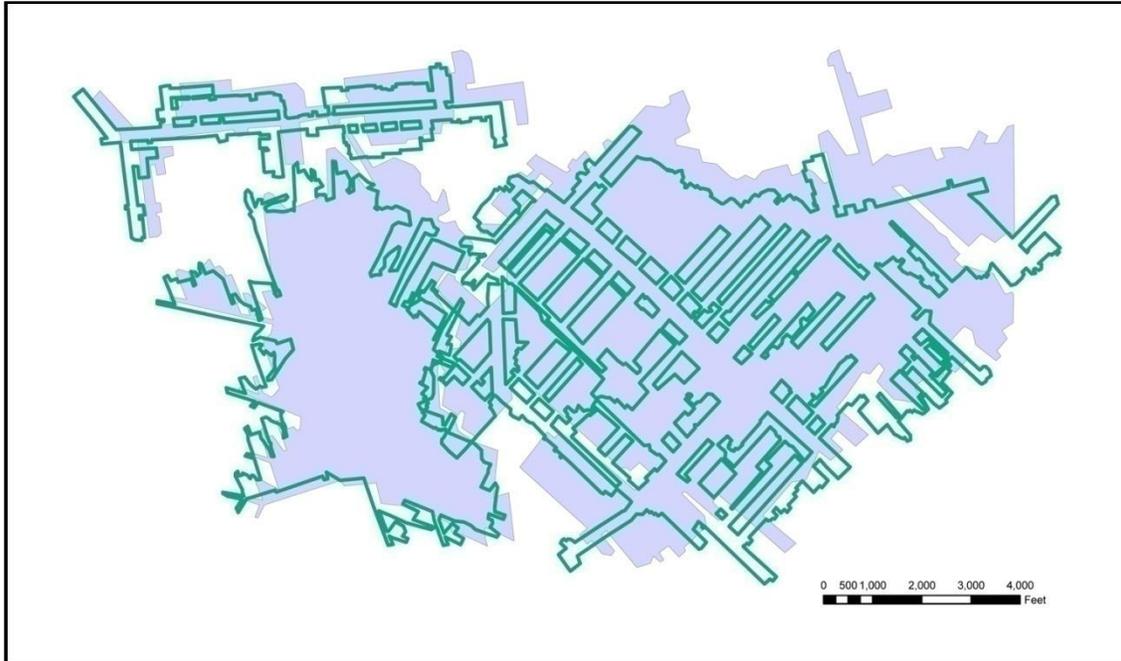


Figure 5: Contrast in the documented location of the same mine workings. The pattern in solid blue was presented in a permit application for additional mining in the coal seam. The map outlined in green was provided by an earlier mining operation. The latter map was obtained from the OSM Mine Map Repository in Pittsburgh, Pennsylvania, and geo-referenced.

Factors that are common to all types of mapping include:

- Variation in the capabilities of surveyors and cartographers;
- Variation in the conditions during performance of surveys;
- Variation in the quality and condition of equipment;
- Inherent human fallibility and the cumulative nature of error.

Factors that are unique to underground mine mapping include (Hartman, 1992):

- Lines of sight are often short, through constricted openings, with awkward setups;
- Lighting is generally poor, requiring specialized illumination;
- Ambient conditions are often difficult; including falling water, poor visibility, and congested traffic;
- Surrounding rock may be unstable, resulting in movement or loss of surveying stations;
- Points to be measured may be difficult, impossible, or dangerous to reach;
- Steep vertical sights are sometimes necessary, requiring specialized equipment and extreme care to minimize introduction of error.
- Multiple levels (seams) are often involved. Extreme care is required when transferring control from one level to another with minimal introduction of error.

It is important to note that the above factors—and considerations described below—are not restricted to the generation of older mine maps. Modern techniques in underground mine surveying have generally increased the accuracy of mine maps but they are not error free.

Surveyor/Cartographer Capabilities

Personnel capabilities can be an issue for surface as well as underground surveying and mapping. However, some of the factors identified above as unique to underground mapping would tend to highlight the need for qualified personnel. Unfortunately, whereas surface mapping can be tied to any number of known locations around the site, allowing errors to be discovered, underground mapping can only be tied to surface points through portals or shafts. As a consequence, even a very small error can result in an entire mine map being rotated slightly about the entrance point, with no way to identify the problem unless multiple entry points exist. Surveyors must be very capable in order to prevent or discover errors of this type.

Variations of Conditions

The ambient conditions in most areas of an underground coal mine are very consistent with respect to time but vary with location. Temperature tends to be relatively constant. Lighting intensity varies from area to area, but tends to remain constant in a given area. Conditions are more variable near the face, as lighting equipment, partitions, and mining equipment may be moved during a survey. Normally, surveying is not performed until the face has advanced well beyond the area of interest. However, some locations may never be precisely surveyed due to safety concerns. These include dead-end sections, which may not be totally supported or roof bolted. Those dead ends can occur near an outcrop abutting an impoundment, or lay beneath an impoundment with thin rock cover.

Survey Equipment Quality

Equipment quality has improved dramatically with the advent of electronics in the last half of the twentieth century. Very high quality angular measurement technology has been available since the early part of the twentieth century. Much of the error in older surveys was attributable to the difficulty of precisely measuring distances over terrain. These difficulties were compounded by the limited light available in the underground environment. Modern electronic distance measurement equipment and techniques have minimized these errors. As is the case with surface maps, mine maps resulting from relatively recent surveys tend to be more reliable than those derived from older surveys. However, this fact does not mean that the more recent surveys are error free, as is amply demonstrated by the Martin County, Quecreek, and Bakerstown examples described above.

Human Fallibility and Accumulation of Error

Human fallibility has always been recognized, and standard surveying procedures were developed largely to provide means for discovering errors during the course of the work. Unfortunately, some of the most useful of these are often unavailable to surveyors of underground mine workings. As noted above, surveyors on the ground surface often tie their

surveys to multiple previously established locations to verify the orientation and location of the lines and points they are generating. This option is seldom available to underground surveys. Unless multiple shafts or openings to the mine are available, there is no guaranteed way to verify the accuracy of underground coordinate systems relative to known locations of survey stations on the surface. Errors that occur early in a survey increase in magnitude with distance. If a mine is hundreds or thousands of feet in extent, points at its extremities (e.g. near the footprint of an impoundment) may be hundreds of feet from their mapped locations.

In conclusion, many factors affect the reliability of maps. The surveying profession has developed over centuries, with methods being devised to discover errors through checks and balances, maximizing map reliability. However, underground conditions place additional hardships on surveyors, and eliminate or reduce the effectiveness of some of the checks and balances. In addition to these factors, some locations in mines cannot be safely surveyed. These include terminated entries near seam outcrops or beneath valley bottoms. Terminated entries are typically not roof bolted, and therefore are not entered for precise survey. Consequently, the horizontal distance from the terminal face to the ground surface is not precisely known. If an impoundment is proposed at the site, the coal barrier thickness will be unknown. Those factors and the historical catastrophic events warrant conservative decision making when based on underground mine mapping. Many mine maps are accurate; however, there is no way to know whether a particular map is accurate without independent confirmation. A mine map should not be accepted as reliable prior to its verification .

(3) How can we determine if minable seams have been mined?

Each coal seam identified as “minable” needs to be thoroughly investigated to determine if it has or has not been mined. The investigation needs to document areas adjacent to and below the impounded slurry area and the embankment. Existing documentation of mining should be researched and evaluated. Site specific information should be collected to verify the existing documentation. For mineable coal seams where no documentation is available, additional investigations will have to be done to identify the presence or absence of mining.

Mine maps are a source of documentation of mined areas. Mine maps may be available through mine map repositories, permit files, regulatory agencies, coal mine operator files, and private map collections. The accuracy of available mapping for coal contours and outcrops can vary depending on the age, location, and source of the mapping. The reliability of available maps also depends on whether they reflect all of the mined areas. Maps marked “final” may have been accurate when they were prepared but they would not show additional mining done at a later date. Therefore, the accuracy of mapping information must be verified through additional site specific evaluations.

Records of previously drilled boreholes are another source of documentation. Drilling records are available through geologic survey offices, mining permits, and drilling companies. For areas where on-site investigation is necessary, additional drilling can be done to determine the location, extent, and variability of subsurface conditions, coal seams, and underground coal mining at specific points. Additional subsurface information can be collected by using borehole

cameras, laser imaging, sonar mapping, and robotics. Drilling logs and down-hole data collection techniques can help verify the accuracy of the underground mine mapping information and subsurface conditions. It can also be used to document the presence or absence of mining.

Horizontal exploratory drilling and directional drilling can also be used to determine if and where a coal seam has been mined. It has previously been used in underground mines for identifying and understanding geological and mining conditions in advance of mining. Directional drilling has the flexibility to alter the position of the drill bit from a straight line. The location of the drill bit can be guided or steered to areas needing investigation. This technique can be used to advance a drill hole within the coal seam and roughly parallel to a coal-outcrop line to establish if the solid outcrop barrier around an impoundment site is of adequate thickness. However, caution should be used when using this technique near water in surface impoundments or flooded underground mines.

For impoundments that have not yet been constructed, surface reconnaissance can be used to document conditions and the location of mineable coal seam outcrops. This reconnaissance would include walking the planned impoundment perimeter and vicinity and observing topography; rock and coal outcrops; and surface cracks, and other potential subsidence features to verify the location and condition of mineable coal seams. This type of reconnaissance and geologic mapping generally requires an experienced geologist or engineer knowledgeable in mining and impoundment design. Reconnaissance should be conducted during times when vegetation is dormant so that site features are more visible. For impoundments that are already operational, surface reconnaissance can still be done for areas that will be inundated in the future.

Geophysical methods (e.g. seismic reflection, electrical resistivity, microgravity) can provide information on conditions underground without surface disturbance. Geophysical methods, through detection of anomalies, can, in some instances, indicate whether mine workings are present and, with other tools, whether available mine maps are accurate. The advantage of successful geophysical applications is that they can provide contiguous subsurface data over a large area in contrast to limited, point sources of data obtained from drilling.

While geophysical methods have been successfully applied to some geotechnical problems, their utility in mine-void detection or location has had mixed results.⁵ Common, site-specific shortcomings include insufficient signal penetration into the subsurface, low data resolution, multiple mined coal seams, geological anomalies and cultural clutter. Geophysical methods have developed significantly in recent years but should be used only in conjunction with other investigative techniques to confirm their results.

Finally, interviewing miners and local residents can provide additional historic coal mine information not documented on mine maps or other information sources. The information provided by these interviews can help to identify areas where the potential extent of mining should be evaluated in greater detail to supplement other investigations. However, it is

⁵ In response to the Martin County impoundment breakthrough and Quecreek mine flooding, an extensive program of mine-void-detection demonstration projects was organized and sponsored by MSHA (2008).

emphasized that the absence of information from interviews should not be regarded as reliable evidence that a minable coal seam has not been mined.

In summary, the significant size of these impoundments and the consequences if failure occurs demand that an exhaustive assessment be conducted to accurately assess the status of all minable coal seams within the critical zones of the impoundment. There are several means by which the presence and location of underground mine workings can be investigated. However, their implementation—within reasonable economic constraints—may not be able to guarantee that all mining surrounding the entire perimeter of an impoundment will be accounted for. A suite of investigative methods and sound judgment based on site-specific circumstances would provide the best determination where the coal has been mined. It is the responsibility of the company requesting the permit to present a reasonable case that they have thoroughly investigated whether there are mine workings proximate to the impoundment.

(4) What do we know about the flowability of fine refuse slurry in active, inactive, and capped impoundments?

When examining the potential for breakthrough of a slurry impoundment into underground mine workings, we typically look at two components: the failure mechanism leading to breakthrough and the potential for the slurry to flow through the mine workings. In considering how best to avoid a breakthrough, assumptions must be made regarding the potential for slurry to flow. It would be prudent to minimize the uncertainty regarding slurry flowability so that estimates of downstream areas that would be affected are conservative, but also as realistic as possible.

Factors that affect flowability of slurry within an impoundment include: (1) Characteristics of the slurry, e.g. its moisture content, void ratio, particle grain size distribution, and contractive vs. dilative behavior under stress;⁶ and (2) the amount of surcharge driving the slurry through potential conduits into the mine.⁷

In the case of a breakthrough into a known underground mine, the driving force can be more readily estimated (based on the depth of slurry to a hypothetical breakthrough point) than can the flowability of the slurry. This is because the flow characteristics of the slurry are affected by numerous variables including, but not limited to:

- The manner in which the impoundment is constructed (e.g. the rate of construction in the case of an upstream embankment will affect the rate of consolidation of the underlying slurry and its consequent susceptibility to flow in the event of a breakthrough);

⁶ A soil is contractive if it tends to reduce in volume when sheared. When the soil is saturated, contraction results in high pore-water pressures within its matrix and consequent flowability.

⁷ The size and roughness of the potential conduits of flow (e.g. the opening to the mine and the entries in the mine) is a third factor only if the slurry behaves as a Newtonian fluid. As discussed below, there is a consensus among engineers working with waste impoundments that fine-refuse slurry is Bingham-Plastic, i.e. a type of non-Newtonian material. Newtonian flow would occur only if a breakthrough resulted in piping of the slurry by clear water (in an active impoundment) as opposed to the slurry flowing en-mass.

- The chemical and physical characteristics of the “impurities” of the mined coal seam (e.g. the resulting fine refuse may be relatively resistant to flow due to the impurities containing cementitious compounds or angular particles); and
- The effectiveness of internal drainage structures, impoundment foundation permeability, and location of aquifers relative to the profile of the basin.

Consequently, flow characteristics of the slurry vary between impoundments, and with time and location within a given impoundment. There are too many variables to allow any standard assumptions to be made about slurry flowability. Impoundments must be designed with the assumption that the slurry will be flowable. This assumption should be considered valid until proven otherwise through site-specific investigation and testing during construction.

It is important to note that there currently are no official requirements or guidelines pertaining to testing the properties of impounded slurry located at a distance in the basin from the embankment. Considerations and methods for determining properties of the fine coal refuse slurry comprising part of an upstream-constructed embankment (see Figure 6) are addressed extensively in the Engineering and Design Manual provided by MSHA (D’Appolonia, 2009, Chapter 7). However, the discussion focuses on the strength-related properties of the slurry impacting embankment stability. The properties of fine refuse slurry near mine barriers can be significantly different from slurry partially comprising the embankment for two reasons. First, as Figure 6 illustrates, slurry is normally discharged into the basin along the waterline on the upstream slope of the embankment. Larger refuse particles settle out near the discharge point (forming part of the embankment) while finer particles remain in suspension as the slurry flows further into the basin. Second, the slurry underlying the upstream portions of the embankment will typically dewater more quickly than the basin material. This occurs because (1) the slurry tends to be compressed by the weight of the overlying embankment components and (2) it is proximate to more permeable coarse refuse and internal drainage structures constructed to control the piezometric surface within the embankment. The MSHA manual includes information and guidance on topics pertinent to preventing impoundment breakthroughs; such as identification of underground mines, calculation of mine-barrier stability, and construction of artificial mine barriers. However, the issue of the flowability of basin slurry away from the embankment is not addressed.

In 2005, OSM conducted a study into the flowability of impounded fine coal waste (Michael et al., 2005). The purpose of the study was to review current knowledge applicable to the potential flow characteristics of the slurry. The review explored two interrelated issues: (a) given the occurrence of a breakthrough event that would result in a potential flow conduit between an underground mine and an impoundment, should we expect fine refuse to flow into the mine? And, (b) if the refuse would flow, what would be the nature (e.g. velocity and extent) of that flow?

Following interviews and a literature review, the investigators could not make assurances that fine refuse in all (or even the majority of) existing refuse impoundments would not flow into an underground mine should a breakthrough occur. The main basis for their concern was the slow rate of consolidated strength development that takes place in the slurry. They were also

concerned about the influence of pore water pressure in the fine refuse and potentiality of static liquefaction; and the sense that at least some impoundments are not constructed to adequately allow drainage of excess water from the fines. Another reason for concern was a property identified with other types of slurry in the literature (e.g. coal-water mixtures and oil-sands tailings), known as thixotropy (Suthaker et al., 1997 and Usui, 1998). Thixotropy is the property of some substances to behave like a fluid when worked or agitated and settle to a semisolid state when at rest. For clays, the mechanism of the softening is thought to include destruction of orderly arrangement of water molecules and ions in the adsorbed layers of the soil, damage to the structure acquired during sedimentation and consolidation, and realignment of clay plates (Terzaghi et al, 1996). The authors of the 2005 report included a discussion on thixotropy as a potentially relevant factor affecting the flowability of impounded slurry.

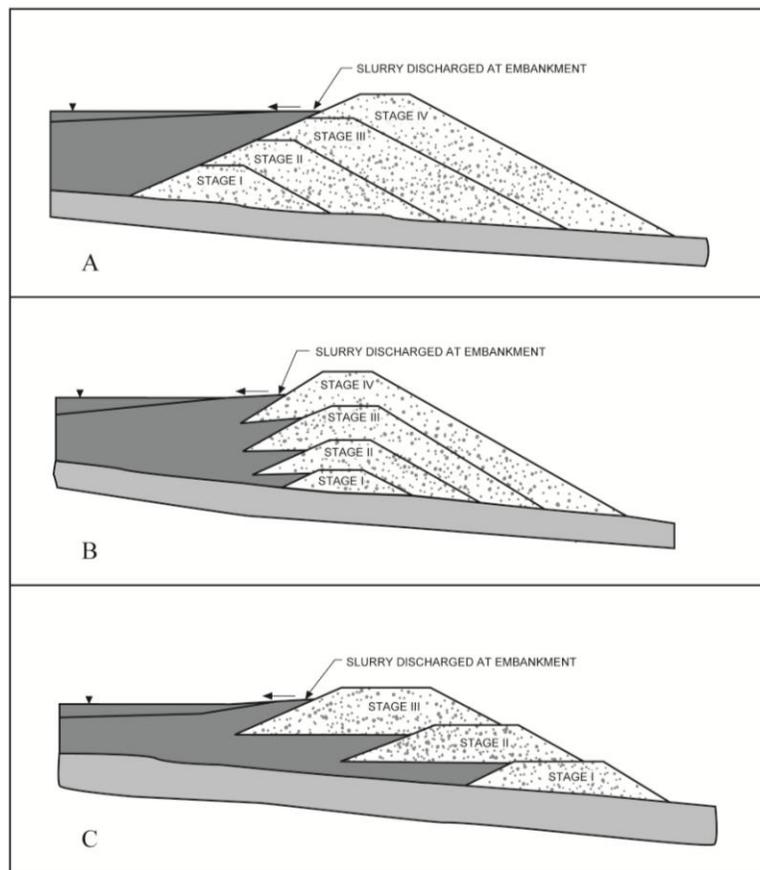


Figure 6: Schematic cross sections of downstream (A), centerline (B), and upstream slurry (C) impoundment construction methods. The fine refuse slurry is shown in dark gray. (Diagrams are from D’Appolonia, 2009.)

The 2005 investigation was primarily concerned with slurry in active and uncapped inactive impoundments. A subsequent 2008 study concluded that an underground mine breakthrough during impoundment capping (Figure 7) is a theoretical but remote possibility (Michael et al., 2008). The authors of that assessment also expressed the strong opinion that reclaiming (which includes capping) a fine coal waste impoundment generally decreases the risk of breakthrough. Ideally, the process eliminates clear water above the slurry, to some extent, and decreases surface

water infiltration into the basin. Consequently, hydrostatic pressure on mine barriers and the flowability of the material should reduce.



Figure 7: Impoundment being capped with surface mine spoil.

However, capping an impoundment does not immediately reduce nor necessarily eliminate breakthrough potential. An impounded coal waste slurry may form a clay outer layer with extremely low hydraulic conductivity as consolidation (i.e. dewatering and densification) occurs. If the outside surface of the three-dimensional mass of slurry in an impoundment dewateres first (e.g. into more permeable rock strata), an unintended artificial liner may form. A continuous liner can form around the ‘soup-bowl’ and prevent interior dewatering. Consequently, the majority of the fines in the basin may retain sufficient moisture to be flowable. Evidence for this phenomenon is exemplified in Figure 8, which is a graph from an impoundment permit file. The graph compares the liquid limit and moisture content of fine refuse slurry at various depths in an impoundment in eastern Kentucky. The liquid limit of six slurry samples was measured between 37 and 41 percent. The graph assumes 37 percent throughout the column.⁸ Most moisture content values approximate the liquid limit. Assuming the slurry is saturated at depth, the anomalously low moisture contents (of 26 and 14 percent) at the bottom of the pool indicate a significant reduction in the material’s void ratio, and hence hydraulic conductivity. The reduced void space likely results from the transmission of pore water into the adjacent rock and consequent consolidation of the refuse.

The soup-bowl effect can also result from reclamation practices. For instance, Burda (2010) points out that the Pennsylvania Department of Environmental Protection (PADEP) requires designed liner systems for all coal waste slurry impoundments to prevent surface and groundwater impacts from refuse leachate. Historically, the PADEP utilized constructed clay liners, but now requires the use of manufactured liner systems (e.g. coated geosynthetic clay liners). Burda reports that recent experience seems to show that even the use of constructed clay

⁸ Although the value of 37 percent is the lowest test result, to apply it to all points where the moisture content was measured is not necessarily conservative, since only four samples were tested for liquid limit.

liners has resulted in reduced rates of fine coal waste consolidation. He suggests that the State will likely see even slower rates of consolidation and dewatering with the use of manufactured liner systems, which are 2 to 3 orders of magnitude less permeable than clay. The authors of this report recognize the value of protecting ground water from contamination and do not question PADEP's policy with respect to the liners. Nevertheless, the potential unintended consequence of reduced slurry consolidation highlights the need for precautionary measures against breakthrough.

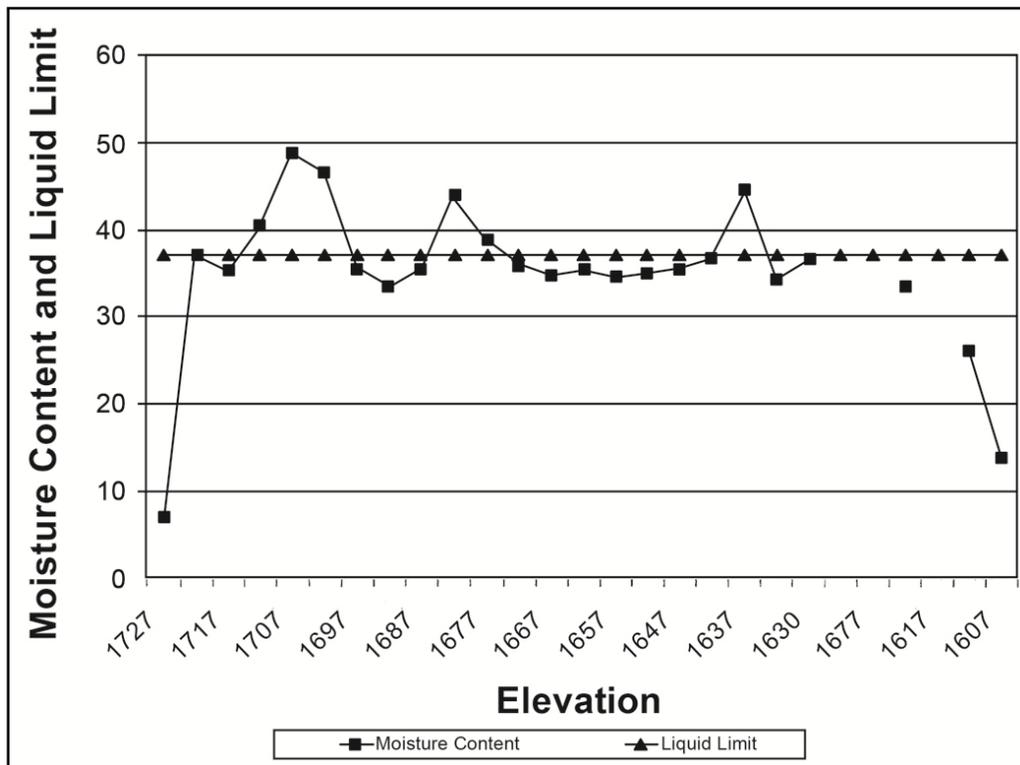


Figure 8: Graph from impoundment permit application comparing the distribution of fine refuse slurry moisture content with depth in the impoundment basin with an assumed liquid limit value of 37 percent (based on four samples). Note low moisture contents starting at elevation 1607 feet msl (and near the bottom of the basin).

Some impoundments are capped specifically because of breakthrough concerns but are then converted to slurry cell structures for continued refuse disposal in the same location (Figures 9 and 10). Slurry cells are small impounding structures holding fine refuse separated by dikes of compacted coarse refuse. They are constructed in layers, the total depth of which can equal or exceed that of the original impoundment. The primary purpose of the cells is for operators to reduce the regulatory hazard-potential classification of the structure so that less stringent design criteria can be employed. Cell construction also limits the volume and flowability of slurry that would be released (relative to an active impoundment of equal size) should a breakthrough into an underground mine occur. However, capping the original impoundment and placing slurry cells on top of the capped area does not necessarily diminish breakthrough potential from the original impoundment. Surcharge from the stacked slurry cells can still increase hydrostatic

pressure in the fine refuse slurry below the impoundment cap. Water from the overlying slurry cells can also migrate into the abandoned slurry pool below.

The 2005 slurry flowability study did not find any empirical data on the potential flow characteristics of coal waste. It became apparent that the flow behavior, or rheology, of viscous fluids is influenced by a complex interrelationship among a number of factors. There was some indication that one particular flow model, called “Bingham Plastic,” may be applicable to coal waste flow. The nature of this non-Newtonian flow (in comparison with other flow models) is graphically illustrated in Figure 11. Bingham-Plastic fluids exhibit a yield stress; that is, they do not begin to flow until a critical shear stress is reached. Once the yield stress is reached, material reacts linearly to increasing shear stress.⁹

The 2005 study report emphasized that a model is only a relationship among constants and variables, and cannot tell us how fine refuse in a specific impoundment—or even in different parts of the impoundment— might respond to an opening to an underground mine.



Figure 9: Aerial photograph of slurry cells.

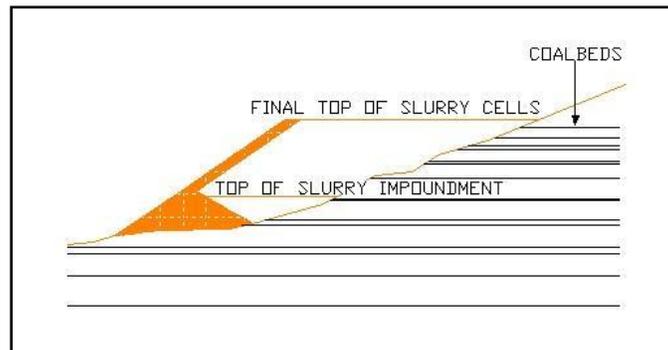


Figure 10: Schematic of slurry cell construction above a capped impoundment.

⁹ Various models of fluid flow are discussed in greater detail in Michael et al. (2005).

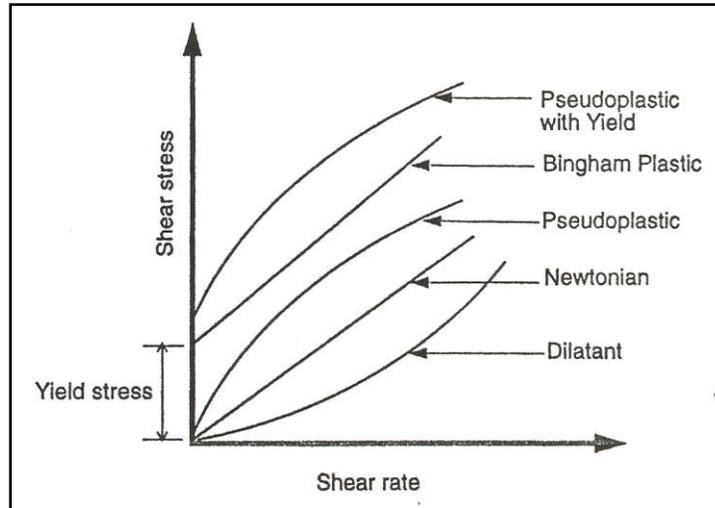


Figure 11: Basic models of rheological behavior (from Kawatra et al., 1995).

(5) How can we test the impounded slurry for its flow characteristics?

What type of testing, and for what material properties, will provide the most useful information? Would it make sense to perform standard penetration, cone penetrometer, or vane shear testing at multiple locations and depths in an impoundment, to define an average, or maximum flowability for the slurry? Or would it make sense to use some sort of index test to define a dividing line between flowable and non-flowable material?

For the breakthrough scenario, since we are concerned with downstream impacts occurring only if material within the impoundment is flowable, it would seem to be appropriate to base our decisions on which type of material we are dealing with: flowable or non-flowable.

Fortunately, the need to know whether soil materials are flowable has applications other than the slurry impoundment breakthrough issue. As a result, test methods have been developed to make this distinction. In particular, the liquid limit test (ASTM D4318-current version) was developed to define “The moisture content above which a soil readily becomes a liquid upon stirring.” The liquid limit of a soil sample can be compared to its moisture content to determine whether it would behave as a liquid when agitated.

The test for liquid limit has been successfully used by engineers for decades to determine the moisture content above which soils can behave as liquids, and below which they behave as plastic solids. Both it and several ASTM methods for determining moisture content are simple and economical relative to other relevant techniques. If, with sufficient sampling and testing, the moisture content of the saturated material within an impoundment is found to be less than its liquid limit, it should be reasonable to assume that the fine refuse is not flowable and the impoundment’s breakthrough potential has been eliminated. Unless a finding that the material will not flow is established, through the use of this or some other relevant test, the material

should be considered flowable and restrictions pertaining to future use of the facility and future mining beneath the impoundment should be applied.

The number of liquid limit tests required would depend on the uniformity of the materials. Tests at several locations and at multiple depths (i.e. near the bottom, mid-depth and near the surface) should be performed. If test results vary significantly, more tests may be prudent. Once the liquid limit is established (lowest test result) only moisture content tests need be performed. In lieu of such testing, the material should conservatively be considered to be flowable.

(6) What precautions and restrictions should we recommend to prevent breakthroughs?

Fine coal waste slurry breakthroughs into underground mines can take place via “punch-ins” through weak horizontal mine barriers, stress relief fractures, and sink holes or sag-subsidence cracks in thin vertical barriers. Concerns relating to potential breakthroughs center on two unknowns. One of those is site-specific in nature: underground mines that occur beneath or adjacent to the footprint of an impoundment and the thickness and competence of the horizontal and vertical barriers between the mines and the impoundment. The other unknown, whether impounded coal waste slurry remains in a liquid state, or can be changed into such a state through liquefaction or thixotropic agitation, is not known generally, let alone site-specifically.

A peer review of the 2005 slurry flowability report included several recommendations for further assessment of fine refuse slurry flowability, including: an in-depth review of the rheology of other materials (e.g. mud, ceramics, refractory clays, and pharmaceuticals); lab and in-situ testing of slurry consolidation, shear strength, liquefaction potential, and rheology; and modeling of coal waste slurry response to breakthroughs. Recommendations for breakthrough prevention measures and requirements and research were also provided by peer reviewers of this report (see the Appendix). Finally, proposed remedies to the slow rate of consolidation in gold and oil-sands tailings that may be applicable to coal waste slurry were noted during a post-2005 report assessment of the literature (Michael et al., 2010). Researchers found that not segregating between coarse and fine tailings (Wong et al., 2008) or incorporating waste rock, such as mine spoil, with the tailings slurry (Wickland and Wilson, 2005) tended to increase strength and reduce water retention of the material relative to fine tailings alone.

The authors of this paper agree that the suggested studies would be instrumental in providing a better understanding of the magnitude of the problem and of factors affecting slurry flowability. Many of the recommended policies and solutions are also worthy of serious consideration. The authors also think that there are preventative site-specific construction practices applicable in the short term that should be evaluated:

- Where, after careful site investigation, there remains uncertainty whether thick coal seams intersecting the impoundment footprint have been underground mined within a “safety zone,” the coal seams can be surface mined some distance into that zone and designed artificial barriers can be constructed on the benches against the highwalls. That way a natural barrier with unknown properties (dimensions, material strength, etc.) is

replaced with a constructed barrier with known properties that does not rely on any remaining coal barrier for support;

- Where there are plans to (a) increase the size of active impoundments (beyond original designs), (b) construct slurry cells or excess spoil fills on top of capped impoundments, or (c) undermine the impoundments, the impounded slurry should be sampled and tested to ensure the material's water content is not above its liquid limit.

(7) If an underground mine close to an impoundment is below drainage, should we still be concerned about breakthrough potential?

Coal seams that do not naturally outcrop are termed “below drainage.” Below drainage underground mine workings may be in hydraulic connection with the slurry through fractures or subsidence sinkholes. Regarding the possibility of breakthrough of a coal waste slurry impoundment into below drainage underground mines, the engineering justification for considering the breakthrough potential to be minimal is often a statement to the effect that “the mine is entirely below drainage, and the breakthrough volume will be contained within the mine”. While it may be true that the slurry will be contained within the mine, it is possible that a mine below drainage is completely or partially flooded. Should a breakthrough into a flooded underground mine occur, any slurry entering the mine will tend to displace an equal volume of water from the mine (Figure 12).

Considering the case of isolated mine workings, the mine pool elevation will rise until the pool water discharges from one or more openings or until equilibrium between the mine pool and impoundment is established. In the case where a mine is already discharging prior to the breakthrough due to the presence of artesian conditions, a breakthrough could result in an increase in discharge volume equal to that of the slurry entering the mine. Should no man-made openings exist, flow will occur through fractures or the water/slurry will become pressurized, possibly resulting in a breakout upward from the mine to the surface. Discharges/blowouts may occur at any elevation below the impoundment pool elevation. The likelihood of a breakout would be greatest at points where the mine workings are nearest to the ground surface in the overlying valleys. Should the mine be interconnected with other workings, the possibility of increased discharges or blowouts at locations some distance from the impoundment should be considered. Even if a blowout does not occur, the breakthrough of the slurry may contaminate local aquifers in hydraulic connectivity with the coal seam.

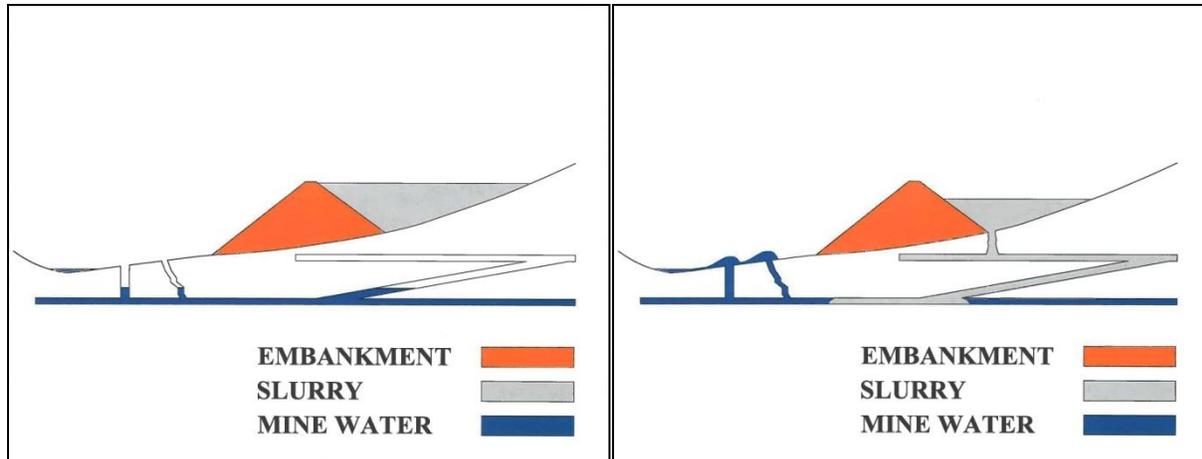


Figure 12: Schematic longitudinal sections of flooded below-drainage mine (left) and artesian mine-water breakouts in reponse to slurry breakthrough into the mine (right).

SUMMARY AND CONCLUSIONS

In order to ensure that the potential of fine coal waste slurry breaking through into underground mines is minimized, the impoundment designer and operator should identify: all minable coal seams intersecting and underlying an impoundment footprint; all adjacent and underlying underground mines and the competence of horizontal and vertical barriers between them and the impoundment; and the flowability of the impounded fine refuse.

Toward this end, the authors offer the following responses to the questions addressed in this paper:

1. What is a mineable seam? To be certain that all seams in the vicinity of major impoundments have been included in a breakthrough analysis, all coal seams with a reported or known thickness equal or greater than 24 inches should be investigated for past underground or auger/highwall mining activity. Alternatively, they can be considered mined within a designated safety zone, and breakthrough prevention measures can be designed and implemented.
2. How available are maps of past mining activity and how reliable are they? With respect to mine outcrop barriers, there are mine maps available that can be employed to estimate distances between the boundary of an impoundment and the closest reach of the mines. However, there are numerous mines without maps; or with maps that are inaccurate or not up-to-date. Investigations into the presence of underground mines proximate to an impoundment footprint and the competence of mine barriers should never rely solely on information provided by mine maps or their absence.
3. How can the possible presence of underground mine workings be investigated? There are several means other than the study of mine maps by which the presence and location of underground mine workings can be investigated. These include: interviews with experienced miners and local residents; surface reconnaissance of outcropping coal

seams and rock cover for mine adits and evidence of mine subsidence; drilling; and (possibly) geophysical surveying. However, employing these techniques, within reasonable economic constraints, may not be able to guarantee discovery of all mining surrounding the perimeter of an impoundment. In cases where seams in question are notably thick, known to be of high quality, or have a history of being mined in the vicinity, a conservative approach to investigating and addressing breakthrough potential would be warranted. In these cases, more expensive techniques, such as horizontal drilling should be considered.

4. What is known concerning the flowability of fine coal waste slurry in impoundments? In the absence of appropriate engineering test data, no assurances can be made that impounded fine refuse in all (or even the majority of) existing coal waste impoundments would not flow if there were a breakthrough into an underground mine. Basis for the authors' concern include the material's high void ratio; low permeability; and consequent high water retention and the slow rate of consolidated strength development. These conditions potentially are conducive to flow in a breakthrough scenario.
5. How can the potential flowability of impounded fine coal waste slurry be determined? Capping of an impoundment should not be considered sufficient to eliminate the potential for breakthrough into underground works. The properties of the impounded coal waste slurry should be tested to ensure the slurry is no longer flowable. One method to determine flowability is to compare the moisture content of sampled slurry with its liquid limit. The test for liquid limit has been routinely and successfully used by engineers for decades to determine the moisture content above which soils can behave as liquids, and below which they behave as plastic solids. Both the liquid limit and several methods for determining moisture content are simple and economical relative to other pertinent techniques.

The number of liquid limit tests required would depend on the uniformity of the materials. Tests at several locations and at multiple depths (e.g. near the bottom, mid-depth, and near the surface) should be performed. If test results vary significantly, more tests may be prudent. Once the liquid limit is established (lowest test result) only moisture content tests need be performed.

6. What precautions should be taken to minimize the potential for slurry impoundment breakthrough into underground mine workings? Recommendations for further assessment of fine refuse slurry flowability and control of flowability have been made in the peer reviews of the 2005 study report and this document. They include: an in-depth review of the rheology of other materials (e.g. mud, ceramics, refractory clays, and pharmaceuticals); lab and in situ testing of slurry consolidation, shear strength, liquefaction potential, and rheology; modeling of coal waste slurry response to breakthroughs; and adding admixtures to the fine refuse or mixing fine refuse with coarse refuse or mine spoil to increase slurry strength.

Special studies would be instrumental in providing a better understanding of the magnitude of the breakthrough-potential problem and of factors affecting slurry

flowability. However, there are also readily available preventative site-specific construction practices that should be considered. Where there remains uncertainty whether thick coal seams intersecting the impoundment footprint have been underground mined within a “safety zone,” the coal seams can be surface mined some distance into that zone; and designed artificial barriers can be constructed on the benches against the highwalls. Also, where there are plans to (a) increase the size of active impoundments (beyond original designs), (b) construct slurry cells or excess spoil fills on top of capped impoundments, or (c) undermine the impoundments, the impounded slurry can be sampled and tested to ensure the material’s water content is not above its liquid limit.

7. Do designers need to be concerned about breakthrough into underground mine workings if the workings are below drainage? Designers and operators of coal waste slurry impoundments should still be concerned about breakthrough potential even where underground mines proximate to an impoundment are below drainage. The mine workings may be interconnected with other works, and consequently the possibility of increased discharges or blowouts at locations some distance from the impoundment should be considered. Even if a blowout does not occur, the breakthrough of the slurry may contaminate local aquifers hydraulically connected with the coal seam.

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¹⁰ The table of peer reviewers should not be interpreted to mean that they agree with all positions expressed in this technical position paper.

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