Potential of Breakthroughs of Impounded Coal Refuse Slurry into Underground Mines

PETER R. MICHAEL[1]

U.S. Office of Surface Mining Reclamation and Enforcement, 3 Parkway Center, Pittsburgh, PA 15220

MICHAEL W. RICHMOND

U.S. Office of Surface Mining Reclamation and Enforcement, 1027 Virginia Street, East, Charleston, WV 25301

MICHAEL J. SUPERFESKY

U.S. Office of Surface Mining Reclamation and Enforcement, 604 Cheat Road, Suite 150, Morgantown, WV 26508

DONALD E. STUMP, JR.

U.S. Office of Surface Mining Reclamation and Enforcement, 3 Parkway Center, Pittsburgh, PA 15220

LISA K. CHAVEL

U.S. Army Corps of Engineers–Chicago District, 111 N Canal Street, Suite 600, Chicago, IL 60606

Key Terms: ***Impoundment, Slurry, Refuse, Mining, Coal, Breakthrough***

ABSTRACT

On October 11, 2000, an estimated 306 million gallons of water and fine coal refuse slurry broke through a bedrock barrier from an impoundment in Martin County, eastern Kentucky, into an adjacent underground mine. Approximately 260 million gallons of the water and coal slurry discharged from two underground mine portals and affected over 75 miles of streams in Kentucky and West Virginia. As a result of this and several other breakthroughs over just half a decade, the U.S. Office of Surface Mining Reclamation and Enforcement (OSM) and other institutions undertook investigations to assess the causes of the events, the potential for additional breakthroughs in the future, and available methods for preventing them. In addition to needed improvements in the design, construction, and inspection of the facilities, the studies have addressed issues pertaining to the flow characteristics of refuse slurry, not only in impoundments still receiving pumped slurry, but also in "idle" and reclaimed facilities. Related questions concern: (1) the effects on breakthrough potential of the impoundment abandonment process and construction of slurry cells on top of capped structures; and (2) appropriate measures and available methods that may be used to ensure that underground mines adjacent to or underlying impoundments are known and accurately located. Current information on the engineering properties of coal refuse in existing facilities provides no assurance against fine refuse flowability during any stage in the impoundment construction and reclamation process or after reclamation has been completed. Due to this uncertainty, thorough site investigations and conservative measures in design, construction, reclamation, and quality control are of paramount importance.

INTRODUCTION

A concern shared by many engineers, geologists, and mine inspectors familiar with coal refuse slurry impoundments is related to the common occurrence of underground mine workings adjacent to or beneath the impoundments: the potential for slurry breakthroughs into mine works and subsequent breakouts into surface waterways. Events of this nature can endanger underground mine workers and downstream inhabitants, and negatively impact local

[1]Corresponding author: Phone: 412-937-2867; fax: 412-937-3012; email: pmichael@osmre.gov.

groundwater resources and stream and river ecosystems. This concern is particularly applicable to impoundments within the steep-slope topography of Central Appalachia where the structures rest on inclined slopes within narrow hollows and consequently are in contact with numerous coal beds.

On October 11, 2000, a combination of coal refuse slurry and water from the Big Branch impoundment in Martin County, Kentucky, broke through into an underground mine and subsequently discharged into the receiving streams (Figure 1). An estimated 306 million gallons of water and coal refuse slurry drained from the impoundment into the adjacent underground mine. Approximately 260 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.

Fortunately, the 2000 event remains the last breakthrough to have occurred to date. Other documented breakthroughs, in addition to the 1994 event at Big Branch, include three breakthroughs in Virginia in 1996. Owing to the short time period over which these events took place and the severity of effects from the one in 2000, several investigations were undertaken with the ultimate goal of preventing future impoundment breakthroughs. A prominent study among those investigations was "Coal Waste Impoundments" by the National Research Council (NRC, 2002), which examined current engineering practices and standards applied to the refuse impoundments, explored ways to improve underground mine location relative to the impoundments, and evaluated alternative technologies that could reduce the amount of coal refuse generated and allow productive use of the material.

Studies that specifically focused on the Big Branch impoundment were conducted by the U.S. Department of Labor, Mine Safety and Health Administration (U.S. MSHA, 2001) and the U.S. Department of the Interior, Office of Surface Mining Reclamation and Enforcement (U.S. OSM, 2002). Both studies evaluated on-site conditions and problems with construction and regulation enforcement practices that led to the failure. MSHA administers the provisions of the Federal Mine Safety and Health Act of 1977 (FMSHA) to enforce compliance with mandatory miner safety and health standards. OSM was established by The Surface Mining Control and Reclamation Act of 1977 (SMCRA) to oversee the enforcement of surface coal mining and reclamation regulations from the standpoint of public safety and environmental protection. The findings of the studies are largely in agreement. However, the studies' conclusion that the mechanism of the 2000 breakthrough involved piping through weathered rock, colluvium, and loose artificial barrier material from the underground mine into the impounded slurry and overlying layer of clear water was challenged. Thacker (2002) and Hagerty and Curini (2004) used finite-element seepage analysis in an attempt to disprove the piping theory and proposed, by elimination, that the thin and weak bedrock mine barrier succumbed to hydrostatic pressure.

Additional studies in response to the breakthrough concern were carried out by OSM staff at the request of management and resulted in internal position papers. Michael et al. (2005) conducted a survey of current knowledge pertaining to the flow properties of impounded refuse (henceforth referred to as the "2005 study"). Under the assumption that at least some of the impounded slurry may be in a flowable state, Michael and Chavel (2008) (henceforth referred to as the "2008 study") evaluated the potential for breakthroughs resulting from additional surcharges imposed on mine outcrop barriers during part of the impoundment-reclamation process, i.e., the placement of cap material over the slurry-containing "basin" of the impoundment.

This paper presents a brief overview of the construction and reclamation of coal refuse slurry impoundments and elaborates the authors' concerns pertaining to the potential for future breakthroughs of fine coal refuse slurry into adjacent or subjacent underground coal mines.

COAL REFUSE IMPOUNDMENTS

"Coal refuse" is waste that results from the preparation of mined coal for energy production. Some of the material is placed in dry landfills, but most is disposed in slurry impoundments. In the latter case, refuse is first separated into relatively coarse and fine fractions. The coarser material (grain sizes ranging from 0.1 to 70 mm) is kept relatively dry and is used to construct the embankment of the

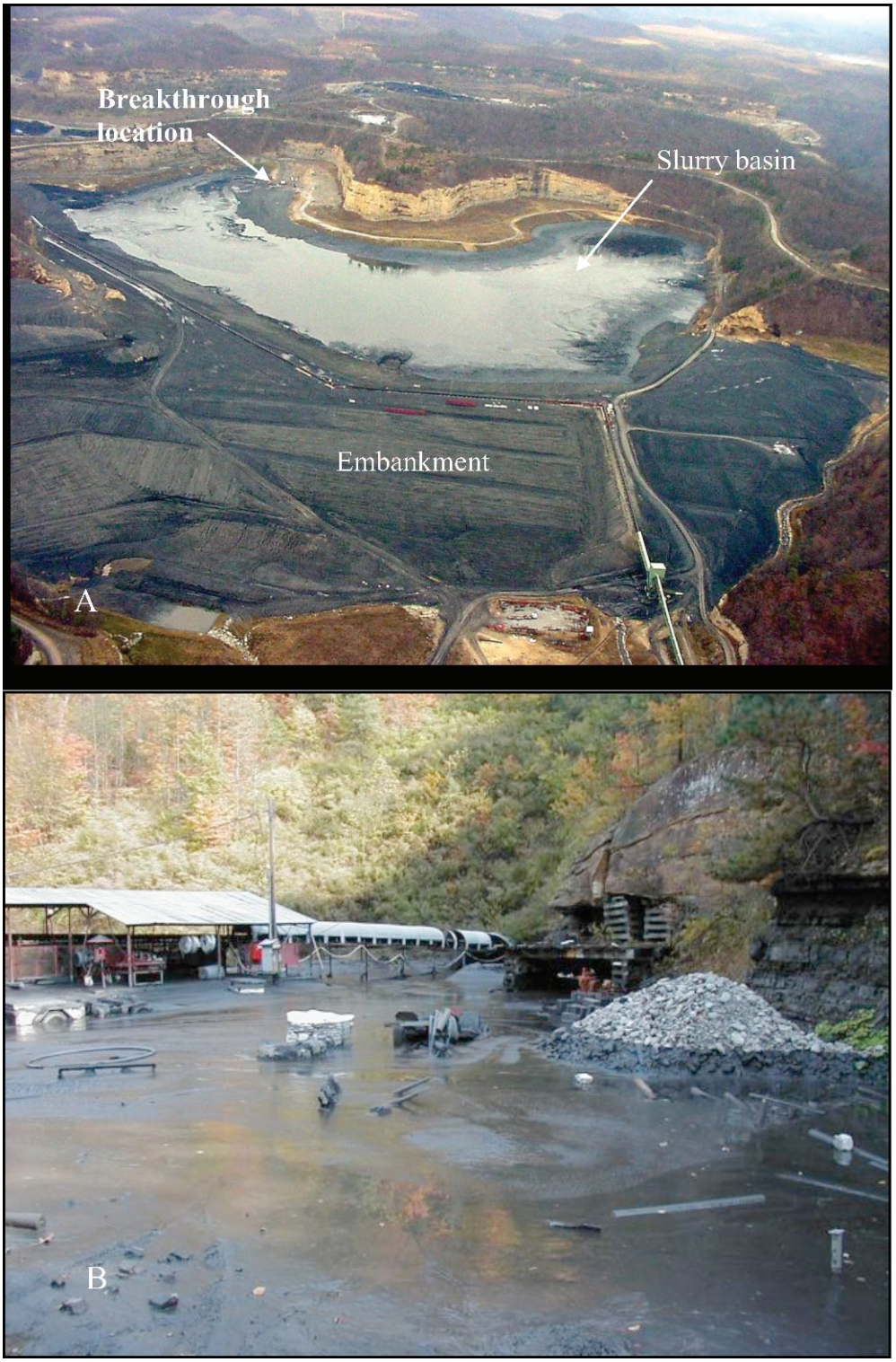

Figure 1. Post-breakthrough overview of Big Branch slurry impoundment (A) and ground-level view of one of two portal breakout points (B).

impoundment. The fine fraction of the refuse (from 0.001 or less to 20 mm) is mixed with water and transported in pipes as slurry to the impoundment "basin."

The proportion between the dry coarse refuse and fine refuse slurry constituting an impoundment depends on the relative amounts of the materials produced at the contributing preparation plant(s) and

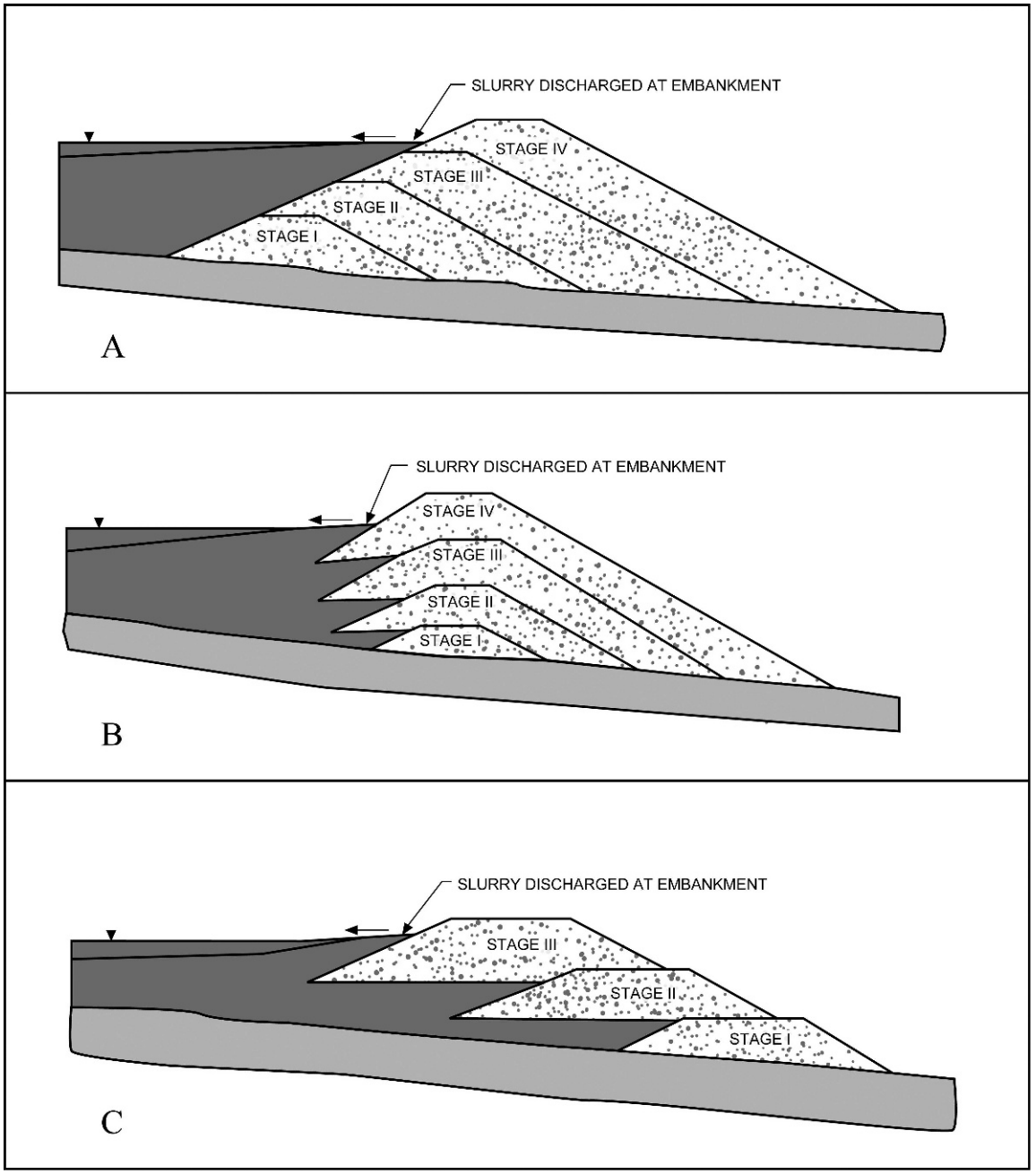

Figure 2. Schematic cross sections of downstream (A), centerline (B), and upstream (C) slurry impoundment construction methods. (Diagrams are from D'Appolonia, 2009.)

commonly governs the way in which the impoundment is constructed. Figure 2 is a schematic diagram of the "downstream," "upstream," and "centerline" construction methods. Many impoundments amount to a hybrid among these three construction methods. It is important to note that there generally is no preconceived final design for these structures. More often than not, coal refuse slurry impoundments are periodically redesigned, i.e., enlarged to accommodate additional refuse as it is generated at the preparation plant(s). In the narrow hollows of steep-slope Appalachia, this enlargement of impoundments requires the structures to increase in size vertically and the impounded slurry to deepen, thus incrementally adding pressure on mine outcrop barriers.

MSHA and OSM regulatory requirements for the engineering design, construction, maintenance, inspection, and elimination of slurry impoundments are provided in Title 30 of the Code of Federal

Regulations (30 CFR), Section 77.216 and Section 780.25, respectively (U.S. Office of the Federal Register, 2007). Detailed guidance is available in MSHA's *Engineering and Design Manual—Coal Refuse Facilities* (D'Appolonia Engineering, 2009). The latter document includes information and guidance pertinent to on-site reconnaissance of foundation conditions—including the identification of underground mines—and evaluation of and prevention against mine subsidence and breakthrough potential (see Chapter 8). Preventative techniques are designed to ensure that adequate horizontal barriers (i.e., outcrop barriers) and vertical barriers (barriers above mines that lie below the bottom of the impoundment) exist or that barriers are improved when necessary (by back-stowing underground mines or covering the outcrops of mined coal beds with a seepage barrier).

The status of a coal refuse slurry impoundment may be active (i.e., still receiving coal refuse slurry from an active coal-cleaning operation), inactive, or reclaimed (Figure 3). Those structures that are inactive may be under a current permit or "orphaned." Orphan impoundments are those for which there is no responsible mine operator accountable for the structure and where the impoundment has not been properly reclaimed under FMSHA and SMCRA standards. Generally, inactive impoundments constructed prior to the passage of the SMCRA are not reclaimed unless they are re-permitted or they present an imminent safety hazard to the public or harm to the environment. Impoundments on bond-forfeiture sites may not be reclaimed if there is insufficient bond or insurance money to cover the cost of the work. Most impoundments that are reclaimed are capped with coarse refuse or surface mine spoil and revegetated. Some have been converted into ponds or lakes for recreational use under the SMCRA experimental practice program. Other impoundments are re-mined. Still others are capped when there are concerns that a breakthrough may occur, but they may also be converted to slurry cell structures to allow for additional refuse disposal.

We are unaware of any national or regional databases that have complete and up-to-date information on the status or condition of all existing fine coal refuse impoundments. As of the 2008 study, the MSHA National Impoundment and Refuse Pile Inventory included a total of 632 structures that met the size criteria for MSHA jurisdiction (see 30 CFR 77.216 (a) for size criteria). However, information on the status of these impoundments was not yet complete. The 2008 study did obtain the following information directly from three Appalachian state regulatory authorities: out of a total of 113 fine coal refuse impoundments in Kentucky, six have been reclaimed; only a "handful" from a total of 110 West Virginia impoundments have been capped; and there are 17 active fine coal refuse impoundments, one pre-law inactive impoundment, and zero reclaimed impoundments in Virginia.

THE BREAKTHROUGH ISSUE

Principle Unknowns

Fine coal refuse slurry breakthroughs into underground mines can take place via "punch-ins" through weak horizontal mine barriers or through sinkholes 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: the location of underground mines that occur beneath or adjacent to the footprint of an impoundment (see Figure 4), and the consequent thickness of the horizontal and vertical barriers between the mines and the impoundment. The other unknown is whether impounded fine coal refuse slurry remains in a liquid state or can be changed into such a state through liquefaction or thixotropic agitation.

Mine Barriers

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 that are not located or are not accurately located on mine maps.

Based on past and present underground mining technology, coal beds that are approximately 2 ft or more thick are potentially minable underground. In cases where there are no records of adjacent mining in seams that intersect the impoundment, there are other methods of mine or mine-void detection, including interviews with experienced miners and the local population, visual field reconnaissance for undocumented mine entries, horizontal drilling, and shallow-subsurface geophysics. However, the employment of these methods—within reasonable economic constraints—cannot guarantee that all mines surrounding the entire perimeter of an impoundment will be accounted for. For mines below the impoundment, barriers above known or possible workings can easily be established through vertical drilling. However, detection of undocumented mines can be even more problematic in comparison to adjacent mines since mine adits may not be proximate to the impoundment site, drill holes may penetrate barriers between underground mine panels or mine pillars, and geophysical methods are more costly and less effective

Figure 3. Comparison between an active (A) and reclaimed impoundment (B).

with depth. It is noteworthy that even where mines may be too deep for potential formation of sinkholes or wide subsidence tension cracks, ground movement resulting from the failure of mine pillars could simultaneously destabilize shallower mine barriers and mobilize impounded slurry. Consequently, accurate mining information for relatively deep coal beds below an impoundment is also important.

It is also important to note that even when coal mines have been identified and accurately located relative to an impoundment, the competence of the mine barriers can be over-estimated. This is what in

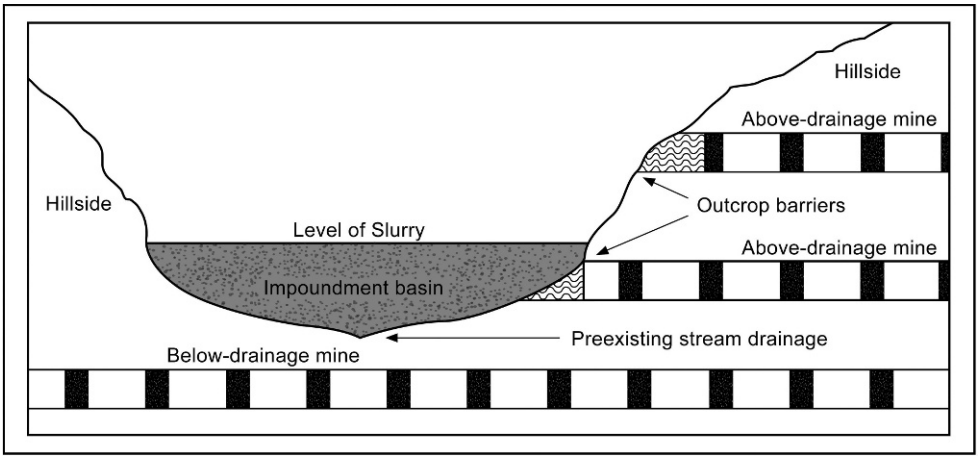

Figure 4. Schematic depiction of a slurry impoundment basin and adjacent and subjacent coal mine workings. (Diagram from NRC, 2002.)

fact happened at the Big Branch impoundment (U.S. OSM, 2002).

Slurry Flowability

Uncertainties pertaining to the presence of underground mines, conditions of mine barriers, and stability of mine pillars would not be as significant as they are if we were confident that deposited fine refuse slurry consolidated, through dewatering and densification, into a statically and dynamically stable material in a predictable time frame. However, the results of the 2005 study provided no such assurance.

The 2005 investigation was primarily concerned with slurry in active and uncapped inactive impoundments. The subsequent 2008 study concluded that an underground mine breakthrough during impoundment capping is a theoretical but remote possibility. The authors of that assessment also expressed the strong opinion that reclaiming (which includes capping) a fine coal refuse impoundment generally decreases the risk of breakthrough. The process eliminates clear water above the slurry (Figure 5), dewaters the fine refuse to some extent, and decreases surface water and groundwater infiltration into the reservoir. Consequently, hydrostatic pressure on mine

Figure 5. Top of dewatered slurry being capped with mine spoil (from Shinavski, 2006).

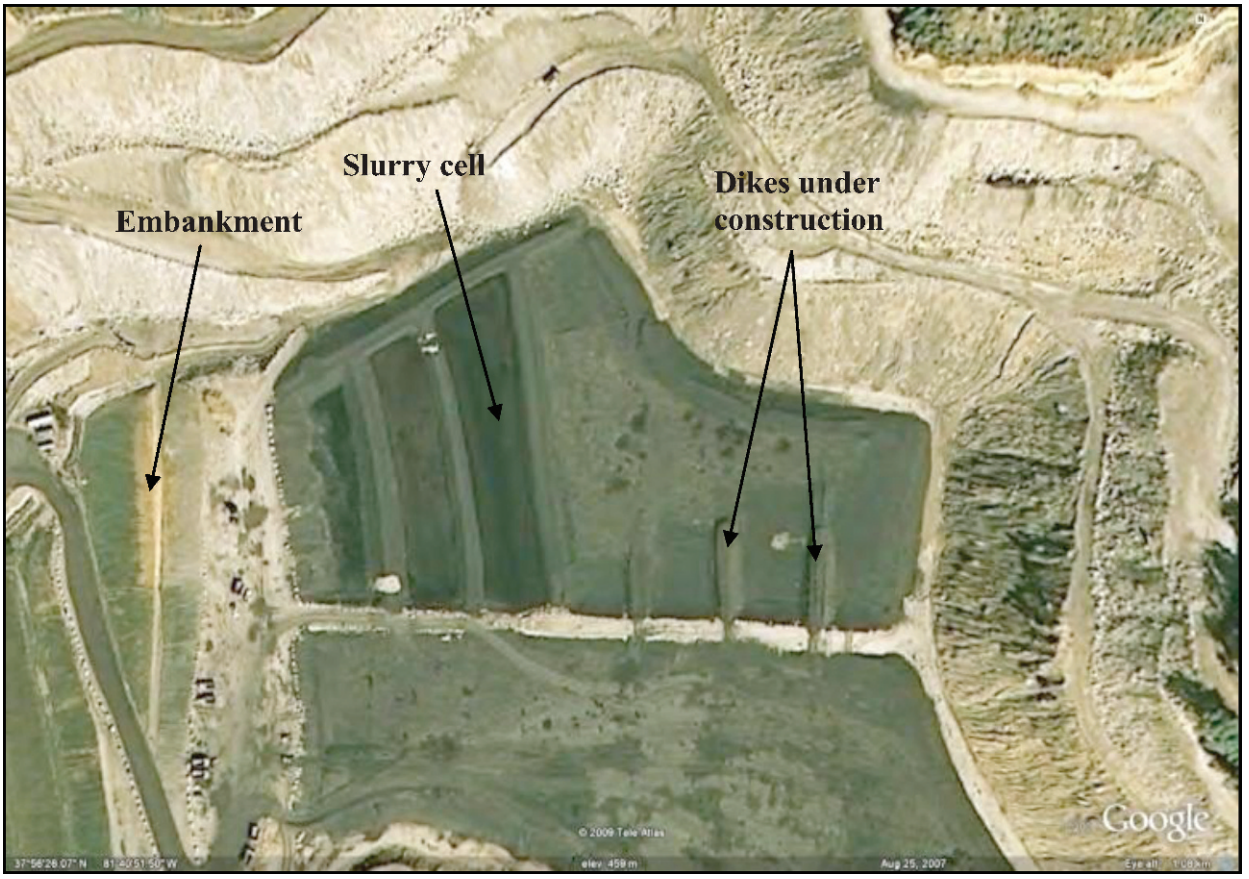

Figure 6. Aerial view of coal refuse slurry cells.

barriers and the flowability of the material are reduced.

Some impoundments are capped specifically because of breakthrough concerns but are also converted to slurry cell structures for continued refuse disposal (Figure 6). 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 (Figure 7). Their use 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, they do 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.

Findings of the 2005 Study

The purpose of the 2005 study was to review current knowledge of—or applicable to—the potential flow characteristics of impounded coal refuse. The review explored two inter-related issues: (1) Given the occurrence of a breakthrough event that would result in a potential flow conduit between an underground mine and an impoundment, should coal refuse be expected to flow into the mine (i.e., is it flowable)? (2) If the refuse would flow, what would be the nature (e.g., velocity and extent) of that flow? This paper summarizes the findings pertaining to only the first (and more important) question.

Sources employed in the review included: (1) interviews with other OSM staff working with impoundments, (2) interviews with geotechnical experts in coal refuse and metal tailings impoundment construction from academia, other federal agencies, and the industry, and (3) geotechnical articles obtained through literature searches and through direct contacts with the authors. The final report included modifications in response to solicited comments on the first draft. Most of the comments were provided by geotechnical engineers and engineering geologists outside of OSM with expertise in mine waste impoundments or similar structures.

It was recognized that the response of the slurry to a barrier failure should vary site specifically according to the strength characteristics of the refuse, depth of

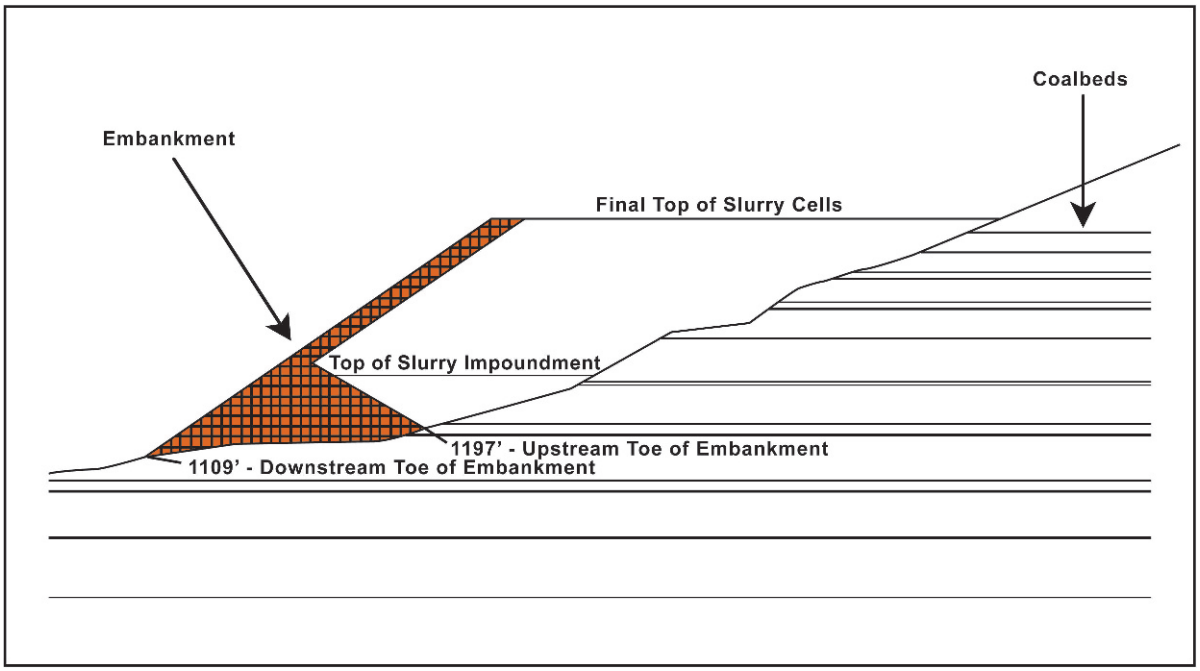

Figure 7. Cross section depicting zone of slurry cell construction above capped impoundment and coal seams subjacent to, and below the structure.

the impoundment (i.e., how much stress might bear on the material if a failure occurred), and nature of an opening into an underground mine (e.g., its position in the impoundment, and its size, length, and inclination). The search did not encounter any study that had scrutinized the interaction of all three of those variables, either empirically or through modeling. However, there existed a considerable amount of work relating to the static, load-bearing strengths of coal refuse, and metal and oil sands tailings. The report distinguished several general properties of this material that are assessed in the literature. Most attention was applied to consolidation strength, i.e., the development of shear strength in the fine refuse during the consolidation process. Another property of interest, thixotropic strength, was found in documents pertaining to tailings deposits. The report included consideration of the potential effect of thixotropy, assuming it was potentially applicable to fine coal refuse. Additional aspects thought to have bearing on fine refuse stability are the design and construction of the impoundments, and potential effects of chemical additives to the slurry.

Consolidation Strength

One of the properties that impacts the stability of an impoundment is consolidation. Consolidation of a soil is defined as a void-ratio reduction that takes place as a function of time and pressure. Consolidation is a gradual process that involves slow drainage, compression (density increase, volume reduction, reduction in void space between particles), and stress transfer or gradual pressure adjustment. The development of engineering strength in the soil during consolidation results from the buildup of effective stress among the soil particles. Consolidation is affected in part by particle size distribution and density or void ratio.

The rate and degree of consolidation depend on the induced load on the soil and the soil's coefficient of consolidation (Cv). Factors influencing Cv include the soil's compressibility and its permeability (or hydraulic conductivity). Compressibility is a ratio of the strain of the material (specifically the rate of volume reduction) to induced stress, and it depends on particle shape, size distribution, and initial void ratio. With higher compressibility, the Cv is lower, and more strain is necessary for the buildup of effective stress in the soil. Permeability is the facility with which water is able to travel through the pores of the soil, and it is a function of the size, number, and interconnection of voids between the soil particles. The higher is the permeability, the higher is the Cv. Figure 8 shows a relationship between compressibility and void ratio for copper, gold, composite tailings, as well as "coal wash tailings" (assumed to the same as—or similar to—coal refuse slurry). Notable factors are the relatively high void ratios of the coal wash tailings when highly compressible. The graph suggests

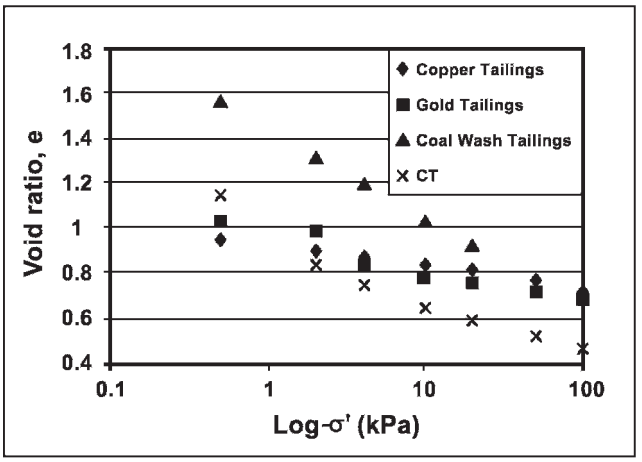

Figure 8. Compressibility of mine tailings as a function of void ratio (from Qiu and Sego, 1998).

that unconsolidated fine coal refuse is capable of relatively high moisture content.

The stability of impounded fine refuse and tailings depends in large part on the development of consolidation strength in the material. Insufficient shear strength under static or dynamic load will result in deformation of the refuse. A major concern is that insufficient drainage during the consolidation process may result in liquefaction, i.e., excessive pore pressures under load and consequent material flow.

The following comments from literature pertaining to coal refuse consolidation strength were noted:

Permeability

Consolidation in impounded coal refuse and tailings is more influenced by permeability than compressibility. The permeability of refuse is low, and the length of the drainage path is long, so that consolidation of the material can take a long time. One should expect high excess pore pressure to exist in fine refuse for years after the initial placement, which will significantly reduce the shear strength of the material. Even after the material is fully consolidated under the imposed load, the void ratio of fine refuse is still high (Zeng et al., 1998a, 1998b; Sweigard et al., 1997; and Suthaker and Scott, 1994, 1996, 1997).

Slow Rate of Consolidation

Suthaker and Scott (1994) and Suthaker et al. (1997) conducted large-scale testing of oil sand fine tails, using 2-m and a 10-m stand pipes. Whereas sedimentation occurred from the bottom up and was rapid (2.5 days), self-weight consolidation occurred from the top down and was long-term (300 days). Tang et al. (1997) examined mature fine tailings with scanning electron microscopy and found that after a certain void ratio was reached (ratio of 6), the rate of consolidation slowed considerably. Suthaker et al. (1997) also found that a decrease in void ratio resulted in a decrease of hydraulic conductivity, resulting in slower consolidation.

Low Shear Strength of Fine Refuse and Tailings in Existing Impoundments

Concern over consolidation strength in impoundments has been expressed by Busch et al. (1975), Zeng et al. (1998a, 1998b), Sweigard et al. (1997), and Suthaker and Scott (1994, 1996, 1997). Related observations include: high moisture contents (some that are above the liquid limit); increases in moisture content, void ratio, compressibility, and pore pressure with depth in the impoundment; and generally low shear strength even after years of consolidation. Suthaker and Scott (1994) and Suthaker et al. (1997), in their large-scale consolidation test, found that there was no effective stress buildup after 14.4 years in the oil-sand tailings except in the bottom part of the stand pipe.

Uncertainty whether the Consolidation Process Results in the Development of Shear Strength in the Impounded Refuse

The foregoing points assume that shear strength in refuse will increase as a result of the consolidation process. That is not the case if consolidation occurs without sufficient dewatering of the material. Sweigard et al. (1997) attempted to address the long-term effect of consolidation of refuse at or above its liquid limit on its shear strength. Their results were inconclusive.

Susceptibility of Refuse and Tailings to Liquefaction

As previously stated, an important issue pertaining to development of consolidation strength in impounded fine refuse and tailings is the avoidance of liquefaction. Most soils continue to behave in a solid state after they fail in shear, i.e., shear strength is not completely lost, and the amount of strain that occurs depends on the duration of sufficient (“residual” or “ultimate”) shear stress. The exception is when liquefaction takes place. Liquefaction is a process by which the soil structure collapses under shock or other type of loading and is associated with a sudden, temporary increase in pore-water pressure. The material then temporarily transforms into a liquid. Liquefaction can occur in response to dynamic forces

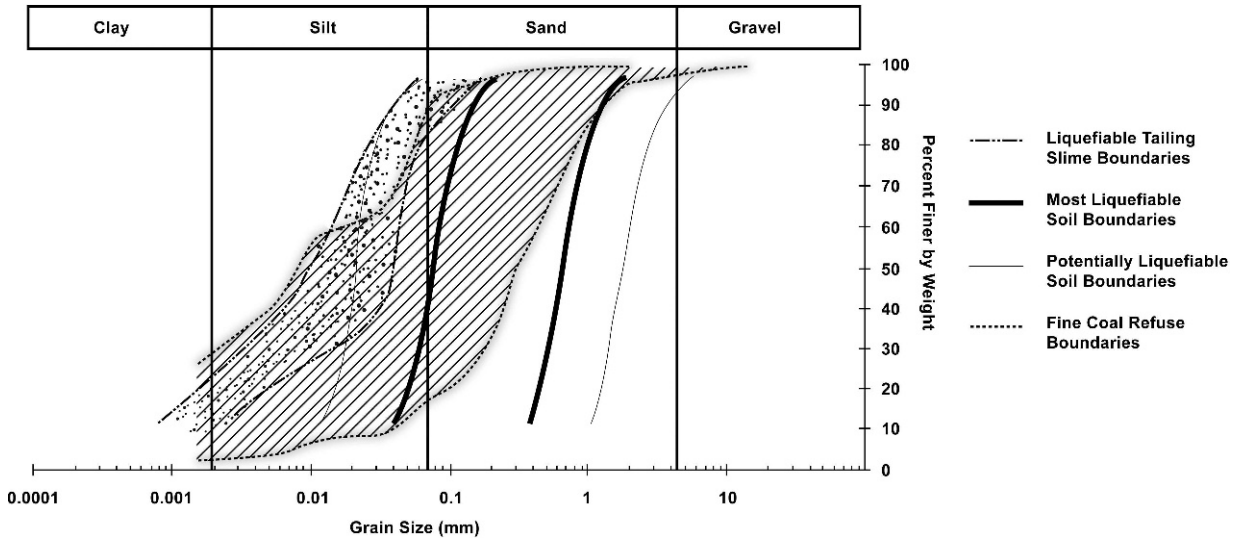

Figure 9. Gradation curves defining boundaries for liquefiable soils (Tsuchida, 1970), liquefiable tailings (Ishihara, 1985), and fine coal refuse (modified from D'Appolonia, 2009). (Liquefiable soils and tailings boundaries were first combined in Terzaghi et al., 1996.)

such as earthquakes and mine blasting. *Static* liquefaction can result from sudden shear stresses induced by mine-barrier breakthroughs, mine subsidence, or other kinds of single-cycle events. The liquefaction potential of unconsolidated sediments is related to the materials' void ratio and mean effective stress.

According to Terzaghi et al. (1996), soils most susceptible to liquefaction: (1) have clean sands and silty sands with minimal clay content, (2) are loose enough to be contractive, and (3) are of sufficiently low permeability to experience no significant drainage during static or dynamic loading. Figure 9 compares grain-size distribution boundaries associated in the literature with liquefiable natural soils and liquefiable "tailings slimes" with the general grain-size distribution boundaries of fine coal refuse reported by D'Appolonia (2009). It is noted that the liquefiable soils boundaries may need to be adjusted to account for gravelly sands also prone to disturbance under cyclic loading (e.g., Evans and Harder, 1993). For purposes of this discussion, it is especially noteworthy that the coal refuse boundaries do not match the liquefiable silts and sands of the tailings and soils, respectively. This suggests that fine refuse with low resistance to liquefaction may have its own unique pair of boundaries.

Fourie (2004) emphasized the important role of liquefaction, referencing his studies of a tailings-dam failure in South Africa (Fourie and Papageorgiou, 2001; Fourie et al., 2001). He pointed out that the susceptibility of a material to liquefaction is governed by the relative values of the material *in situ* density (or void ratio) and effective stress.

Liquefaction potential relates to the conditions under which deposition of tailings occurred and the inter-grain "fabric" that thus developed. For example, subaqueous deposition will result in a much lower density and effective stress than subaerial deposition, even when the deposit is fully consolidated. Such material then behaves in a contractive fashion when loaded undrained, i.e., the solid content of the material contracts and induces excess pore-water pressures. Recognition that fine coal refuse consolidated in upstream impoundments is "usually highly contractive" is documented by Genes et al. (2000). Volpe (2004) cited conditions in fine refuse conducive to contractive behavior in reference to the tragic Buffalo Creek failure in 1972, i.e., very low density and a high void ratio.

Moisture Content

The work of Huang et al. (1987) emphasizes how the flowability and flow behavior of coal refuse slurry can vary. They point out that unless the refuse is relatively dry, the undrained shear strength of even partially saturated fine coal refuse is very sensitive to moisture contents. A change in moisture content of only one percent may cause a large change in the undrained strength.

Thixotropic Strength

Usui (1998) and Suthaker et al. (1997) identified coal-water slurry and oil-sand tailings, respectively, as thixotropic in nature. Since coal refuse slurry may have some engineering properties similar to those

mixtures, the study in this report considered thixotropy as a potential factor affecting the shear strength of impounded refuse.

The term thixotropy was originally introduced to describe the well-known phenomenon of isothermal, reversible gel-sol (solid-liquid) transformation in colloidal suspensions due to mechanical agitation. 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. Thixotropy is also classified as a rheological process. From this perspective, it is described as a continuous decrease in apparent viscosity with time under shear, and subsequent recovery of viscosity after cessation of flow. From a geotechnical point of view, thixotropy is a process of softening caused by remolding, followed by a time-dependent return to the original harder state at a constant water content and constant porosity (in contrast to consolidation). For remolded 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). Thixotropic strength gain is measured as a ratio of the strength after an elapsed time to the strength immediately after remolding (or compaction) and is called thixotropic strength ratio. Generally, the ratio is determined in terms of undrained shear strength, not effective (i.e., drained) shear strength.

Information about thixotropy as it may pertain to the stability of coal refuse impoundments was acquired from the work of Suthaker et al. (1997) on oil-sand tailings. Several of his comments and findings are as follows:

Factors Affecting Thixotropy

Several factors such as the mineralogy of the clay, water content, and rate of loading directly affect thixotropy of fine tailings. Some clays exhibit high thixotropy naturally. Kaolinite and illite of oil sands are not thixotropic. However, because of the addition of a dispersing agent, organic matter in the form of bitumen, and organic acids in the pore water, fine tailings are thixotropic in nature.

Duration of Thixotropic Strength Gain

Using cavity-expansion, vane-shear, and viscometer testing equipment, Suthaker et al. (1997) conducted three tests at different water contents up to 450 days. Thixotropic strength increased quadratically and was still increasing at 450 days.

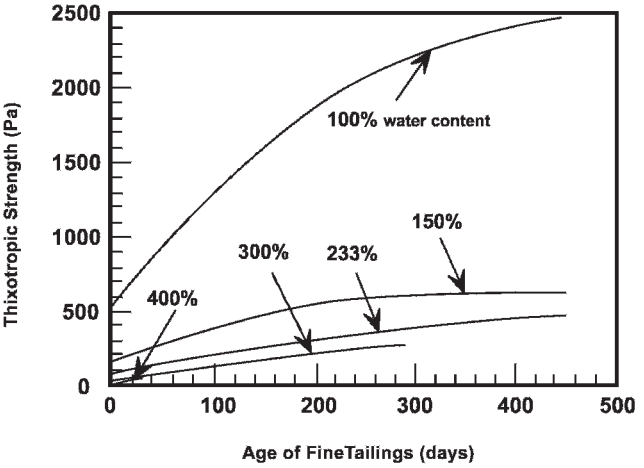

Figure 10. Thixotropic strength with time for a number of water contents (Suthaker et al., 1997).

Relationship between Thixotropy and Consolidation

Long-term strength development in slurries can be either thixotropic or have a combination of thixotropic and consolidation strengths. At low water content (<100 percent), there was no consolidation strength development, as the water content remained unchanged. At higher water contents, water content changes were prominent, indicating the existence of consolidation effects.

Effect of Self-Weight Consolidation on Thixotropy

Shearing strains resulting from consolidation impede the physicochemical bonding that produces thixotropic strength. The higher is the rate of consolidation, that is, the shearing rate, the smaller is the thixotropic strength gain.

Effect of Moisture Content on Thixotropy

The thixotropy of fine tailings is highly dependent on water content. Substantial thixotropic strength increases were seen for fine tailings with water contents less than 150 percent (Figure 10). The lower is the water content, the higher is the thixotropic strength.

Design, Construction, and Performance of Impoundments

It is apparent from the points listed previously that one very important consideration in the design and construction of an impoundment should be the effective drainage of the impounded fine refuse or tailings. The following papers focus on the danger of embankment failure, but the negative impact of

inadequate drainage is also pertinent to breakthrough potential:

Comparison of Failed and Stable Impoundments

Mittal and Morgenstern (1977) compared the tailings dams of five large mines in Canada and listed the characteristics of failed and stable impoundments. Failed impoundments had high phreatic surfaces, in addition to overly steep downstream slopes and weak foundation soils. The qualities of stable impounding structures included pervious foundations, in addition to relatively course impounded fines and slow impoundment construction rates.

Consolidation Rate and Rate of Impoundment Construction

Huang et al. (1987) and Zeng et al. (1998a) both recommended a rate of upstream impoundment construction slow enough to provide sufficient time for consolidation strength development in the fine refuse. For instance, Zeng et al. (1998a and b) conducted centrifuge experiments on three models to assess the response of coal refuse impoundments to seismic loading: The models corresponded to the downstream method, upstream method, and centerline method with induced consolidation. The downstream model resulted in a small amount of deformation but remained stable. The upstream model resulted in catastrophic failure. The centerline model had more deformation than the downstream but was still stable after the simulated earthquake. Zeng et al. concluded that it is imperative for consolidation of in-place coal refuse to be monitored in the field during upstream impoundment construction.

Case Histories of Impoundment Failures

Most documented impoundment failure events entail failures of the dams or embankments of the impoundments. Quite frequently, these follow storm events that suddenly and drastically increase the load of the impounded material on the dam and, following the breach, lubricate the flow of the fine material. In such cases, the potential flow properties, or rheology, of the slurry may become considerably different from what they were prior to the storm event. Such cases provide little information about the potential rheology—and even flowability—of impounded refuse that may enter into an underground mine. This is particularly significant with respect to capped structures overlain by layers of slurry cells, since there is no clear water above the impounded slurry. Two possible exceptions follow.

The Martin County Coal Company, Big Branch Surface Impoundment Breakthrough in Martin County, KY

Several studies of this breakthrough event concluded that the breakthrough resulted from water seeping through a thin barrier to an underground coal mine and weakening of the barrier to where it could no longer withstand the stress exerted by the coal slurry (U.S. MSHA, 2001; NRC, 2002). Under this scenario, it may be an open question as to if the slurry itself flowed into the mine, or was piped into it by clear water. Short an answer, we know nothing of the flowability of the slurry itself prior to the breakthrough. However, two documents question the significance of the piping effect (Thacker, 2002; Hagerty and Curini, 2004). Using finite-element seepage analyses, they demonstrated that the piping process would have drained the clear water and slurry pore water enough to dissipate the excess pore pressure in the fine refuse well before reaching the elevation of the clear water. The reduction of pore pressure should have forestalled flow into the mine. Their alternative conclusion is that the hydrostatic pressure from the impounded slurry and rainwater surcharge was sufficient to push through the barrier (i.e., without the assistance of seepage). If that is correct, the hydrodynamic pressures at the time of the breakthrough, size of the conduit to the mine, and initial slurry rheology were enough for the flow to begin.

Failure of the Los Frailes Tailings Dam

Another example of tailings flow without the assistance of clear-water piping is available from the web site: http://www.antenna.nl/wise/uranium/mdaflf.html. The failure of the Los Frailes tailings impoundment in Aznalcollar, Spain, in 1998, involved a breach of the dam. However, the mechanism of the breach was a bearing failure in the dam foundation, composed of impervious Tertiary marl, in response to extra stress buildup from water above the fine tailings during a heavy rain. The tailings flow is depicted as initially following the slide of the foundation material from underneath the impoundment.

Effect of Additives on Impounded Refuse and Tailings

In our review, it became apparent that at least some of the existing impounded coal refuse may have been treated with additives for various purposes. At this time, we do not know how frequently such treatment takes place or how much of it is strictly experimental versus standard practice. Indications that additives

are applied to coal refuse slurry or tailings in some cases come from Puri et al. (1990), Tang et al. (1997), Suthaker et al. (1997), Liu and McKenna (1999), and Heywood and Alderman (2003). Potential objectives of the additives include accelerating consolidation and increasing shear strength of impounded refuse, and reduction of slurry viscosity for pipeline transport to the impoundment. Michalek (2005) has stated that, in the experience of U.S. MSHA, mining companies generally use additives to accelerate slurry particle sedimentation in order to decant clear water back into the mine operation. We believe that an accurate analysis of the strength and stability of fine coal refuse will have to account for the extent and variety of additive use, regardless of its purpose, and identify its effect(s) on the material.

Assessment of Literature Published after the 2005 Study

From our review of literature published from 2005 to the present, it is apparent that there remains keen interest in the flow-related engineering properties of fine coal refuse and other types of tailings deposits. Ongoing work includes the development of field and laboratory methods to determine the liquefaction potential of the materials. For example, Chang and Heymann (2005) tested the relationships between shear wave velocity and void ratios and effective stresses in gold tailings. They confirmed that the relationships for the silty material differed from conventional correlations associated with sands. Fourie and Tshabalala (2005) proposed use of the "collapse surface" determined from the locus of peak stress values from undrained compression tests on isotropically consolidated tailings specimens to predict the onset of liquefaction. Kalinski and Phillips (2008) employed several field and laboratory methods, including standard penetration, seismic cone penetration, surface wave, and vane shear testing, with the objective of developing a universal approach to predicting the seismic behavior of coal refuse slurry impoundments. Recent work also includes attempts to model tailings dewatering (de Oliveira-Filho and van Zyl, 2006) and the effect of capillarity on the stability of nickel tailings dams (Zandarin et al., 2009). The latter modeling study is particularly significant with respect to the subject of this paper, since it not only: (1) confirms that low tailings permeability can maintain an elevated phreatic surface during and after the impoundment construction, but (2) it also suggests that capillarity in the tailings causes a rapid rise in the phreatic surface during rain storms. This seems to support the prospect of coal refuse slurry remaining saturated for indefinite time periods even in capped impoundments if they cover points of groundwater discharge.

Recent literature also presents potential solutions to slow consolidation in tailings deposits. Wong et al. (2008) found that "nonsegregating tailings," i.e., homogenized fine and coarse oil sands tailings, exhibit enhanced performance in consolidation and strength, and reduction in water retention in comparison to fine tailings. Wickland and Wilson (2005) described mixtures of gold tailings and "waste rock" (analogous to surface coal mine spoil) as having lower total settlements and faster consolidation times than tailings alone. They suggested that combining tailings with waste rock helps to solve "…the two biggest problems associated with conventional methods of mine waste disposal…." The low permeability of the fine tailings control acid mine drainage from the waste rock, and the high shear strength provided by the waste rock prevents catastrophic liquefaction of impounded tailings. Finally, Noakes (2005) reported that as early as 1974, professor David Boger added polymers to tailings slurry to keep it flowing through pipelines without adding water, thus allowing the dry stacking of the tailings and limiting land use to half that required by conventional impoundments. Researchers are attempting to develop this technology into an economically viable tool for tailings disposal.

A final note pertains to improvements in mine barrier stability analysis. Rohlf and Sweigard (2009) have developed a two-dimensional analysis that considers inclined slices through the barrier as potential critical failure surfaces. Interestingly, an application of their analysis to an example barrier results in a small increase in safety factor with slurry depth (from 12.2 to 48.8 m). This implies that barrier stability (assuming piping is not a factor) should progressively become less of a concern as the elevation of an impoundment—or stack of slurry cells above a capped impoundment—increases. This is good news if true. However, the catastrophic effects of a slurry breakthrough, if a barrier fails, should still increase with load. Further, the utility of this analytical approach, like all others, depends on accurate information about the location of the mine relative to the edge of the impoundment.

CONCLUSIONS AND RECOMMENDATIONS

Based on our review of published information on refuse and tailings shear strength, we are not confident that all or even the majority of existing impoundments (yet under construction or reclaimed) would avoid flows of fine refuse through breakthroughs into underground mines. There is significant

uncertainty regarding the effectiveness of strength development through consolidation in the fine refuse. Other reasons for our concern include the influence of pore-water pressure in the refuse and potentiality of liquefaction—and the sense that at least some impoundments are not constructed to effectively drain water from the material. Further, whereas in one sense, the effect of thixotropy may temporarily supplement what consolidation strength may occur under conditions of high moisture content, its reversibility may only induce a "false sense of security." That is, wet, thixotropic refuse may appear to be stable under static conditions before changing to a liquid state when agitated.

The peer review of the 2005 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); laboratory and *in situ* testing of slurry consolidation, shear strength, liquefaction potential, and rheology; and modeling of fine coal refuse response to breakthroughs. We feel that the suggested studies would be instrumental in providing a better understanding of the magnitude of the problem and of factors affecting slurry flowability. However, those studies would not address breakthrough concerns pertinent to specific impoundment sites. There are optional preventative site-specific construction practices that should be evaluated. For instance where, after careful site investigation, there remains uncertainty whether thick coal beds 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 high walls. Also, where there are plans to increase the size of active impoundments (beyond original designs) or construct slurry cells on top of capped impoundments, the impounded slurry can be sampled and tested to ensure that the material's water content is not above its liquid limit.

Finally, research and development of methods to better detect and position inadequately documented underground mines and to prevent coal refuse slurry flowability are strongly encouraged.

ACKNOWLEDGMENTS

The authors wish to thank Roger Calhoun, Lois Uranowski, David Lane, and this journal's peer reviewers for their constructive comments on the draft manuscript. The assistance of Tiara Neal and Tom Mastrorocco with the illustrations is also deeply appreciated. Finally, special thanks are due to Brian Greene for inviting us to make this contribution to the Dams Special Edition.

REFERENCES

Busch, R. A.; Backer, R. R.; Atkins, L. A.; and Kealy, C. D., 1975, *Physical Property Data on fine Coal Refuse*: U.S. Department of Interior Bureau of Mines Report of Investigation 8062.

Chang, H. P. N. and Heymann, G., 2005, Shear wave velocity of gold tailings: *Journal of the South African Institution of Civil Engineering*, Vol. 47, No. 2, pp. 15–19.

D'Appolonia Engineering, Inc., 2009, *Engineering and Design Manual: Coal Refuse Disposal Facilities*: prepared for the U.S. Mine Safety and Health Administration, Pittsburgh, PA, 826 p., plus appendices.

de Oliveira-Filho, W. L. and van Zyl, D., 2006, Modeling discharge of interstitial water from tailings following deposition. Part 1: Phenomenology and model description: *Solos e Rochas*, Vol. 29, No. 2, pp. 199–209.

Evans, M. D. and Harder, L. F., 1993, Evaluating liquefaction potential of gravelly soil in dams. In *Geotechnical Practice in Dam Rehabilitation*: American Society of Civil Engineers Special Publication 35. pp. 467–481.

Fourie, A. B., 2004, *Comments to Peter Michael of the U.S. Office of Surface Mining re: Request for Assistance—Review of Draft Report*: University of Witwatersrand Department of Civil Engineering, Witwatersrand, South Africa, 2 p.

Fourie, A. B.; Blight, G. E.; and Papageorgiou, G., 2001, Static liquefaction as a possible explanation for the Merriespruit dam failure: *Canadian Geotechnical Journal*, Vol. 38, pp. 707–719.

Fourie, A. B. and Papageorgiou, G., 2001, Defining an appropriate steady state line for Merriespruit gold tailings: *Canadian Geotechnical Journal*, Vol. 38, pp. 695–707.

Fourie, A. B. and Tshabalala, L., 2005, Initiation of static liquefaction and the role of K_0 consolidation: *Canadian Geotechnical Journal*, Vol. 42, pp. 892–906.

Genes, B.; Keller, T.; and Laird, J., 2000, Steady state liquefaction susceptibility of high hazard upstream-constructed coal refuse disposal facilities. In *Proceedings, Tailings Dams 2000*: Association of State Dam Safety Officials and U.S. Society of Dams, Las Vegas, NV, pp. 47–58.

Hagerty, D. J. and Curini, A., 2004, Impoundment failure seepage analyses: *Environmental and Engineering Geoscience*, Vol. 10, No. 1, pp. 57–68.

Heywood, N. I. and Alderman, N., 2003, Developments in slurry pipeline technologies: *CEP Magazine*: April 2003.

Huang, Yang H.; Li Junli; and Weeratunga Gamini, 1987, *Strength and Consolidation Characteristics of Fine Coal Refuse*: University of Kentucky Contract Report J5140126 prepared for U.S. Department of Interior Office of Surface Mining Reclamation and Enforcement, Lexington, KY, 115 p.

Ishihara, K., 1985, Stability of natural deposits during earthquakes. In *Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering*. AA. Bolhema, Vol. 1, pp. 321–326.

Kalinski, M. E. and Phillips, J. L., 2008, Development of methods to predict the dynamic behavior of fine coal refuse: Preliminary results from two sites in Appalachia. In Zeng, X.; Manzari, M. T.; and Hitunen, D. R. (Editors), *Proceedings of the Conference of Geotechnical Earthquake Engineering and Soil Dynamics IV*: GSP-181, pp. 1–10, American Society of Civil Engineers, Reston, VA, 10 p.

Liu, B. Y. and McKenna, G., 1999, Application of wickdrains in composite tailings. In *Proceedings of the 52nd Canadian Geotechnical Conference*: Canadian Geotechnical Society, Regina, SK (Canada), pp. 487–494.

Michael, P. R. and Chavel, L., 2008, *Environmental Risks Associated with Coal Refuse Impoundment Reclamation: An Assessment of the Possibility of an Underground Mine Breakthrough Occurring as a Result of the Impoundment Reclamation Process*: U.S. Office of Surface Mining Appalachian Region Management Council Open-File Report, Pittsburgh, PA, 14 p.

Michael, P.; Murguia, R.; and Kosareo, L., 2005, *The Flowability of Impounded Coal Refuse: A Review of Recent Work and Current Ideas in the Engineering Profession*: U.S. Office of Surface Mining Appalachian Region Management Council Open-File Report, Pittsburgh, PA, 25 p.

Michalek, S. J., 2005, *Comments to Peter Michael of the U.S. Office of Surface Mining re: Comments on Office of Surface Mining Report—"Flow Characteristics of Impounded Coal Refuse Material"*: U.S. Mine Safety and Health Administration, Pittsburgh Safety and Health Technology Center, Mine Waste and Geotechnical Engineering Division, Bruceton, PA, 3 p.

Mittal, H. K. and Morgenstern, N., 1977, Design and performance of tailings dams. In Landva, A. and Knowles, G. D. (Editors), *Proceedings of the Conference on Geotechnical Practice for Disposal of Solid Waste Materials*: American Society of Civil Engineers, Ann Arbor, MI, pp. 475–492.

National Research Council (NRC), 2002, *Coal Waste Impoundments: Risks, Responses, and Alternatives*: National Academy Press, Washington, D.C., 185 p., plus appendices.

Noakes, F., 2005, An end to tailings dams is in sight waste disposal: *Australian Mining*, Vol. 97, No. 10, p. 18.

Puri, V. K.; Das, B. M.; and Devkota, B. C., 1990, Geotechnical properties of coal mine slurry waste. In Chugh, Y. P.; Davin, D. C.; and Dietz, K. R. (Editors), *Proceedings First Midwestern Region Reclamation Conference*: Southern Illinois University, Carbondale, IL, pp. 11.1–11.10.

Qiu Yunxin and Sego, D. C., 1998, Engineering properties of mine tailings. In *Proceedings of the 51st Canadian Geotechnical Conference*: Canadian Geotechnical Society, Vancouver, BC (Canada), pp. 149–154.

Rohlf, R. A. and Sweigard, R. J., 2009, Stability analysis of barriers protecting underground mine entries in coal slurry impoundments: *Mining Engineering*, Vol. 60, pp. 37–42.

Shinavski, L., 2006, Overview of impoundment abandonment. In *Power Point Presentation at the U.S. Mine Safety and Health Administration 2006 Annual Dam Safety Seminar*: National Mine Health and Safety Academy, Beaver, WV, 48 slides.

Suthaker, N. N. and Scott, J. D., 1994, Large scale consolidation testing of oil sand fine tails. In *Proceedings of the International; Congress of Environmental Geotechnics: Geotechnical and Related Aspects of Waste Management Associated with Municipal, Mine, Industrial, and Nuclear Wastes*: Canadian Geotechnical Society, Edmonton, AB (Canada), pp. 149–154.

Suthaker, N. N. and Scott, J. D., 1996, Measurement of hydraulic conductivity in oil sand tailings slurries: *Canadian Geotechnical Journal*, Vol. 33, No. 1, February 1996, pp. 642–653.

Suthaker, N. N. and Scott, J. D., 1997, Thixotropic strength measurement of oil sand fine tailings: *Canadian Geotechnical Journal*, Vol. 34, pp. 974–984.

Suthaker, N. N.; Scott, J. D.; and Miller, W. G., 1997, The first fifteen years of a large scale consolidation test. In Bauer, G. E. (Editor), *Proceedings of the 50th Canadian Geotechnical Conference*: Canadian Geotechnical Society, Ottawa, Ontario, pp. 476–483.

Sweigard, R. J.; Hopkins, T. C.; Justice, C. T.; Beckman, T.; Thompson, E. D.; and Rohlf, R. A., 1997, Impact of consolidation on the shear strength of coal refuse impoundments: *Transactions of the Society for Mining, Metallurgy, and Exploration*, Vol. 302, pp. 141–144.

Tang, J.; Biggar, K. W.; Scott, J. D.; and Sego, D. C., 1997, Examination of mature fine tailings using a scanning electron microscope. In Bauer, G. E. (Editor), *Proceedings of the 50th Canadian Geotechnical Conference*: Canadian Geotechnical Society, Ottawa, Ontario, pp. 746–753.

Terzaghi, K.; Peck, R.; and Mesri, G., 1996, *Soil Mechanics in Engineering Practice,* 3rd ed.: John Wiley & Sons, Inc., New York, NY, pp. 193–198.

Thacker, B. K., 2002, Big Branch slurry impoundment breakthrough: Why it happened and lessons learned. In *Proceedings, Tailings Dams 2002*: Association of State Dam Safety Officials and U.S. Society of Dams, Las Vegas, NV, pp. 47–58.

Tsuchida, H., 1970, Prediction and countermeans against the liquefaction in sand deposits. In *Abstract of the Seminar in the Port and Harbor Research Institute*. Yokohama, Japan, pp. 3.1–3.33.

U.S. Department of Interior, Office of Surface Mining Reclamation and Enforcement (U.S. OSM), 2002, *Report on October 2000 Breakthrough at the Big Branch Slurry Impoundment*: Office of Surface Mining, Lexington, KY, 80 p., plus appendices.

U.S. Department of Labor, Mine Safety and Health Administration (U.S. MSHA), 2001, *Report of Investigation: Noninjury Impoundment Failure/Mine Inundation Accident, October 11, 2000*: Mine Safety and Health Administration, Arlington, VA, 71 p., plus appendices.

U.S. Office of the Federal Register, National Archives and Records Administration, 2007, *Title 30 of the Code of Federal Regulations*: U.S. Government Printing Office, Washington, D.C.

Usui, H., 1998, Prediction of slurry viscosity by a thixotropy model for dispersion systems. In Wypych, P. W. (Editor), *Proceedings from the 6th International Conference on Bulk Materials Storage, Handling, and Transportation*: Institution of Engineers, Wollongong, NSW, Australia, pp. 257–263.

Volpe, R., 2004, *Comments to Peter Michael of the U.S. Office of Surface Mining re*: Draft Refuse Flowability Report, Santa Clara Valley Water District, Santa Clara, CA, 2 p.

Wickland, B. and Wilson, G. W., 2005, Research of co-disposal of tailings and waste rock: *Geotechnical News*, Vol. 23, No. 3, pp. 35–38.

Wong, R. C. K.; Mills, B. N.; and Liu, Y. B., 2008, Mechanistic model for one-dimensional consolidation behavior of non-segregating oil sands tailings: *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 134, No. 2, pp. 195–202.

Zandarin, M. T.; Oldecop, L. A.; Rodrequez, R.; and Zabala, F., 2009, The role of capillary water in the stability of tailing dams: *Engineering Geology*, Vol. 105, pp. 108–118.

Zeng, Xiangwu; Wu, Jiaer; and Rohlf, R., 1998a, Modeling the seismic response of coal-waste tailings dams: *Geotechnical News*: June 1998, pp. 29–32.

Zeng, Xiangwu; Wu, Jiaer; and Rohlf, R., 1998b, Seismic stability of coal-waste tailings dams: *Geotechnical Earthquake Engineering and Soil Dynamics III*: pp. 951–961.