

HYDRAULIC PROPERTIES OF SURFACE MINE SPOILS OF THE NORTHERN APPALACHIAN PLATEAU¹

by

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Abstract. Aquifer tests were conducted on over 125 mine spoil wells from 18 surface mines located in Pennsylvania, West Virginia, Ohio, and Kentucky. These tests (primarily slug tests) were used to determine the range, variability, and predictability of surface mine spoil hydraulic properties (hydraulic conductivity and transmissivity). Test results show that hydraulic properties of mine spoil aquifers are highly variable and relatively unpredictable. Hydraulic conductivity ranged over 7 orders of magnitude from a very low permeability of 4.45×10^{-9} m/s to a highly transmissive 7.58×10^{-2} m/s. The hydraulic conductivity measured at mines with 5 or more wells frequently ranged over 3 orders of magnitude and none ranged less than one. A few statistical relationships between geologic and mining conditions and the hydraulic properties were observed. Spoil aquifers that were under 30 months old and those over 100 months old exhibited significantly lower (95 percent confidence level) hydraulic conductivities than those between 30 and 100 months old. The influence of spoil lithology on the hydraulic conductivity does not appear to be strong, probably because of masking by other factors introduced during reclamation. No significant trends were observed between spoil thickness and hydraulic conductivity. A comparison of hydraulic conductivity derived from slug and constant-discharge tests performed on the same wells indicate that slug tests tend to yield lower values. A few spoil wells exhibited an oscillatory water-level response during slug testing, similar to that observed during testing of some karst and glacial aquifers.

Additional Key Words: double porosity, underdamped oscillation, anomalous aquifer responses

Introduction

The understanding of mine spoil hydrology is a crucial element for the prediction of mine drainage. However, it is also one of the least understood and analyzed aspects of mine drainage prediction. Ground water is an integral chemical component of acid mine drainage formation and it also serves as the contaminant transport medium. Therefore, prediction of post-mining drainage quality and quantity requires a strong ground-water hydrology element in the methodology.

The highly heterogeneous and anisotropic nature of surface mine spoils makes hydrologic characterization problematic. Particle sizes for mine spoil

are broad, ranging from clay (<0.002 mm) to very large boulder (>2048 mm) sized particles. The spoil particles are irregularly shaped and commonly angular. Spoil sorting ranges from very to extremely poorly sorted (Jones and Anderson, 1994). Spoil sorting classification values are similar to those associated with glacio-fluvial sediments (Folk, 1974). The similarity of hydrologic properties of surface mine spoil and poorly sorted glacial sediments were observed by Hawkins and Aljoe (1991).

In the past, ground-water flow through surface mine spoil has been assumed to be diffuse flow through a "sandbox-type" porous medium. However, Caruccio and others (1984) reported pseudokarst characteristics in a mine spoil aquifer in central West Virginia. Pseudokarst characteristics are similar to true karst aquifer characteristics; however, the mechanism of conduit or void formation differs. Caruccio and others (1984) also noted that ground-water flow in reclaimed surface mines is "highly channelized" and may not be intercepted during drilling unless one of these "randomly located" conduits is encountered. Hawkins and Aljoe (1990;1991) subsequently noted that reclaimed mine spoil exhibits characteristics of both porous medium and conduit-flow systems. They observed that on a large (mine-wide) scale and under steady-state conditions spoil

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aquifers exhibit porous media characteristics. However, when a spoil aquifer is subjected to transient conditions or a stress (e.g., constant-discharge test) the conduit-flow characteristics become a dominant component of ground-water flow. Conduit-flow characteristics are also frequently observed within localized areas of a mine backfill. Large voids or conduits that exist within the spoil exert a substantial influence on the ground-water flow regime. Ground-water velocity, aquifer discharge rate, flow direction, and overall hydrologic properties are ultimately controlled by the lower hydraulic conductivity zones within the spoil between the large voids. Ground-water flow in a matrix of smaller particle sizes and pores is diffuse porous media in nature. Overall, these types of ground-water systems are best described as a double-porosity system.

Background

Over 125 monitoring wells located in surface mine spoil from 18 sites in Pennsylvania, West Virginia, Ohio, and Kentucky were tested using slug and constant-discharge tests. Single well recovery and tracer tests were also performed at a few sites; however, the results are not discussed herein. The test sites are shown on figure 1. Aquifer testing was performed to determine the effects, if any, of mine age, spoil lithology, types of mining equipment used, and other factors on spoil hydraulic properties. Using this data, the predictability of hydraulic properties of mine spoils is explored. Unless otherwise stated, the hydrologic data presented here were derived from slug testing.

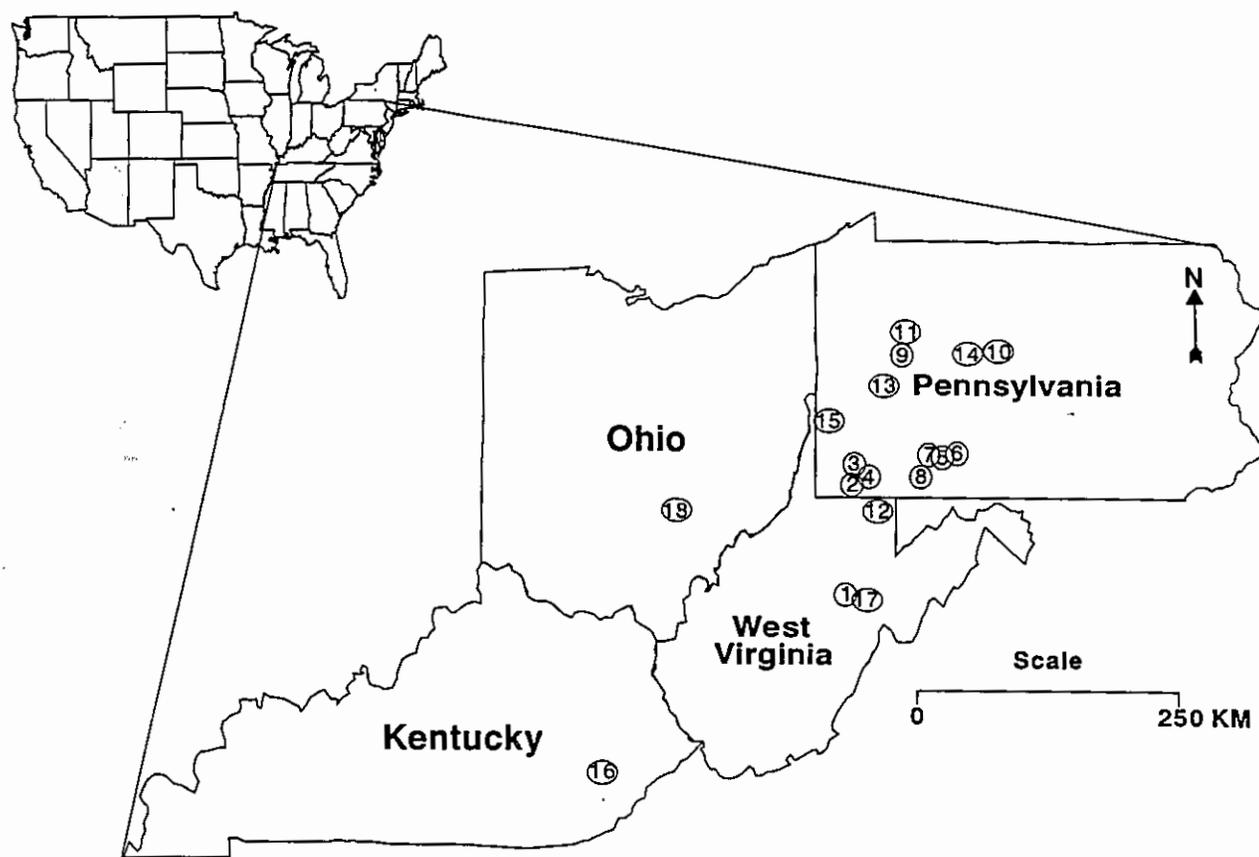


Figure 1. Test site location map.

Aquifer Testing Methods

The bulk of the aquifer tests conducted in mine spoil were slug tests (injection and withdrawal). A solid cylinder or a predetermined volume of water was used to

raise the water level in the monitoring wells during the slug injection tests. A bailer or a solid cylinder was used to lower the water level during the slug withdrawal tests. Water level displacement ranged from less than 1 to over 10 meters. Recovery to static water level was measured

using pressure transducers connected to data loggers. The data loggers, in the log mode, initially record water levels at 0.2 second intervals to the nearest 5 mm. The time interval between water level measurements increased with each log cycle with the maximum interval established at one minute. Test times ranged from less than ten seconds to over two hours. The slug tests results were analyzed using a method developed by Bouwer and Rice (1976) and Bouwer (1989). This method was designed for unconfined conditions. Mine spoil acts as an unconfined aquifer under most circumstances.

Constant-discharge tests were performed using a small portable submersible pump. Pumping rate ranged from 1 to 16 liters per minute. In a few cases, a hand pump was employed. The pumped well and one or two adjacent wells were monitored for drawdown with pressure transducers coupled to data loggers. The data were analyzed using the curve-matching method developed by Theis (1935).

General Spoil Aquifer Properties

Slug test results of surface mine spoils show a broad range of hydraulic conductivity and transmissivity values. These parameters exhibit a broad range across the

region and commonly exhibit a wide range within individual mine sites. Over 125 wells were tested; however, a few tests that yielded spurious results were excluded from the analyses. Table 1 illustrates that hydraulic conductivity ranged over 7 orders magnitude (4.45×10^{-9} to 7.58×10^{-2} m/s) for the 124 wells analyzed. A similar range was observed with transmissivity values. As with much of the data collected in the natural sciences, the hydraulic conductivity values are shown to be nonnormally distributed, strongly skewed to the right. The broad range of values and nonnormal data distribution make analysis, prediction, and modeling of mine spoil ground water systems difficult. However, some general trends have been observed and broad scale prediction is possible.

The data were analyzed using exploratory data analysis and elementary statistics. A logarithmic (base 10) transformation was used to approximate a normal distribution, which permits analysis with parametric statistics. Table 1 lists the summary statistics for all of the wells tested. With a logarithmic transformation, the data become somewhat more predictable. However, given the wide ranges of values observed and the highly skewed distribution, the predictive capabilities are limited.

Table 1. Summary Statistics

Parameter	Hydraulic Conductivity	Transmissivity
n	124	124\
Arithmetic Average	1.93×10^{-3} m/s	4.79×10^{-3} m ² /s
Median	1.72×10^{-5} m/s	4.58×10^{-5} m ² /s
Geometric Mean	1.70×10^{-5} m/s	4.30×10^{-5} m ² /s
Minimum	4.45×10^{-9} m/s	1.18×10^{-9} m ² /s
Maximum	7.58×10^{-2} m/s	2.04×10^{-1} m ² /s
Range (orders of magnitude)	7.23	8.24
Lower Quartile	1.63×10^{-6} m/s	4.30×10^{-6} m ² /s
Upper Quartile	1.67×10^{-4} m/s	3.66×10^{-4} m ² /s

Spoil Age, Lithology, and Thickness

The data were analyzed to determine potential impacts of geological conditions, mining methodology,

and time-related processes on the aquifer properties of surface mine spoil. Several factors can impact the transmissive properties of surface mine spoil, including age of the backfill, lithology of the spoil, spoil thickness,

topography, haulroads, equipment used, or whether nor not blasting was conducted. Experience and previous studies (Helgesen and Razem, 1980; Phelps, 1983; Aljoe and Hawkins, 1994) indicate that age of the backfill, spoil thickness, and spoil lithology may significantly influence spoil transmissive properties. It is often difficult to obtain accurate accounts of the mining equipment used and the equipment frequently changes during the operation. Accurate documentation of the degree and extent of blasting is often difficult to assess. Therefore, the factors of equipment used during mining and blasting were excluded from this study. However, because these factors likely impact spoil aquifer characteristics, it is recommended that future studies should consider them.

Exploratory data analysis indicates that spoil age has a direct relationship to hydraulic conductivity. For this study, spoil age was established as the time between completion of rough backfilling and the date of the aquifer test. For analysis, the spoil ages were divided into three groups: less than 31 months, 31 to 100 months, and over 100 months. The first group was based on the timing of complete water table re-establishment and a post-backfilling period of significant settling in this region. Helgesen and Razem (1980) observed that the water table re-establishment in eastern Ohio was nearly complete after 22 months. Whereas, Cunningham and Jones (1990) reported that the water table stabilized in approximately 30 months in a backfill in eastern Ohio. Experience in western Pennsylvania indicates that roughly 24 to 30 months is required for water table re-establishment (Hawkins, In-press). Similar climatic conditions exist throughout the northern Appalachian Plateau, therefore it is reasonable to expect a similar water table re-establishment time period for all the mines tested. Considerable settling of spoil has been documented to occur during the first 2 to 3 years after backfilling (Sweigard, 1987). Based on these studies, the first grouping was established at 30 months or less. The division between the second and third groupings (100 months) was established by an iterative process to determine where over time additional changes occur.

Figure 2 graphically illustrates the results of exploratory data analysis. The hydraulic conductivity values were log transformed to better visually plot on an arithmetic scale. Median hydraulic conductivity of sites 31 to 100 months old (2.4×10^{-4} m/s) is significantly higher than sites less than 31 months (6.1×10^{-7} m/s) and greater than 100 months old (2.4×10^{-5} m/s) at a 95% confidence level. This is indicated by the lack of overlap of the notches on the box-and-whisker plots. The greater

hydraulic conductivity at sites in the second group compared to the first group may be related to the improved interconnectedness of voids created during backfilling that occurs with complete re-establishment of the water table around the 24 to 30 month period. As the water table begins to re-establish, vertical and horizontal ground water movement can cause piping and settling of the fine-grained spoil particles, thus opening up more direct ground-water flow paths. The changes associated with the third group (>100 months) compared to the second group (31-100 months) appear to be more gradual. The decreasing hydraulic conductivity of the older spoils may be due to settling, piping, and compaction over the long term. These processes act to decrease the void and pore spaces, thus decreasing the effective porosity and increasing the bulk density. This interpretation of relationship between mine spoil age and hydraulic conductivity implies that spoil aquifers continue in a state of flux long after reclamation. Spoil continues to settle and subside well beyond the 2 to 3 year period observed by Sweigard (1987), but apparently at a lower rate as indicated by the aquifer testing.

Data were also analyzed for an anticipated relationship between spoil lithology and hydraulic conductivity. Backfill lithology was determined from premining drill hole logs. The areal extent of each site was also planimetered to permit determination of the lithologic content of the spoil based on volume.

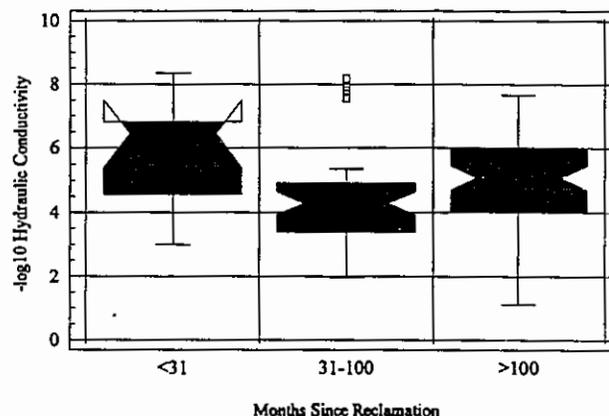


Figure 2. Notched box-and-whisker plot of spoil hydraulic conductivity versus age.

Numerous iterations analyzing variable sandstone and shale percentages against hydraulic conductivity showed few significant groupings. However, figure 3 illustrates a slight trend of increasing hydraulic conductivity with increasing sandstone percent. Sites

over 100 months old, with sandstone content over 80%, have significantly higher K than sites between 20 and 80%. This significant difference does not continue to sites with less than 20% sandstone. This lack of difference may be related to the relatively small number sites in the first grouping, which tends to give an artificially broad 95% confidence interval (notch). The higher hydraulic conductivity values associated with increasing sandstone content probably results from differences in spoil particles sizes. During mining and reclamation, sandstone tends to break into larger fragments than shale. If the rocks are conducive to weathering, sandstones tend to breakdown into sand-sized particles, while shales tend to breakdown into smaller clay-sized particles. Therefore, such tendencies may account for the relationships observed in this study.

Lack of additional trends in the lithology analysis may be caused by several factors including, significant differences between sandstones and shales across the region. Some sandstones or shales are hard and well cemented compared to others. However, in drill hole logs they are all classified as to their lithology and not degree of cementation. The better cemented units will not fragment the same during the mining operation and tend to weather at substantially slower rates than poorly indurated units. If these differences could be factored into the analysis, perhaps other more clearly defined trends would be observed. Lithologic impacts may also be masked by the previously discussed settling and subsidence that occurs in the backfill over time. The rate of continued settling and subsidence after 100 months since backfilling is substantially less than at earlier times, therefore the lithologic trend discussed above became noticeable. A tertiary factor is the random monitoring well placement relative to the location of spoil ridges and valleys, covered over during reclamation, which are known to exhibit significantly different transmissive properties (Groenwald and Bailey, 1979; Hawkins and Aljoe, 1991). Additionally, discrete monolithic zones created by the mining and reclamation operation (e.g., removal of overburden in layers or self sorting that occurs by particle size, hence lithology) can exist within mines. These monolithic zones can be created at sites where the overburden composed mainly of a single rock type as well as lithologically-mixed sites (Hawkins, In-press). For example, it is not unexpected that a mine with a spoil content of 80 percent sandstone and 20 percent shale may have one in five randomly-drilled wells located in a shale-rich zone. Therefore, even though the spoil may be predominantly one rock type, there can be a wide range of transmissive values across the site given a sufficient number of monitoring wells; thus obscuring expected trends or predictability.

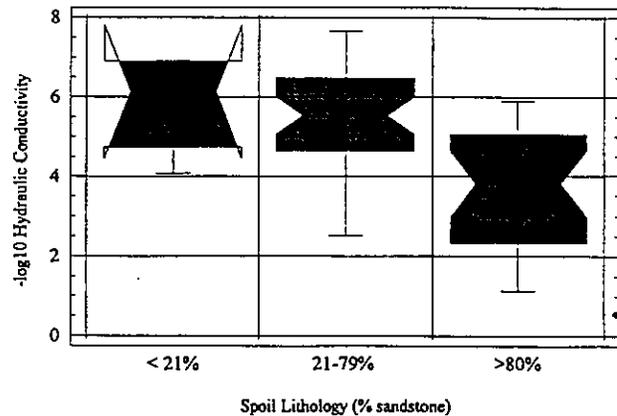


Figure 3. Notched box-and-whisker plot of spoil hydraulic conductivity versus lithology at sites greater than 100 months old.

The effect of spoil thickness on hydraulic conductivity was examined with the hypothesis that deeper saturated zones of thicker spoil areas would be more compacted and therefore less transmissive. These data were analyzed employing several statistical procedures; however, no significant relationships were observed. However, some individual sites exhibit moderate trends where decreasing hydraulic conductivity corresponds to increasing spoil thickness. Figure 4 is an example of this relationship. This trend contradicts Phelps (1983), who observed a general decrease in bulk density with depth. When all of the sites are plotted the scatter greatly increases and no distinct trend is noted.

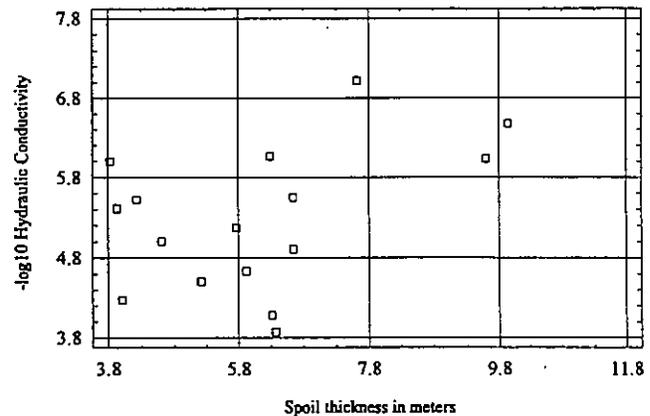


Figure 4. Relationship of hydraulic conductivity and spoil thickness at site 1.

Variability Within and Between Mines

Great variability of hydraulic properties are frequently observed within individual mine sites. At sites that 5 or more wells were tested, hydraulic conductivity and transmissivity values ranged up to 5 and 6 orders of magnitude, respectively. Most sites ranged at least 3 orders of magnitude for either parameter. Two of the mine sites had hydraulic properties that ranged 1 one order of magnitude and none of the sites had a range of less than an order of magnitude.

Median hydraulic conductivity values ranged over 3 orders of magnitude (2.63×10^{-7} to 1.1×10^{-3} m/s) between mine sites. The majority of mines had median hydraulic conductivity values ranging less than 2 orders of magnitude, 10^{-6} to 10^{-5} m/s. Transmissivity median values ranged over 3 orders of magnitude (3.72×10^{-7} to 2.14×10^{-3} m²/s) with the majority of sites ranging more than 2 orders of magnitude (10^{-6} to 10^{-4} m²/s).

Constant-Discharge Tests

Constant-discharge tests were conducted on 10 wells from 6 mines where slug tests were likewise

performed. These paired tests were conducted to evaluate the consistency of methods for characterizing mine spoil aquifers and to qualitatively ascertain aquifer heterogeneities over short distances. It is known that the transmissive properties of mine spoil are highly heterogeneous and anisotropic (Hawkins and Aljoe, 1990). Slug tests by their nature are short in duration and test a limited area around wells. The area of influence around a well is a few meters for most slug tests. Whereas, constant-discharge test are generally conducted for longer time periods than slug tests and test a much larger area surrounding the well. Depending on the length of a constant-discharge test, several hundred meters of aquifer about the pumping well may be effected.

As shown in Table 2, five of the paired tests exhibited hydraulic conductivity values within an order of magnitude. However, constant-discharge tests in three of ten pairs yielded substantially higher hydraulic conductivity values, 3 or 4 orders of magnitude greater. For seven of ten pairs the slug tests yielded lower hydraulic values than the constant-discharge tests. Similar results were exhibited by a comparison of the transmissivity values.

Table 2. Paired Aquifer Test Results

Site Number	Well	Hydraulic Conductivity (m/s)		Transmissivity (m ² /s)	
		Slug Test	Constant-Discharge Test	Slug Test	Constant-Discharge Test
1	A	9.36×10^{-7}	1.16×10^{-2}	4.71×10^{-6}	5.80×10^{-2}
1	B	1.24×10^{-5}	3.35×10^{-2}	3.86×10^{-5}	1.14×10^{-1}
1	C	9.54×10^{-8}	5.61×10^{-3}	1.37×10^{-7}	8.76×10^{-3}
9	A	2.97×10^{-4}	6.90×10^{-4}	2.49×10^{-4}	1.63×10^{-3}
11	A	3.28×10^{-5}	3.60×10^{-7}	1.49×10^{-4}	1.64×10^{-6}
15	A	1.19×10^{-4}	2.28×10^{-4}	7.70×10^{-4}	4.49×10^{-4}
16	A	1.01×10^{-5}	1.42×10^{-6}	3.62×10^{-5}	5.06×10^{-6}
17	A	6.93×10^{-8}	1.33×10^{-7}	1.77×10^{-7}	5.96×10^{-7}
17	B	2.50×10^{-8}	2.12×10^{-6}	9.63×10^{-8}	5.47×10^{-6}
17	C	3.88×10^{-6}	4.54×10^{-7}	2.84×10^{-5}	2.90×10^{-6}

Anomalous Aquifer Responses

Unusual responses to aquifer testing, specifically the slug testing, were observed at a few spoil wells in the

region. These unusual responses are directly related to the heterogeneous nature of mine spoil. Spoil aquifers at times can be highly conductive in one direction, while exhibiting very low conductance in others.

The well response to a slug injection test conducted at a monitoring well in relatively fresh spoil (<1 year old) at site number 8 was conspicuous by a lack of response. The well was slugged with 36.9 liters (9.75 gallons) of water with a projected displacement of 2 meters (6.5 feet). The initial water level reading, which was 0.2 seconds into the test, showed no measurable water level rise. The water used for the slug test exited the well as fast as it was introduced. This indicates that the well was in direct contact with ultratransmissive spoil having large well-interconnected voids that can accept water as fast as the physical constraints of the well permit. An initial oscillatory water-level response to the slug introduction was observed at a few wells throughout the region. Underdamped water level oscillations in response to a slug test are allowed at wells where the water level reacts to the inertia of the displacing slug mass (van der Kamp, 1976). The inertial effect of the water mass can be ignored in most slug tests because of dampening caused by aquifers with low to moderate transmissive properties. Analyses for these low to moderately permeable (dampened) aquifers have been developed by Cooper and others (1967); Papadopulos and others, (1973); and Bouwer and Rice, (1976). Conversely, underdamped aquifers require different methodologies to analyze the test results (van der Kamp, 1976 and Kipp, 1985). Underdamped water-level oscillations are common to highly transmissive aquifers (e.g., karstic limestones and unconsolidated glacial sediments) and some extremely deep wells.

Figure 5 is an example of an oscillatory water-level response that was observed from one of the slug tested spoil wells. The oscillations observed in the spoil wells generally subsided relatively rapidly compared to published tests from other aquifers (Kipp, 1985). Most spoil responses ceased within 10 seconds after the initial water level displacement. This indicates that, although these aquifers are transmissive, the associated water-level oscillations are dampened to a minor extent by comparison to other aquifers exhibiting an oscillatory response. After this initial oscillating period, the water level recovered monotonically, as expected in dampened system of low to moderately transmissive aquifers. For these wells, the initial oscillating period was excluded

from the hydraulic conductivity determination, because the later portion of the test, which lasted considerably longer (1 to over 120 minutes) is more indicative of the overall transmissive properties of the spoil aquifer surrounding the test well. The larger voids and conduits immediately adjacent to the well facilitate the water-level oscillations; however, the lower transmissive spoil material that encompasses the voids is the controlling factor for ground water movement. Therefore, the transmissive properties determined by the later and longer portions of the tests were used in this study.

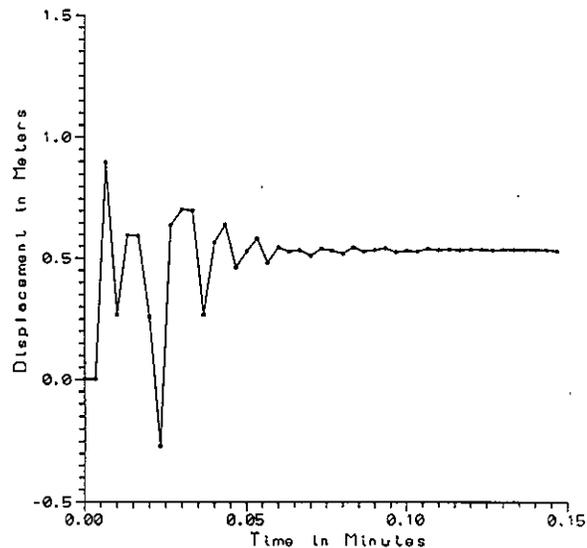


Figure 5. Example of an underdamped oscillatory water level response to a slug injection.

Conclusions and Recommendations

The wide range of hydraulic parameters is directly related to the highly heterogeneous and anisotropic nature of surface mine spoil. Unless specifically located, monitoring wells installed in a mine backfill with a mixed lithology will, in all likelihood, randomly access substantially different spoil zones. Some wells may access spoil zones with large void spaces surrounding large spoil fragments (high permeability areas), other wells may access zones with substantially smaller voids surrounding smaller spoil fragments (low permeability areas), and still others may access mixed spoil zones with moderate pore spaces (intermediate permeability areas). The spoil zones with smaller fragments are commonly comprised of shales and claystones that weather to form clay materials which tends to make these zones even less permeable over time.

Conversely, the high permeability zones tend to be sandstone-rich that can weather to form sand-sized particles. The sand particles tend to fill in the existing voids which will reduce the permeability somewhat, however, permeability will still be significantly greater than the shale-rich zones. The number of any randomly drilled wells that will intersect a relatively monolithic zone is directly related to: the percentage of each rock type, the equipment used, and mining methods.

The hydraulic properties of spoil evolves with age. Lower hydraulic conductivity values are associated with young spoil (<31 months) and old spoil (>100 months) compared to moderately aged spoil (31-100 months). These differences are apparently associated with settling, compaction, subsidence, and piping within the backfill. The impact of spoil lithologic differences exhibited few trends in relationship to the hydraulic properties. This lack of relationship appears to be caused by poorly defined lithologic properties and/or masking of trends by the substantial state of flux exhibited by spoil after backfilling.

In the future, additional testing of spoil aquifers coupled with better definition of geologic and mining-related factors is needed. This may illustrate additional relationships and/or more clearly define those observed herein. A "cradle-to-grave" type of study where a surface mine is monitored and documented prior to mining, extensively during mining, and after mining is recommended. In this type of study, the location of spoil ridges and valleys and monolithic and mixed zones could be mapped so that monitoring wells could be installed into these areas of interest. Spoil lithology and particle size analyses would be conducted as backfilling progressed. This type of study would provide significant insight into the influence that particle size, lithology, well location, and changes over time may have on spoil hydraulic properties.

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