

Hydrogeological behaviour of an unsaturated waste rock pile: a case study at the Golden Sunlight Mine, Montana, USA

Shahid Azam · G. Ward Wilson · Greg Herasymuik ·
Craig Nichol · Lee S. Barbour

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Abstract Parent geology, mining operation, construction practice and weathering processes govern the hydrogeological behaviour of waste rock piles. Variable heterogeneity in such earth structures requires site specific correlations. Based on field investigation and laboratory characterization, this paper developed a physical model for the unsaturated East Pile at the Golden Sunlight Mine in Montana, USA. Results indicate that the pile had interfingering dipping beds characterized by a matrix-supported structure in the fine grained layers and a clast-supported structure in the coarse grained layers. Waste rock with at least 45% sand retained water ($\psi_a = 2\text{--}4$ kPa, $\psi_r = 20\text{--}40$ kPa, $k_{\text{sat}} = 3.5 \times 10^{-3}$ cm/s, $k_{\text{unsat}} = 2\text{--}3$ orders of magnitude lower at 100 kPa) whereas materials with less than

45% sand drained rapidly ($\psi_a < 1$ kPa, $\psi_r < 10$ kPa, $k_{\text{sat}} = 1 \times 10^{-1}$ cm/s, $k_{\text{unsat}} > 6$ orders of magnitude lower at 10 kPa).

Résumé Le contexte géologique, les opérations minières, le mode de mise en place des stériles et les processus d'altération régissent le comportement hydrogéologique des verses à stériles. La forte hétérogénéité de ce type de structure demande des investigations détaillées. Sur la base de travaux de terrain et de caractérisations au laboratoire, l'article présente un modèle physique pour milieux non saturés, développé pour le stockage Est de la mine de Golden Sunlight au Montana (USA). Les résultats montrent que la verse à stérile est constituée de lits différents interstratifiés suivant un certain pendage, les niveaux à grains fins présentant une structure à matrice portante, les niveaux à grains grossiers présentant une structure à éléments grossiers jointifs. Les stériles avec au moins 45% de sable retiennent l'eau ($\psi_a = 2\text{--}4$ kPa, $\psi_r = 20\text{--}40$ kPa, $k_{\text{sat}} = 3.5 \times 10^{-3}$ cm/s, $k_{\text{unsat}} = 2\text{--}3$ ordres de grandeur inférieur au cas saturé, avec une succion de 100 kPa), tandis que les matériaux avec moins de 45% de sable se drainent très rapidement ($\psi_a < 1$ kPa, $\psi_r < 10$ kPa, $k_{\text{sat}} = 1 \times 10^{-1}$ cm/s, $k_{\text{unsat}} > 6$ ordres de grandeur inférieur au cas saturé, avec une succion de 10 kPa).

S. Azam (✉)
Department of Mining Engineering,
University of British Columbia, 6350 Stores Road,
V6T 1Z4 Vancouver, B.C., Canada
e-mail: shahid_azam@hotmail.com

G. W. Wilson
Department of Mining Engineering,
University of British Columbia,
Vancouver, B.C., Canada

G. Herasymuik
Golder Associates Limited,
Edmonton, AB, Canada

C. Nichol
Department of Civil and Geological Engineering,
University of Saskatchewan, Saskatoon, SK, Canada

L. S. Barbour
Department of Civil and Geological Engineering,
University of Saskatchewan, Saskatoon, SK, Canada

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Introduction

Knowledge of the hydrogeological behaviour of soil and rock masses is indispensable in developing sustainable (cost effective, environment friendly, socially viable) solutions for metal leaching and acid rock drainage (Azam 2000). This is particularly true for large-scale mining operations where huge quantities of waste rock with no economic value are generated as a by-product over a number of years (Wickland and Wilson 2005). The waste rock comprises of low-grade and barren materials which have to be excavated to access the underlying metal-rich ore body. During active mining, the intact rocks from different geological facies are broken down to various degrees by blasting and sequentially deposited along a hillside. The conventional pile construction method, known as *end dumping*, results in material segregation as the coarse chunks travel longer distances than the fine particles (Herasymuik et al. 2006). As the pile face advances, the heterogeneity within the pile gradually increases owing to repetitive trafficking of heavy machinery. The internal configuration of the deposited material evolves over time due to physical and chemical weathering under the prevalent climatic conditions (Molson et al. 2005). This internal structure governs the hydrogeological behaviour of the man-made earth structure.

The heterogeneity of waste rock piles has been recently recognized in several studies, for example those focusing on field monitoring (Morin et al. 1994), large-scale testing (Nichol et al. 2000) and numerical modelling (Fala et al. 2003). Whereas most studies have consistently postulated that the spatial variability of materials contributes to the presence of preferential water flow paths in the piles, a generalized physical model describing waste rock hydrogeology does not exist. This is because the internal structure of waste rock piles is influenced by several factors including: (1) parent geology (material properties and mineral composition); (2) mining operation (blasting and sequencing); (3) construction practice (transportation and dumping); and (4) climatic conditions (temperature and precipitation). Lefebvre et al. (2001) compared the physicochemical properties of two waste rock piles: Doyon (Canada) and Nordhalde (Germany). These authors found significant variations between the two piles and developed separate models to explain the observed water flow. Clearly, material heterogeneity and the resulting hydrogeological behaviour in waste rock piles is site specific.

This paper presents the hydrogeological behaviour of a waste rock pile at the Golden Sunlight Mine in

Montana, USA. Field investigation and laboratory characterization were used to describe the unsaturated pile. Physical appearance, water content, temperature and dry density were directly determined in the field. Laboratory characterization included the determination of grain size distribution, soil water characteristic curve (SWCC) and saturated hydraulic conductivity (k_{sat}) thereby estimating the hydraulic conductivity functions. Results were combined to develop a physical model for the East Pile.

Site description

The Golden Sunlight Mine is an open pit gold mine located at latitude 46°N and longitude 112°W in south western Montana, USA. The mine site lies on the eastern flank of a fault-bounded mountain range known as the Bull Mountains. Mine development began in 1982 and construction of waste rock piles was initiated almost simultaneously. The waste rock deposition reactivated an ancient low-angle slip in the underlying pre-sheared clay and affected an area of more than 3 km². Operations were suspended in the summer of 1994 to undertake remedial measures. The removal of 15 million tons of overburden waste rock stopped the slip block movement and operations resumed in early 1995. Remedial excavations also provided access to in situ waste rock that ranged from recently deposited to several years old. Field investigations were conducted from September 1994 through February 1995.

The East Pile was constructed by end dumping the waste rock from several platforms directly along an existing hillside. Haul trucks were used to dump the waste and the surface was levelled by pushing the deposited material using bulldozers. The pile front gradually advanced as the waste material was allowed to run downslope at the angle of repose (measured as 38°). Based on configuration, the pile is categorized as a *terraced side valley pile* as defined by Taylor and Greenwood (1985).

The geology of the mine site includes Proterozoic clastic sedimentary rock which was intensively intruded by latite magma during the Cretaceous. The East Pile lithology primarily comprises shale and latite porphyry rocks with massive dissemination of sulphide minerals; mafic rocks such as potassic trachybasalts and basaltic andesites and lamprophyry are also present. According to Herasymuik et al. (2006), the unoxidized rock contains 2–5% pyritic sulphur and has negligible neutralizing capacity.

South western Montana falls within the Semi Arid (BSk) climate according to the Köppen Climate

Classification. The average annual rainfall at the mine site is 240 mm, of which more than 75% falls between April and September; the average annual pan evaporation equals 1,050 mm (Newman 1999). Typical temperature fluctuations of the continental climate are locally buffered by Pacific air masses, cool air movement from the Rocky Mountains into the valleys and mountain shielding. The average annual temperature is 7°C but varies over a wide range of -40°C to +38°C. Ground freezing at the mine site can occur from September to early June. The relative humidity averages 50% during summer and can increase up to 65% during winter months. According to Azam (2000), fluctuating temperature and relative humidity in semi arid climates lead to variations in the behaviour of soil deposits. Swanson (1995) estimated the annual net infiltration through uncovered waste rock piles to be between 20 and 100 mm.

Research program

The research program comprised two main parts. Field investigations were conducted to determine the texture and internal structure as well as water and temperature distribution in the East Pile. Laboratory characterization focused on the determination of grain size distribution, SWCC, and k_{sat} thereby estimating the hydraulic conductivity functions.

The field investigations carried out during the remedial excavation were initiated at the pile surface (1,682.5 m (5,520 ft) a.m.s.l) and continued down to 1,634 m (5,360 ft) a.m.s.l in 18 m high benches. Simultaneously, 29 test pits (3.0–4.6 m deep) were excavated on four separate benches along two north-south and two east-west transect lines, all of which were routinely surveyed. Using a Kobelco tracked mounted hoe and D8 CAT, the near wall of each test pit was angled and the far wall left vertical. The inclined surface was used as an access for personnel and equipment to and from the test pit whereas logging and sampling were carried out in the vertical face. The exposed stratigraphy in each test pit was recorded as a function of grain size and colour change and the conspicuous layers were photographed and logged with respect to their physical appearance: texture, structure, degree of voids infilling, weathering state and strike/dip angle.

Water content was measured according to the ASTM Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass (D2216-05). A total of 242 representative samples were retrieved from selected locations in the test pits using 250 mL plastic bottles, which were

immediately sealed to preserve the field moisture. The in situ temperature was directly measured using a portable digital indicator (Vaisala HMI 31). The probe was inserted into a pre-drilled hole, sealed in place and allowed to equilibrate. The in situ dry density was measured according to the ASTM Standard Test Methods for Density of Soil and Rock in Place by the Sand Replacement Method in a Test Pit (D4914-99).

Laboratory characterization was conducted on waste rock obtained from the various test pits. With the exception of very coarse material, two bulk samples were retrieved from selected layers providing 242 air-dried samples (weighing in excess of 2,100 kg). The grain size distribution was determined according to the ASTM Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates (C136-05). Based on grain size distribution, five representative waste rock samples were selected for detailed laboratory testing.

The SWCC test was conducted according to the ASTM Standard Test Method for Capillary Moisture Relationships for Coarse and Medium Textured Soils by Porous Plate Apparatus (D2325-68, re-approved 2000). A large pressure plate (156 mm internal diameter and 178 mm high) with a high air-entry ceramic disk was used to determine the drying SWCC. Each sample was placed in the cell in a saturated state and incrementally drained by applying a pre-determined air pressure through an inlet tube. The matric suction was equal to the pressure difference across the air-water interface. Water flow through the sample and the ceramic disk was initially rapid and gradually decreased with time. When the flow ceased, the measurement of water volume under the applied matric suction was stopped and the air pressure was increased to the next higher value. At 100 kPa matric suction the sample was dismantled and the final water content determined by oven drying.

The k_{sat} was determined according to the ASTM Standard Test Method for Permeability of Granular Soils (Constant Head) (D2434-68(2000)). The tests were conducted on three of the five selected samples containing at least 45% material finer than 4.75 mm. The other two samples were too coarse and therefore not compatible with the small size (73 mm internal diameter and 168 mm high) of the constant head permeameter. Such tests would have yielded erroneous results unsuitable for meaningful interpretation.

Field investigations

A visual inspection of waste rock at the East Pile indicated typical material segregation, with the grain

size increasing with depth leading to the formation of a distinct rubble zone at the base of successive lifts. Figure 1 gives the texture of the waste rock at the East Pile. At the pile scale (A), compacted horizontal layers were commonly found at the top of each 18 m high bench where heavy equipment trafficking caused particle break down in the placed material. Layers inclined at the angle of repose (38°) were observed below the pile platforms. Attributed to gravity sorting and material intermixing, these layers varied in thickness from 100 mm to 2 m. At the bench scale (B), multiple inter-fingered dipping beds were distinguishable because of variation in grain size, texture, colour and composition. Continuous beds extending from the surface to the pile toe were generally absent in the investigated waste rock pile.

Figure 2 presents the internal structure of the East Pile. The deeply embedded material (A) appeared to have undergone excessive weathering compared to that on the outer rim of the pile. A grain size larger than 25 mm was associated with latite (near hammer in Fig. 2) that is relatively more resistant to weathering. The relatively smaller grain size was related to the

oxidation of shale (upper layer). The freshly deposited fine-grained shale (B) completely lacked a coherent structure and ferric hydroxide staining was virtually absent in the waste rock. At the time of placement, the shale exhibits a fairly uniform grain size distribution that gradually weathers to a much finer material (Morin et al. 1994). The variable degree of weathering increased spatial heterogeneity within the pile and the internal structure of the waste rock could be divided into two distinct types (Nichol et al. 2000). A clast supported structure was mainly observed in the coarse grained material due to the large voids that were devoid of fines. Conversely, silt and fine sand filled the voids between the larger clasts and formed a matrix-supported structure in the fine grained layers.

Figure 3 gives the measured water content versus depth below ground in the East Pile. A relatively high water content (4–14%) existed in the upper 3 m of the pile and a lower water content ($3 \pm 1\%$) in subsequent benches up to a depth of 42 m. The median of the observed data is envisaged to gradually decrease and eventually convert to a near vertical line (representing 1–2% water) from 42 to 85 m. The figure suggests the

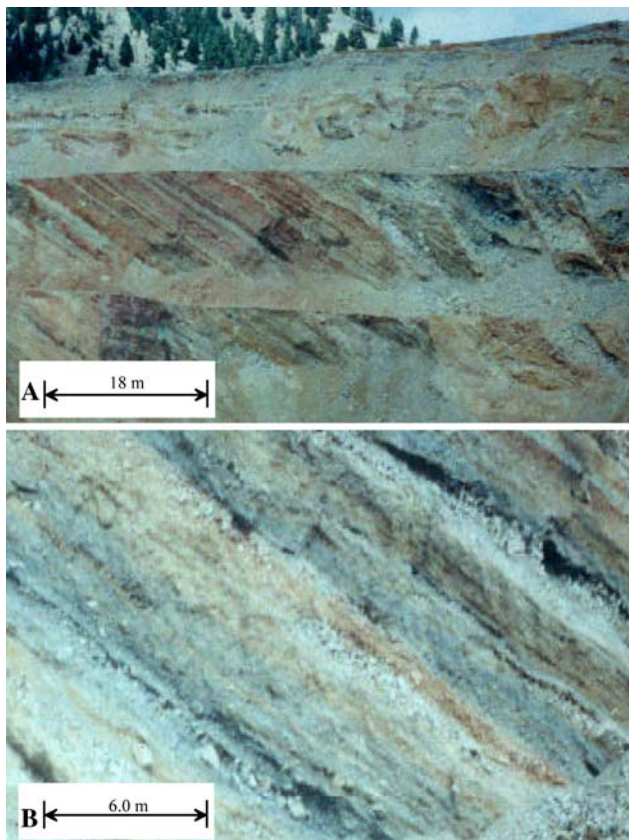


Fig. 1 Material texture in the East Pile: **a** pile scale; and **b** bench scale

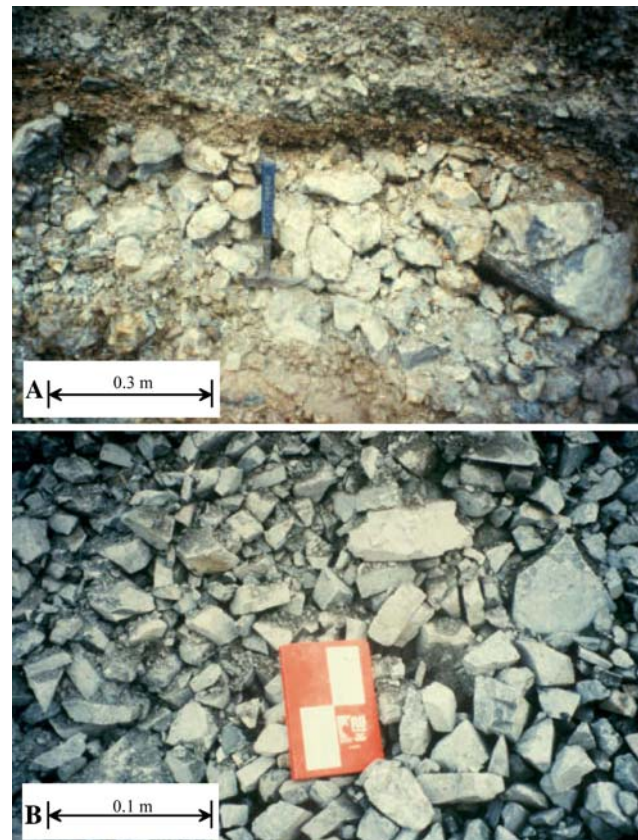


Fig. 2 Internal structure of the East Pile: **a** embedded material; and **b** fresh material

presence of a wetting front from the surface down within the pile. The measured water content in the surface layer corresponds to the estimated value of about 3% water content for fresh waste rock (Swanson 1995). The desiccation of waste rock with depth is attributed to water escape through venting, water consumption during pyrite oxidation and a low recharge in the semi-arid climate of the area (Lefebvre et al. 2001).

The in situ dry density measured between 1,500 kg/m³ and 2,100 kg/m³, with an average of 1,900 kg/m³. The measurements were only possible in the areas of fine waste rock and do not capture the full range of possible densities within the pile. The in situ dry density of the materials was used to prepare samples for the determination of k_{sat} .

Figure 4 plots the measured temperature as a function of depth below the surface in the East Pile. The average temperature in the upper 3 m was found to be 30°C and gradually decreased to about 10°C at a depth of 60 m. During the entire 6 month long field investigation, the observed average exceeded the annual average air temperature (7°C). This is attributed to exothermic reactions associated with mineral oxidation within the pile (Molson et al. 2005). The temperature gradient governed the movement of water vapour through the East Pile, as highlighted by the venting of high temperature (37–58°C) and moist (100% RH) air at a depth of 25 m from a coarse grained layer. The upward movement of vaporized water significantly affects water distribution within waste rock piles (Fala et al. 2003). Water recycling due to vapour transport from the bottom up hampered the advancement of a wetting front in the East Pile.

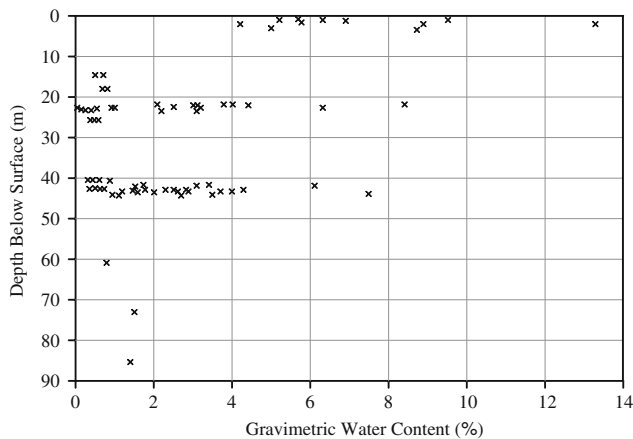


Fig. 3 Measured water content profile, East Pile

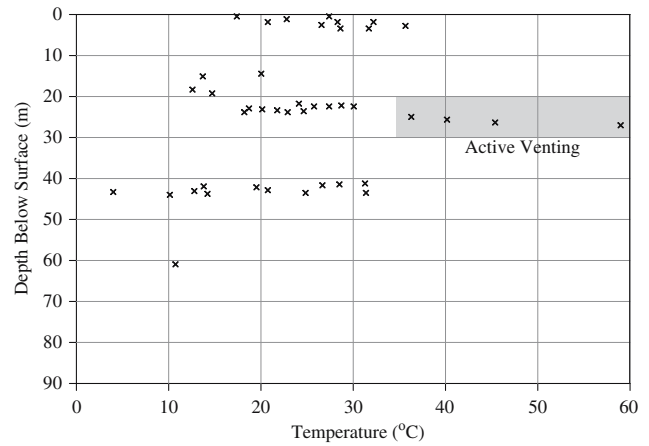


Fig. 4 Measured temperature profile, East Pile

Material characterization

Figure 5 gives the grain size distribution of the waste rock samples. The various grain sizes were defined as follows: fine sand (0.075–0.425 mm); medium sand (0.425–2.0 mm); coarse sand (2.0–4.75 mm); fine gravel (4.75–19 mm); coarse gravel (19–75 mm); and cobbles (75–300 mm). The investigated waste rock samples varied from gravelly sands (U, upper limit) to gravelly cobbles (L, lower limit). The latter limit of the investigated samples was not essentially the limit for the in situ waste rock materials because boulders larger than 100 mm were excluded from laboratory tests due to sampling difficulty. To determine the transition from a soil-like behaviour to a rock-like behaviour, five waste rock samples adjacent to the upper limit of the envelope were selected for detailed material characterization. This selection was based on the percentage of material passing the ASTM Sieve No. 4 (4.75 mm),

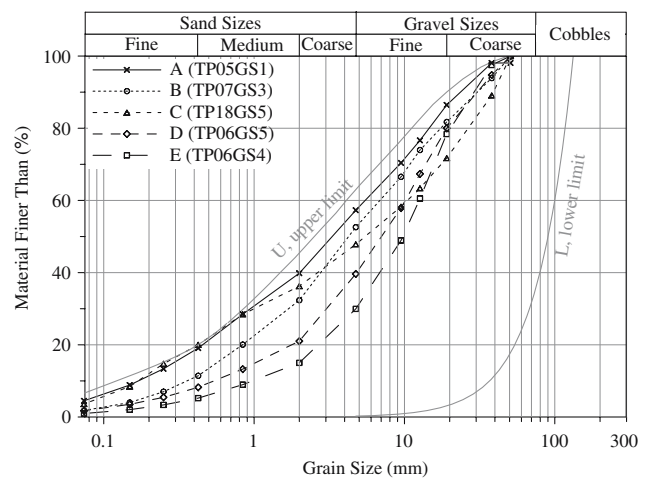


Fig. 5 Grain size distribution of waste rock samples

which marks the boundary between gravel and sand sizes. The selected samples, designated as A, B, C, D, and E, contained 57, 53, 48, 40, and 30% material finer than 4.75 mm, respectively.

Table 1 summarizes the grain size distribution analyses for the selected waste rock samples. The material fraction finer than 4.75 mm was used along with the coefficient of curvature (C_c) and the coefficient of uniformity (C_u) to classify the waste rock samples according to the Unified Soil Classification System (USCS). Samples containing more than 50% material finer than 4.75 mm were classified as sands and the reverse was true for gravels. Likewise, well graded materials exhibited a C_c of at least 1.0 together with a C_u of more than 6 for sands or more than 4 for gravels. The amount of gravel gradually increased from sample A through E and the samples ranged from well graded gravelly sands through well graded sandy gravels. The selected samples were classified as SW, SW, GP, GW and GW respectively.

Figure 6 gives the SWCC for the selected waste rock samples. The measured data were fitted according to the following function (Fredlund and Xing 1994):

$$\theta = \frac{\theta_s}{\left\{ \ln \left[e + \left(\frac{\psi}{a} \right)^b \right] \right\}^m} \quad (1)$$

where, θ was the volumetric water content, θ_s was the saturated volumetric water content, ψ was the soil suction (kPa), and a , b , and m were constants. Table 2 summarizes the SWCC of the selected samples. Studying Fig. 6 in conjunction with Table 2 indicates two types of hydrogeological behaviour for the investigated materials.

Samples A, B and C exhibited identical water retention characteristics and their air entry values (ψ_a) were between 2 and 4 kPa (corresponding to 0.2 m and 0.4 m of water). For these samples, the volumetric water contents declined with an increase in suction such that the residual matric suction (ψ_r) values were between 20 and 40 kPa. These characteristics are

attributed to the relatively small pore spaces that were effective with respect to capillary flow through the samples (Diodato and Parizek 1993). The low θ_s (water storage) of sample C was primarily due to the gap-graded grain size distribution that overshadowed the effect of the fine and medium sand size material. The presence of coarse particles reduced sample porosity and the larger voids were mostly not filled by the fines. Despite these small variations, the SWCC for samples A, B and C clearly indicated that the behaviour of such waste rock materials is similar to that of sandy soils as generally encountered in geotechnical engineering practice (Fredlund and Rahardjo 1993). The almost 10% decrease in the material finer than 4.75 mm from sample A through C was not sufficient to result in a completely changed hydrogeological behaviour.

The addition of gravel to sand replaced a portion of the fine grained material and the accompanying capillary water as shown by samples D and E. Based on experimental data, both of these samples did not exhibit distinct air entry values and the fitted SWCC indicated ψ_a well below 1 kPa. Likewise, the residual water content (θ_r) for both samples was reached at a matric suction of less than 10 kPa. Figure 6 shows that

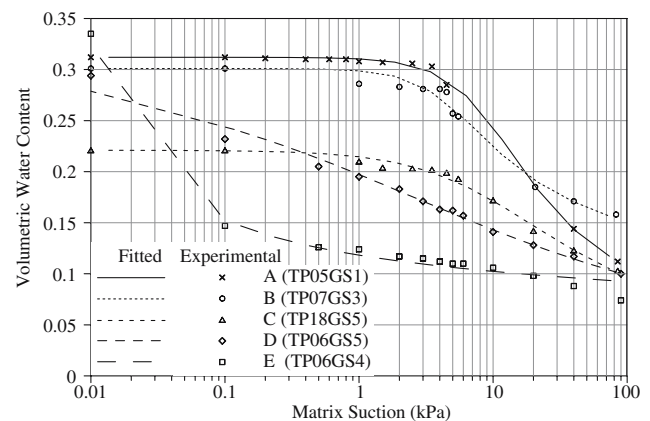


Fig. 6 Soil waste characteristic curves for selected waste rock samples

Table 1 Summary of grain size distribution of selected waste rock samples

Sample ID	-4.75 mm (%)	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_c^a	C_u^b	USCS classification/description
A (TP05GS1)	57.3	0.2	1.1	5.7	1.2	28.5	SW/well graded gravelly sand
B (TP07GS3)	52.6	0.4	1.8	7.3	1.1	18.3	SW/well graded gravelly sand
C (TP18GS5)	47.9	0.2	1.1	10.6	0.6	53.0	GP/gap graded sandy gravel
D (TP06GS5)	39.7	0.6	3.3	10.2	1.8	17.0	GW/well graded sandy gravel
E (TP06GS4)	29.9	1.0	4.8	12.6	1.8	12.6	GW/well graded sandy gravel

^a Coefficient of curvature, $C_c = (D_{30})^2 / (D_{10})(D_{60})$

^b Coefficient of uniformity, $C_u = D_{60} / D_{10}$

Table 2 Summary of the SWCC of selected waste rock samples

Sample ID	Saturated volumetric water content θ_s	Air entry value ψ_a (kPa)	Residual volumetric water content θ_r	Residual matric suction ψ_r (kPa)	Fitting parameters		
					a (kPa)	b	m
A (TP05GS1)	0.31	3.42	0.14	39.80	8.08	1.88	0.68
B (TP07GS3)	0.30	2.56	0.19	21.54	3.98	2.07	0.36
C (TP18GS5)	0.22	3.10	0.12	40.06	7.70	1.08	0.76
D (TP06GS5)	0.29	0.16	0.14	9.62	0.53	0.42	1.21
E (TP06GS4)	0.34	0.02	0.13	0.38	0.12	5.94	0.32

the volumetric water content of sample D varied steadily through the entire range of applied suction. When the amount of fines was further reduced (sample E), the void spaces between the gravels were substantially larger and remained unsaturated (Fredlund and Rahardjo 1993). Sample E exhibited a sharp drop in the volumetric water content from 0.01 to 0.1 kPa and thereafter decreased gradually. Collectively, samples D and E exhibited a rock-like hydrogeological behaviour that was different from the soil-like behaviour displayed by samples A, B, and C.

The observed SWCC of the selected samples is attributed to the type of internal structure developed by the waste rock materials. Based on a material fraction finer than 4.75 mm, a 45% sand size in the samples was found to be sufficient to create a fines matrix that contained some of the individual gravel particles. Irrespective of whether the coarse particles were in contact or not, the fines filled the entire space left vacant by the coarse particles (Wickland and Wilson 2005). The smaller void sizes in this matrix-supported internal structure were responsible for some water retention as indicated by a ψ_a equal to 2–4 kPa (samples A, B, and C). On the contrary, when the amount of fines was lower than 45% of the above grain size limit, the coarse particles were touching one another and left behind larger void spaces. The larger pores in such a clast-supported internal structure were insignificant in water retention and hence the air entry values were negligibly small (Indrawan et al. 2006). The coarse grained waste rock material (samples D and E) was observed to start de-saturating at $\psi = 0.01$ kPa and was found to be almost completely drained before an applied matric suction of only 10 kPa.

Table 3 gives the measured saturated hydraulic conductivity for the fine grained waste rock (samples A, B, and C). The average of the observed k_{sat} values was 3.5×10^{-3} cm/s with a standard deviation of 1.2. The almost constant k_{sat} confirms the predominance of a matrix-supported internal structure in these samples. The removal of about 10% material finer than 4.75 mm from sample A through C was inconsequential in a significant increase in the saturated hydraulic conductivity. This is similar to the findings of Indrawan et al. (2006) for mixtures of a fine grained residual soil and gravel. The small variations in the observed k_{sat} are attributed to the combined effect of dry density and grain size distribution.

The k_{sat} of samples D and E was not measured because of their large grain size which was incompatible with the conventional size testing equipment. Measurements using a sub-fraction would have resulted in lower values because of the preclusion of porosity associated with the larger grain size material. According to Newman (1999), an average value of 1×10^{-1} cm/s should be taken as the k_{sat} of coarse waste rocks such as those obtained from the Golden Sunlight Mines. Under saturated conditions, the coarse grained waste rock can drain several orders of magnitude faster than the fine grained material (Diodato and Parizek 1993).

Figure 7 plots the estimated hydraulic conductivity functions for the selected waste rock samples. The hydraulic conductivity functions were determined by dividing the SWCC into several equal volumetric water content increments as described by Fredlund et al. (1994). This method requires the use of various parameters obtained from the SWCC and k_{sat} data as input. Since the continuous mathematical function

Table 3 Measured saturated hydraulic conductivity of selected waste rock samples

Sample ID	–4.75 mm (%)	Dry density (kg/m ³)	Void ratio	$k_{sat} \times 10^{-3}$ (cm/s)
A (TP05GS1)	57.3	1,900	0.36	3.4
B (TP07GS3)	52.6	1,990	0.30	2.3
C (TP18GS5)	47.9	1,990	0.30	4.7

developed by Fredlund and Xing (1994) for the SWCC closely matched the measured data, the parameters given in Table 2 were used. Likewise, the measured k_{sat} data depicted in Table 3 (for samples A, B and C) along with the assumed k_{sat} of 1×10^{-1} cm/s (for samples D and E) were used.

For samples A, B and C, k_{sat} was found to be constant up to the respective air entry values. Thereafter, air began to replace water in the pore space and the hydraulic conductivity dropped rapidly such that it ranged between 7×10^{-6} and 1×10^{-5} cm/s at 100 kPa. The shapes of the hydraulic conductivity functions were similar due to the similarity in SWCC depicted in Fig. 6 (Fredlund et al. 1994). The insignificant variation in the rate of decrease in the unsaturated hydraulic conductivity of these three samples highlights the influence of a matrix-supported internal structure.

The selection of an average k_{sat} for samples D and E affected the absolute value of the resulting hydraulic conductivity functions but not the shape as reflected by the air entry values, which closely matched those depicted in Table 2. The unsaturated hydraulic conductivity decreased to 5×10^{-7} cm/s at a matric suction of 7.4 kPa for sample D and 0.4 kPa for sample E. Clearly, the rate of decrease of unsaturated hydraulic conductivity in these samples was much higher than the former set of samples (A, B and C). The low water retention capability resulted in rapid drainage in the clast-supported internal structure of samples D and E.

Physical model of east pile

Figure 8 gives a physical model to describe the hydrogeological behaviour of the East Pile. The waste

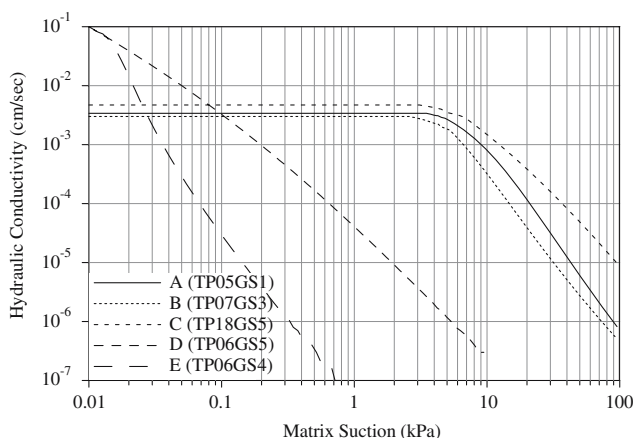


Fig. 7 Estimated hydraulic conductivity functions for selected waste rock samples

rock pile was bounded by a natural side hill along which the deposited material developed an angle of repose face (38°), and a traffic surface at the top. Material segregation during end dumping resulted in a distinct rubble zone at the base of the pile. The presence of interfingering dipping beds was also related to gravity sorting of the deposited material exhibiting extensive grain size variation. Since the waste rock was dumped from various platforms in the pile, the fine grained portion of one load mixed with the coarse fraction of a previous load and vice versa. Therefore, continuous beds extending from the surface to the pile toe did not exist in the pile.

In addition to end dump construction (causing material segregation) and mine sequencing (causing interfingering bedding), the spatial variability within the waste rock pile was affected by the geological origin of the materials and the weathering processes. The predominantly shale and latite rocks with extensive sulphide disseminations underwent both physical and chemical weathering due to the fluctuating temperature and relative humidity in the semi arid climate of south western Montana. The interrelated physical processes (abrasion, particle crushing, growth of mineral and ice crystals and slaking due to volume changes in clay minerals) and chemical processes (dissolution, oxidation, hydrolysis, diffusion and precipitation) imparted extensive material heterogeneity in the East Pile. The appearance of weathering increased with material age (since deposition in the pile) as marked by particle breakdown and pyrite staining. The degree of weathering varied between layers but was greater in the predominantly shale layers.

The internal structure of the waste rock governs the hydrogeological behaviour of the East Pile which

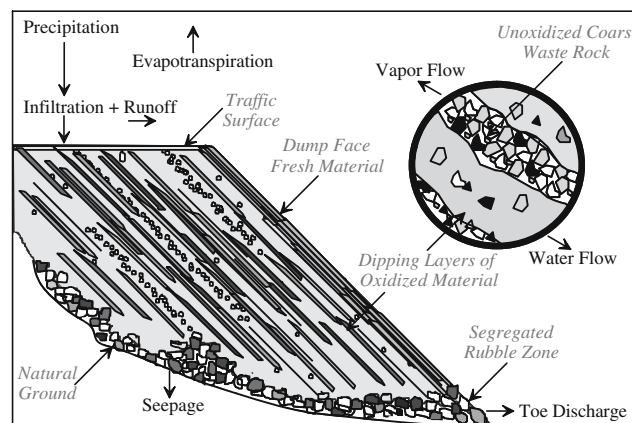


Fig. 8 Physical model describing the hydrogeological behaviour of the East Pile

remains unsaturated most of the year because of the low precipitation and the high evapotranspiration prevalent in the region. The fine grained layers developed a matrix-supported internal structure that retained water due to their small pore sizes. These layers formed the principle pathways for water flow in the desiccated pile. Conversely, the coarse grained layers formed a clast-supported internal structure that was generally dry and acted as a vent for the flow of water vapour. The coarse basal rubble zone provided access for the entry of oxygen through advective and diffusive gas flow along the foundation of the waste rock pile. In the case of occasional high infiltration events, the fine grained layers will act as capillary barriers thereby locally reducing stability due to pore pressure increase. This can be offset by the coarse grained layers through which water moves rapidly; the basal rubble zone can serve as a toe drain (Taylor and Greenwood 1985).

Summary and conclusions

The hydrogeological behaviour of waste rock piles is governed by parent geology, mining operation, construction practice and weathering processes. The resulting variable heterogeneity in such man-made earth structures require site specific correlations. Based on field investigations and laboratory characterization, a physical model was developed for the East Pile at the Golden Sunlight Mine in Montana, USA. The pile was bounded by a top traffic surface, a basal rubble zone and a 38° face. Internally, the pile comprised of interfingering dipping beds of fine and coarse materials. The fine grained layers developed a matrix-supported structure that retained water due to their small pore sizes. Conversely, the coarse grained layers formed a clast-supported structure that was generally dry and acted as a vent for the flow of water vapour.

The matrix-supported internal structure was found in waste rock with more than 45% material finer than 4.75 mm. The behaviour of the investigated samples containing 57, 53, and 48% material finer than 4.75 mm can be categorized as soil-like. The air entry values and the residual matric suction for these samples ranged from 2 to 4 kPa and from 20 to 40 kPa, respectively. Likewise, the average of the measured k_{sat} values was 3.5×10^{-3} cm/s. The hydraulic conductivity maintained the saturated value up to the air entry value and varied from 7×10^{-6} to 1×10^{-5} cm/s at 100 kPa matric suction.

The clast-supported internal structure resulted in a rock-like hydrogeological behaviour of waste rock samples that were classified as well graded sandy gravel. Comprising of 40 and 30% material finer than 4.75 mm, the two selected samples exhibited air entry values well below 1 kPa and residual matric suctions of less than 10 kPa. The assumed k_{sat} of 1×10^{-1} cm/s dropped by more than six orders of magnitude (5×10^{-7} cm/s) at low matric suctions of 7.4 kPa and 0.4 kPa for the investigated samples, respectively.

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