

# HYDROLOGICAL CHARACTERIZATION OF AN UNSATURATED WASTE ROCK DUMP

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## ABSTRACT

Parent geology, mining operation, construction practice, and climatic conditions impart extensive heterogeneity to waste rock piles. Their internal structure governs water flow and the potential for acid rock drainage. This paper presents the hydrological characteristics of an unsaturated waste rock pile at the Golden Sunlight Mine in Montana, USA. The East Dump exhibited high spatial variability and its internal structure consisted of fine grained haul traffic surfaces, inclined layering, and a basal rubble zone. The waste rock was classified using grain size analysis and the hydraulic properties were determined by soil water characteristic curves and hydraulic conductivity functions. Materials containing less than 45% passing the 4.75 mm sieve drained rapidly under 1 kPa whereas those with more than 45% passing the 4.75 mm sieve retained a higher unsaturated hydraulic conductivity above 5 kPa matric suction. The fine grained layers act as preferential zones for water storage and provide pathways for water flow in the unsaturated waste rock pile.

## RÉSUMÉ

Différents facteurs tels la géologie de la roche mère, le type d'opération minière, la méthode de construction, et les conditions climatiques entraînent une hétérogénéité considérable dans les haldes de roches stériles. Les différentes structures à l'intérieur de la halde régissent la circulation de l'eau et le potentiel de l'empilement à générer du drainage de roche acide. Cet article présente les caractéristiques hydriques d'une halde de roche stérile non saturée de la mine de Golden Sunlight au Montana, aux États-Unis. La Halde Est a une grande variabilité spatiale et sa structure interne est principalement constituée de particules fines en surface résultant du trafic des équipements lourds, de couches inclinées et d'une zone à la base constituée de gros blocs de roche. La roche stérile a été classifiée à partir des résultats des analyses granulométriques et des propriétés hydriques (la courbe de rétention d'eau et la conductivité hydraulique non saturée). Les matériaux contenant moins de 45% passant le tamis de 4,75 mm se sont drainés rapidement lorsque soumis à des succions inférieures à 1 kPa tandis que ceux ayant plus de 45% passant le tamis de 4,75 mm ont maintenu une conductivité hydraulique non saturée plus élevée au-dessus de la succion de 5 kPa. Les couches de matériaux fins agissent en tant que zones préférentielles pour le stockage de l'eau et offrent des voies préférentielles pour l'écoulement de l'eau dans la halde de stériles non saturée.

## 1. INTRODUCTION

Large amounts of waste rock are generated when low-grade and barren material is excavated to access the underlying ore. Materials from different geological facies are broken down to various degrees by blasting and sequentially deposited along a hillside throughout active mining operations. The conventional end dump construction method increases the heterogeneity within the waste rock piles owing to the formation of an internal structure containing dipping beds of coarse and fine materials (Diodato and Parizek 1993). This structure undergoes further changes as the deposited materials weather due to periodic variations in climatic events. Over time, the entire dump produces preferential seepage pathways within the unsaturated waste rock layers thereby affecting the rate of water flow and the migration of contaminants (Newman 1999). A clear understanding of the hydrological characteristics of the waste rock piles is obligatory to control metal leaching and acid drainage.

Heterogeneity of waste rock piles has been recognized in some recent studies focusing on field monitoring (Morin

1994), physical characterization (Pedersen 1996), large-scale testing (Nichol et al. 2000), and numerical modeling (Fala et al. 2003). However, these studies have only postulated that the spatial variability of materials contributes to the presence of preferential flow paths in waste rock dumps. The limited amount of quantitative data has always precluded the formulation of a theoretical framework. Therefore, there is an exigent need to develop a research protocol for hydrological characterization of unsaturated waste rock dumps.

This paper presents the hydrological characteristics of a waste rock pile at the Golden Sunlight mine in Montana, USA. Field investigation, laboratory characterization, and numerical modeling were used to describe the unsaturated dump. 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, and saturated hydraulic conductivity thereby predicting the hydraulic conductivity functions. All of the results were combined to develop a conceptual model for hydrological characterization of the East Dump.

## 2. SITE DESCRIPTION

The Golden Sunlight mine is an open pit gold mine located at latitude 46°00' N and longitude 112°00' W in South West Montana, United States of America. The mine site lies on the eastern flank of a fault-bounded mountain range known as the Bull Mountains. Development of the mine began in 1982 and construction of the waste rock piles was initiated almost simultaneously. Deposition of the waste rock re-activated an ancient low-angle slip in the underlying pre-sheared clay and affected an area of more than 3.0 km<sup>2</sup>. Operations were suspended in the summer of 1994 and remedial measures were undertaken. The removal of 15 million ton 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 reported in this study were conducted from September 1994 through February 1995 (Herasymiuk 1996).

The East Dump was constructed by end dumping the waste material from several dump platforms directly along an existing hillside. Haul trucks were used for main dumping and the surface was leveled by pushing the material using bulldozers. The pile front gradually advanced as the waste material was allowed to flow down slope at the angle of repose. Based on configuration, the pile is categorized as a terraced side valley dump as defined by Taylor and Greenwood (1985).

The geology of the mine site includes Proterozoic clastic sedimentary rock that was intensively intruded by latite magma during the Cretaceous. The East Dump lithology primarily comprises of 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 Schafer and Associates (1995), the unoxidized rock contains 2% to 5% pyritic sulfur and possesses 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% is accumulated from April through September; the average annual pan evaporation equals 1050 mm (Herasymiuk 1996). Locally, the typical temperature fluctuations of the continental climate are 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, that is, between - 40°C and + 38°C. Ground freezing at the mine site can occur from late September to early June. The relative humidity averages 50% during summer and can increase up to 65% during the winter months. Fluctuating temperature and relative humidity in a semi arid climate results in large variations in the hydrological properties of local soil deposits. Swanson (1995) estimated the annual net infiltration through the uncovered waste rock piles to be in the range of 20 mm and 100 mm.

## 3. RESEARCH PROGRAM

A comprehensive research program was carried out in this study. The field investigations were conducted to determine waste rock texture and internal structure as well as water and temperature distribution within the dump. Likewise, the laboratory characterization focused on the determination of grain size distribution, soil water characteristic curve, and saturated hydraulic conductivity ( $k_{sat}$ ). Finally, the results were used to numerically model the hydraulic conductivity functions.

### 3.1 Field Investigations

The field investigations were carried out during the remedial excavation that was initiated at the top of the waste rock pile at an elevation of 5520 m a.m.s.l in approximately 18 m high benches and was completed at an elevation of 5360 m a.m.s.l. Simultaneously, 29 test pits were excavated on four separate benches along two north-south and two east-west transect lines that were routinely re-surveyed. The test pits were excavated to variable depths (ranging from 3.0 m to 4.6 m) using Kobelco tracked mounted hoe and D8 CAT. One wall of each test pit was kept vertical for logging and sampling whereas the opposite wall was sloped for safety. The exposed stratigraphy of the waste rock material in each test pit was recorded as a function of grain size and color change. All identifiable layers within the pit were photographed and logged with respect to their physical appearance: grain size and texture; structure and degree of voids infilling; color and weathering state; and strike and dip angle.

The gravimetric water content was measured for all (but not too coarse to sample) layers according to the ASTM Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass (D2216-05). Representative bulk samples were retrieved from randomly selected locations in each layer using 250 mL plastic bottles. The containers were immediately sealed to preserve the in situ moisture in the samples. A total of 242 samples were transported to the on site geotechnical laboratory for testing. The in situ waste rock temperature was directly measured using a portable digital indicator (Vaisala HMI 31). The measurement probe was inserted into a pre-drilled hole, sealed in place and allowed to equilibrate with the in situ conditions. The instrument was also used to determine the air temperature. Finally, 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).

### 3.2 Laboratory Characterization

Laboratory characterization was conducted on material finer than 50 mm obtained from the various test pits. With the exception of very coarse material, two bulk samples were retrieved from each layer and a total of 242 air-dried samples (weighing in excess of 2100 kg) were transported to the University of Saskatchewan, Saskatoon, Canada.

The grain size distribution was determined for a total of 96 samples according to the ASTM Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates (C136-05). As will be explained later in this paper, the waste rock samples were classified based on the percentage of material passing the ASTM Sieve No. 4 (4.75 mm), which marks the boundary between gravel and sand sizes. Five representative samples were selected for detailed hydrological characterization.

The soil water characteristics curves were determined using a large pressure plate apparatus (156 mm diameter and 178 mm high). The maximum grain size was kept as 38 mm to facilitate proper material packing in the cell. Samples with more than 45% material finer than 4.75 mm were placed in the cell as saturated slurries. Alternatively, samples with less than 45% material finer than 4.75 mm were placed in a moist state and slowly saturated from the base upwards.

The saturated hydraulic conductivity was determined according to the ASTM Standard Test Method for Permeability of Granular Soils (Constant Head) (D2434-68(2000)). Tests were conducted on selected waste rock samples (A, B, and C) containing at least 45% material finer than 4.75 mm. The small size of the constant head permeameter necessitated the use of a small maximum particle size in the sample. Sieved material finer than 4.75 mm (Sieve No. 4) was used for  $k_{sat}$  determination.

### 3.3 Numerical Modeling

The hydraulic conductivity functions were numerically determined using laboratory test data. The continuous mathematical function developed by Fredlund and Xing (1994), best matched the laboratory measured soil water characteristics curves. The hydraulic conductivity functions were then calculated using grain size data, porosity, the fitted soil water characteristics curves and the saturated hydraulic conductivity measurements following the method described by Fredlund et al. (1994).

## 4. FIELD INVESTIGATIONS

A visual inspection of waste rock at the East Dump indicated typical material segregation such that the grain size increased with depth thereby leading to the formation of a distinct rubble zone at the base of successive lifts. Figure 1 gives the texture of waste rock at the East Dump. At the dump 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 ( $38^\circ$ ) were observed below the dump platforms. Attributed to the end-dumping method of construction, these layers varied in thickness from 100 mm to more than 2 m. At the bench scale (B), layering was associated with variation in grain size, texture, color, and composition and exhibited multiple inter-fingered dipping beds. Continuous beds extending from the surface to the dump toe were generally absent in the investigated waste rock pile.

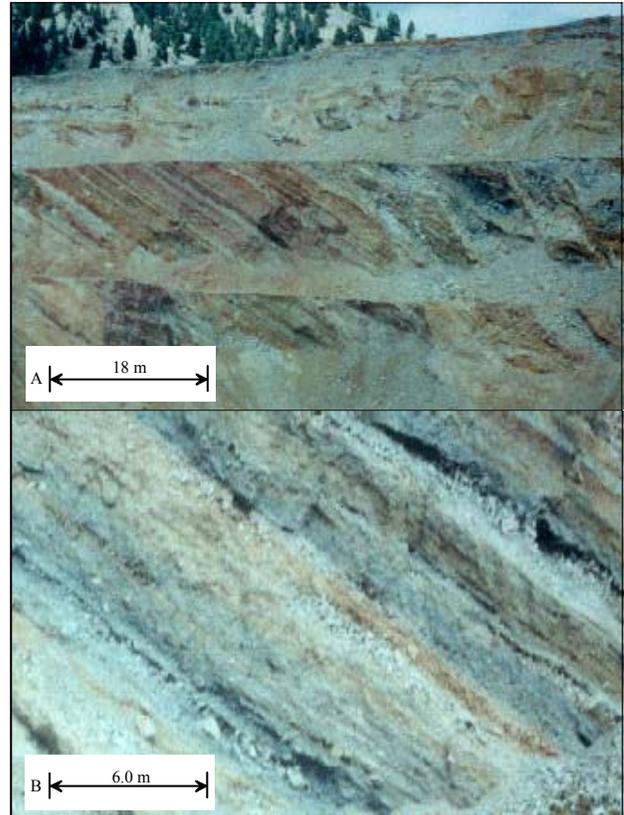


Figure 1: Texture of waste rock at East Dump: (A) dump scale; and (B) bench scale

The physical and chemical weathering processes within waste rock dumps are generally influenced by parent geology (material properties and mineral composition), mining operation (blasting and sequencing), construction method (handling and transportation), and climatic conditions (temperature and precipitation). Figure 2 presents the internal structure of the East Dump. The deeply embedded material (A) appeared to have undergone excessive weathering compared to that on the outer rim of the dump. A grain size larger than 25 mm was associated with latite (near hammer) 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 exhibited a fairly uniform grain size distribution that gradually evolved to a much finer material due to weathering (Herasymuik 1996). Variation in the degree of weathering of materials increased spatial heterogeneity within the waste dump. 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 their large voids that were devoid of fines. On the contrary, silt and fine sand filled the voids between the larger clasts and formed a matrix-supported structure in the fine-grained layers.

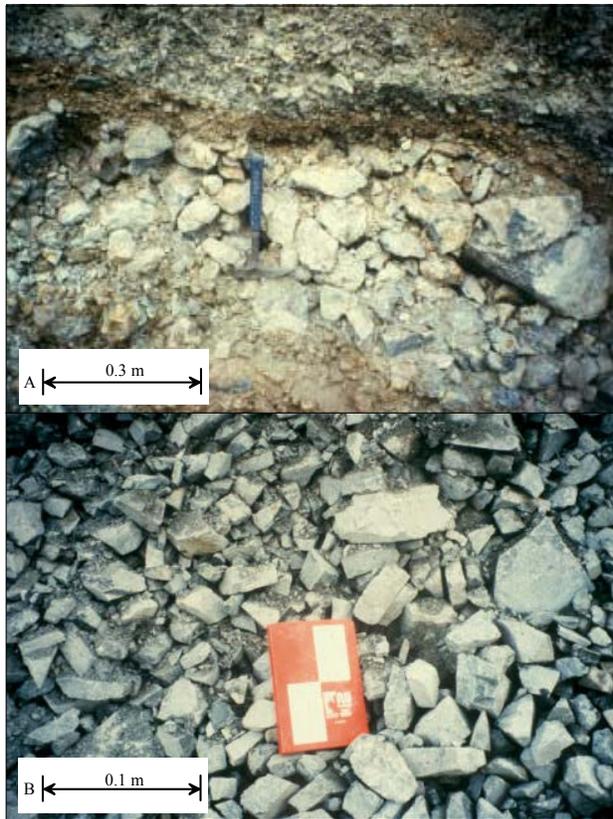


Figure 2: Internal structure of waste rock at East Dump: (A) embedded material; and (B) fresh material

Changes in grain size distribution within the pile were observed in both vertical and horizontal directions (Pedersen et al. 1966). Material variation with depth is attributed to waste rock segregation during end dumping at the angle of repose. The coarse rubble zone at the base of the pile was due to gravity sorting on the dump face. However, coarse-grained waste rock including cobbles and boulder size material was found throughout the pile and was not restricted to the basal region. As mentioned earlier, heterogeneity of the dumped material was due to variations in compositional properties as affected by geologic origin, mining operation, construction practice, and weathering processes. The existence of alternating coarse and fine layers was mainly governed by variation in the original lithology (Newman 1999). The appearance of weathering increased with age as marked by the degree of pyrite oxidation, ferric hydroxide staining, breakdown of rock particles, and secondary mineral precipitation. The degree of weathering varied between layers, but was greater in the predominantly shale layers.

The in situ dry density measured between 1500 and 2100  $\text{kg/m}^3$ , with an average of 1900  $\text{kg/m}^3$ . The measurements were only possible in the areas of fine waste rock and do not capture the full range of possible densities within the piles. The in situ dry density of the materials was used to prepare samples for the determination of  $k_{sat}$ .

Figure 3 gives the measured gravimetric water content versus depth below the original ground surface in the East Dump. The samples, collected from successive 18 m thick benches, indicated a relatively higher water content (4% to 14%) in the upper 3 m of the waste rock 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 can be envisaged to gradually decrease and eventually converting to a near vertical line (representing 1% to 2% water) from 42 m to 85 m. The figure generally suggests the presence of a wetting front from the surface down within the East Dump. The measured water content in the surface layer of the dump corresponds to the estimated value of about 3% water content for fresh waste rock as reported by Schafer and Associates (1995). The desiccation of the waste rock materials 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 (Morin et al. 1994).

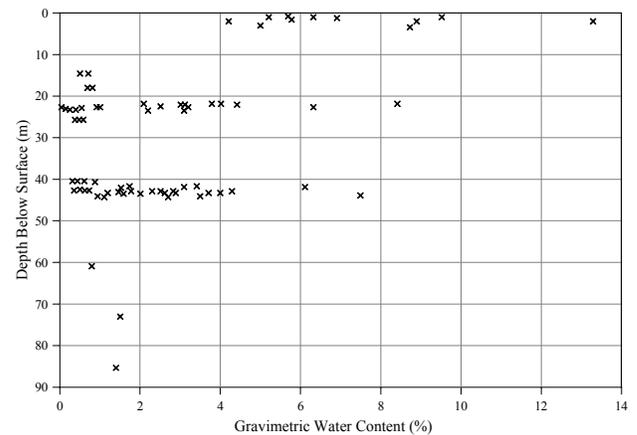


Figure 3: Measured water content profile in East Dump

Figure 4 gives the measured temperature as a function of the depth below surface in the East Dump. 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. The average waste rock temperature exceeded the annual average air temperature (7°C) during the entire duration of the field investigation program that spanned over a six month period. A higher waste rock temperature is attributed to exothermic reactions associated with mineral oxidation within the pile. The temperature gradient governed the movement of water vapor through the East Dump as highlighted by the venting of high temperature (37°C to 58°C) and moist (100% RH) air at a depth of 25 m from a coarse grained layer. Earlier studies focusing on field monitoring (Diodato and Parizek 1993; Nichol et al. 2000) and numerical modeling (Fala et al. 2003; Swanson 1995) indicated that the upward movement of vaporized water significantly affects water distribution within waste rock piles. Water recycling due to vapor transport from the bottom up hampered the advancement of the wetting front in the East Dump.

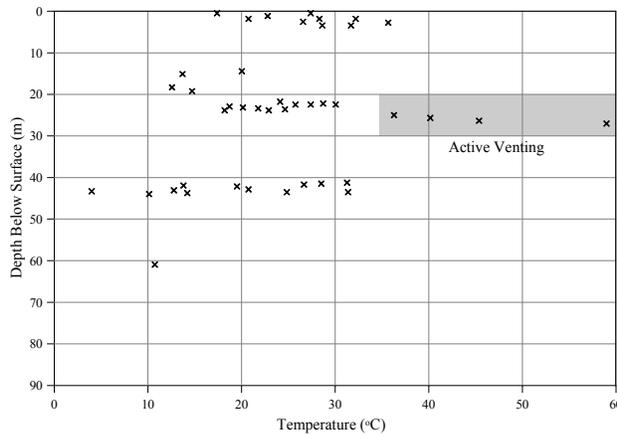


Figure 4: Measured temperature profile in East Dump

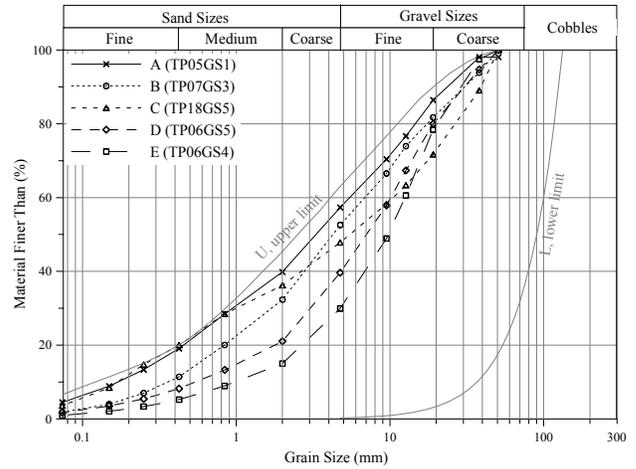


Figure 5: Grain size distribution of waste rock samples

5. MATERIAL CHARACTERIZATION

Figure 5 gives the grain size distribution of the waste rock samples. Grain sizes were defined as: fine sand (0.075 mm to 0.425 mm); medium sand (0.425 mm to 2.0 mm); coarse sand (2.0 mm to 4.75 mm); fine gravel (4.75 mm to 19 mm); coarse gravel (19 mm to 75 mm); and cobbles (75 mm to 300 mm). The 96 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 materials because boulders larger than 100 mm were excluded from laboratory tests due to sampling difficulty. The selected waste rock samples were adjacent to the upper limit of the envelope. These samples contained 57%, 53%, 48%, 40%, and 30% material finer than 4.75 mm.

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.

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

Sample ID	-4.75 mm (%)	D <sub>10</sub> (mm)	D <sub>30</sub> (mm)	D <sub>60</sub> (mm)	C <sub>c</sub> *	C <sub>u</sub> †	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

\* Coefficient of Curvature,  $C_c = (D_{30})^2 / (D_{10})(D_{60})$

† Coefficient of Uniformity,  $C_u = D_{60} / D_{10}$

Figure 6 gives the soil water characteristics curves for the selected waste rock samples. The volumetric water content at 0.01 kPa matric suction corresponds to the saturation (or porosity value) of the pressure plate apparatus. Samples A, B, and C exhibited identical water retention characteristics and their air entry values were between 3 kPa and 5 kPa. For these samples, the volumetric water contents declined at higher matric suctions such that the residual values were obtained around 100 kPa. These characteristics are attributed to the relatively small pore spaces that were effective with respect to capillary flow through the samples

(Fredlund and Rahardjo 1993). The low saturated water content (low water storage) of sample C was primarily due to the gap-graded grain size distribution that overshadowed the effect of fine and medium sand size material. The presence of coarse particles reduced sample porosity and the larger voids were not mostly filled by the fines. Despite these variations, the soil water characteristics curves for samples A, B, and C clearly indicated that the hydrological behaviour of such waste rock materials is similar to that of sandy soils generally encountered in geotechnical engineering practice (Fredlund and Rahardjo 1993).

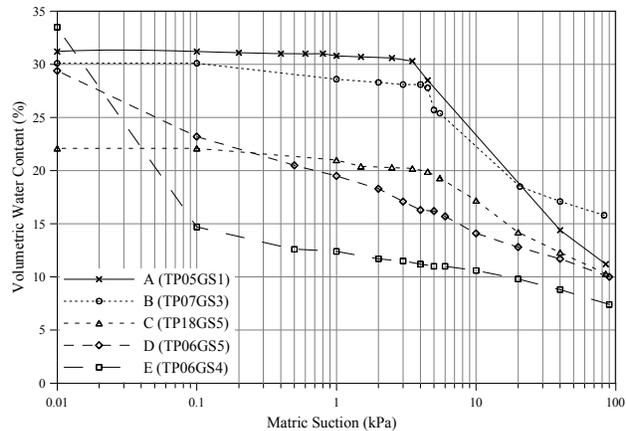


Figure 6: Soil water characteristic curves for selected waste rock samples

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. Both of these samples had no distinct air entry values and the residual water contents were not reached at the applied matric suction of 100 kPa. 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. Sample E exhibited a sharp drop in the volumetric water content from 0.01 kPa to 0.1 kPa and thereafter decreased gradually.

The observed soil water characteristic curves of the investigated waste rock samples indicated a gradual change with changing the grain size distribution. The 4.75 mm size fraction was useful in distinguishing between two types of hydrological behaviour of the waste rock materials (Taylor and Greenwood 1985). A  $45 \pm 2\%$  sand size (material finer than 4.75 mm) in the samples was found to be sufficient in creating 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. The smaller void sizes in this matrix supported structure were responsible for water retention and air entry values of 3 kPa to 5 kPa (corresponding to 0.3 m to 0.5 m of water) were observed. On the contrary, when the amount of fines was lower than the above grain size limit, the larger particles were in contact and the voids between them were also larger. The larger pores in such a clast supported structure were inconsequential in water retention and hence the air entry values were negligibly small. The coarse grained waste rock material was observed to start de-saturating at zero matric suction and the entire material was found to be almost completely drained at 5 kPa matric suction.

Table 2 gives the measured saturated hydraulic conductivity for selected fine grained waste rock samples

A, B, and C. The saturated hydraulic conductivity ranged from  $2.3 \times 10^{-3}$  cm/s to  $4.7 \times 10^{-3}$  cm/s. The  $k_{sat}$  of samples D and E was not measured because of their large grain size that 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. Therefore, an average  $k_{sat}$  of  $1 \times 10^{-1}$  cm/s was assumed based upon the value of saturated hydraulic conductivity used to model the coarse waste rock materials at the Golden Sunlight mines (Schafer and Associates 1995).

Table 2: Measured saturated hydraulic conductivity of selected waste rock samples

Sample ID	Dry Density (kg/m <sup>3</sup> )	Void Ratio	$k_{sat} \times 10^{-3}$ (cm/s)
A (TP05GS1)	1900	0.36	3.4
B (TP07GS3)	1990	0.30	2.3
C (TP18GS5)	1990	0.30	4.7

Figure 7 gives the estimated hydraulic conductivity functions for the selected waste rock samples. For samples A, B, and C, the saturated hydraulic conductivity was set at the measured values and was found to be constant up to the respective air entry value. Thereafter, air began to replace water in the pore space and the hydraulic conductivity dropped rapidly such that it ranged between  $7 \times 10^{-6}$  cm/s and  $1 \times 10^{-5}$  cm/s at 100 kPa. The shapes of the hydraulic conductivity functions were similar due to similarity in the soil water characteristic curves (Figure 6). The selection of an average saturated hydraulic conductivity for samples D and E affected the absolute value of the resulting hydraulic conductivity functions but not the shape as reflected by the negligibly small air entry values of these materials. The unsaturated hydraulic conductivity decreased to  $5 \times 10^{-7}$  cm/s at a matric suction of 7.4 kPa for sample D and 0.4 kPa for sample E.

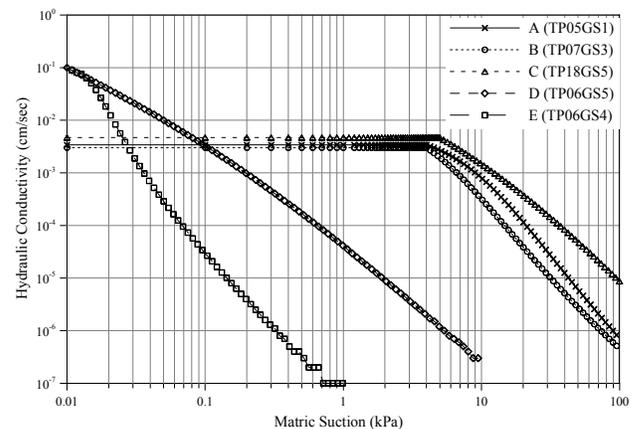


Figure 7: Estimated hydraulic conductivity functions for selected waste rock samples

## 6. SUMMARY AND CONCLUSIONS

Parent geology, mining operation, construction practice, and climatic conditions impart extensive heterogeneity to mine waste rock piles. The internal structure of the waste rock governs the hydrological characteristics of the East Dump at the Golden Sunlight mine in Montana, USA. The hydrological behaviour of the dump was determined using field investigations, laboratory characterization, and numerical modeling. Results of this research are summarized in Figure 8 in the form of a conceptual model of the dump. The waste rock pile is bounded by a natural side hill along which the deposited material develops an angle of repose slope and a traffic surface at the top. Due to the low precipitation and the high evapotranspiration in the region, the East Dump remains unsaturated most of the year. The pile is composed of dipping beds of coarse and fine material. The coarse grained layers (clast supported structure) are generally drained and act as vents for the flow of water vapor and gases whereas the fine grained layers (matrix supported structure) retain water due to their small pore sizes. These later layers form the principle pathways for water flow since they maintain a relatively high water content. The coarse grained layers may form faster pathways during the unlikely event of high infiltration. In such cases, the coarse basal rubble zone formed due to segregation will serve as a toe drain. However, under unsaturated conditions, this zone provides access for the entry of oxygen through advective and diffusive gas flow along the foundation of the waste rock dump.

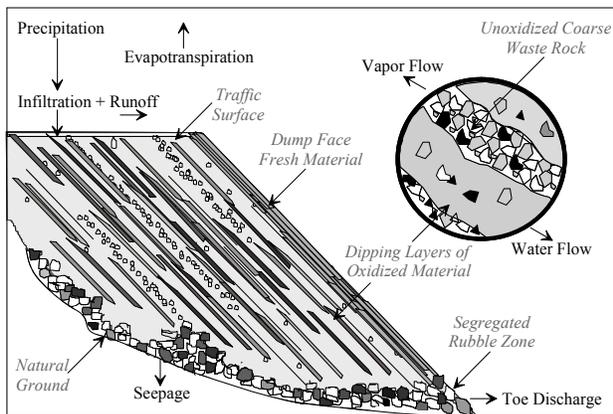


Figure 8: Conceptual model for hydrological characterization of East Dump

The waste rock materials containing less than 45% passing the 4.75 mm sieve drain rapidly under 1 kPa whereas those with more than 45% passing the 4.75 mm sieve retain a higher unsaturated hydraulic conductivity above 5 kPa matric suction. The measured soil water characteristic curves and the estimated hydraulic conductivity functions showed that the fine grained layers act as preferential water storage zones and provide the pathways for water flow in the unsaturated dump.

## 7. ACKNOWLEDGEMENTS

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