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Journal of Hazardous Materials 147 (2007) 288–296

Journal of Hazardous Materials

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Adequate drainage system design for heap leaching structures

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Received 12 November 2005; received in revised form 2 January 2007; accepted 2 January 2007

Available online 14 January 2007

Abstract

The paper describes an optimum design of a drainage system for a heap leaching structure which has positive impacts on both mine environment and mine economics. In order to properly design a drainage system the causes of an increase in the acid level of the heap which in turn produces severe problems in the hydrometallurgy processes must be evaluated. One of the most significant negative impacts induced by an increase in the acid level within a heap structure is the increase of pore acid pressure which in turn increases the potential of a heap-slide that may endanger the mine environment. In this paper, initially the thickness of gravelly drainage layer is determined via existing empirical equations. Then by assuming that the calculated thickness is constant throughout the heap structure, an approach has been proposed to calculate the required internal diameter of the slotted polyethylene pipes which are used for auxiliary drainage purposes. In order to adequately design this diameter, the pipe's cross-sectional deformation due to stepped heap structure overburden pressure is taken into account. Finally, a design of an adequate drainage system for the heap structure 2 at Sarcheshmeh copper mine is presented and the results are compared with those calculated by exiting equations.

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Keywords: Drainage design; Heap leaching structures; Acid pressure; Sarcheshmeh copper mine

1. Introduction

Design of a heap structure for the hydrometallurgy process plays a significant role in the heap leaching scheme. This structure is the primary component for the overall procedure. The construction of such a structure usually requires a large area, approximately 0.5 km^2, with a slope ranging from 5% to 15% chosen close to the outer edge of the mine waste. The slope of the area should be such that the pregnant leach solution (PLS) containing copper oxide flows through the heap while ensuring mine environment safety in order to prevent ground water pollution [1]. Steeply sloping sectors are leveled out and the overall surface soil of the heap is compacted in order to prevent inadmissible surface settlement. Successions of natural and artificial layers are generally placed to isolate the floor of the base-rock. Natural layers consist of compacted clay and cushion and artificial layers of geomembrane. Geomembrane has a thickness between 1 and 2 mm and low punchability strength. Correct installation of the non-penetrable geomembrane layer is crucial. Thus, in order to prevent any potential damage a layer ranging from 20 to 25 cm of non-compacted cushion or geotextile is placed over the geomembrane. Subsequently, a layer of gravels bearing a high coefficient of permeability is placed above these layers. The high permeability of this layer makes it practically suitable to transfer the PLS through the heap. The thickness of this layer depends on several factors such as [2]:

- site slopes,
- permeability of gravels, and
- leach solution supply.

The gravelly layer along the valley walls and the floor is the primary drainage system used to drain the acid down towards the bottom of the valley. However, since the retained acid levels are fairly high, gravelly drainage alone is not sufficiently capable of draining the entire PLS through the heap. Thus, slotted polyethylene pipes are placed along the floor of the base-rock to increase the drainage capacity. These pipes are used as an auxiliary drainage system to drain a portion of the PLS through the heap towards the designated basin.

In order to prevent clogging of the gravelly layer, due to migration of fine grain particles, a filter consisting of one or

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0304-3894/$ – see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.jhazmat.2007.01.038

more layers of geotextile are placed over the gravels. Stepped layers of copper oxide waste rock are placed over these filters which are then acid washed. The acid dissolves the copper content in the waste rock and the resulting PLS is transferred to the leaching complex to extract the copper. Within this unit, copper is separated and deposited and the remaining acid solution, known as raffinate, is returned to the heap once again to continue the leaching process (Fig. 1).

In certain cases the thickness and type of the gravelly drainage layer and/or internal diameter of the polyethylene pipes are chosen incorrectly. In several instances, due to overburden pressures induced by the weight of copper oxide waste rock, the internal diameter and hence cross-sectional area of the pipes are severely reduced [3], which in turn causes a considerable reduction in the acid discharge. Under such circumstances, the acid inflow to the heap will not be drained equally. If the acid levels within the heap continue to increase, it will cause severe problems in the hydrometallurgy processes. A few of these problems are summarized as follows:

- An increase in the hydro-static pressure of the acid solution at the interfacing layer between heap structure and the floor causes a reduction in stability and increases heap-slide potential.
- An increase in the contact time between the acid and minerals in the copper oxide waste rock thus increasing the impurity due to the dissolution of unwanted minerals in the acid.
- An increase in the amount of acid absorbed by the environment which in turn increases the risks of both soil and groundwater pollution.
- An increase in liquefaction potential due to earthquake and mine blasting activities [4].

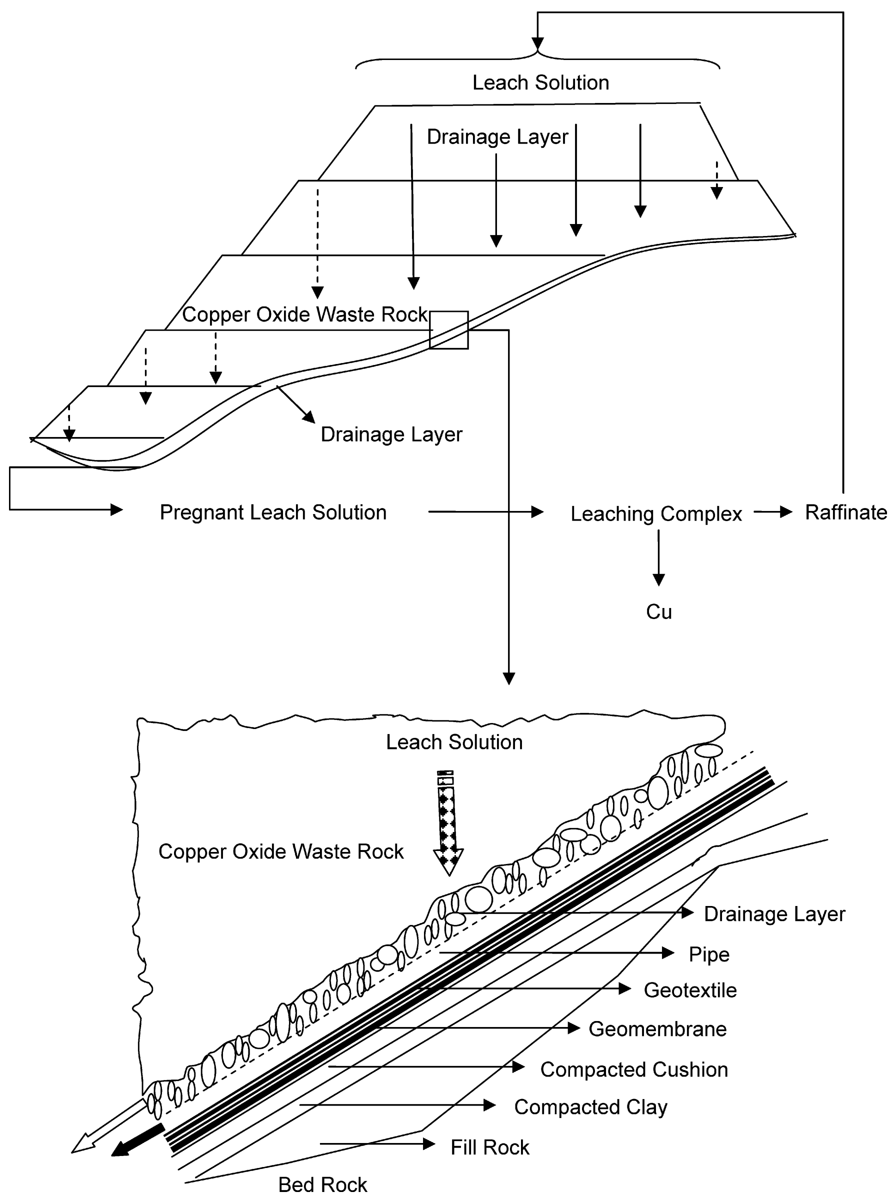

Fig. 1. Slotted polyethylene pipes placed along the base of the heap structure as an auxiliary drainage source.

2. Thickness computation of the gravelly drainage layer

A highly permeable gravelly layer, placed at the bottom of the heap, is used as the main drainage system. Thus, it is both technically and economically important to choose the thickness of this layer as adequately as possible. Technically, the slightest variation in the thickness of the drainage layer directly affects the increase/decrease of the acid liquid level within the structure. Economically however, these changes can play an important role in the overall cost evaluation of the project.

The leach solution, which is a weak sulphuric acid, flows through the heap structure under gravitational forces [5] dissolving the copper content and leaches downwards until it reaches the gravelly drainage layer. The resulting solution is known as the PLS which continues to flow through the gravelly drainage layer freely parallel to the natural slope of the heap base rock. Fig. 2 illustrates the flow pattern within the gravelly drainage layer of the heap. Giroud et al. [6] proposed an equation which is used to determine the thickness of the drainage layer in landfills which is similar to that of the heap structure if the primary drainage layer is taken to be gravels. Hence, in this paper, it is suggested to determine the thickness of the gravelly drainage layer via Giroud's equation, providing that the rate of liquid supply, q_h, of the original equation is replaced by Q_t as follows

$$H = \frac{j(\sqrt{1+4\lambda}-1)L\tan\beta}{2\cos\beta}F_S \qquad (1)$$

where $j = 1 - 0.12\exp[-[\log(8\lambda/5)^{5/8}]^2]$, in which, $\lambda = q_h/K_{Lt}\tan^2\beta$ and $K_{Lt} = k_{La}/\mathrm{RF_{PC}\,RF_{CC}\,RF_{BC}}$, H is the admissible thickness of the gravelly drainage layer, j the dimensionless factor, defined as above, λ the dimensionless factor, defined as above, L the length of base rock, β the base rock slope, q_h the rate of liquid supply per square meter, K_{Lt} the coefficient of

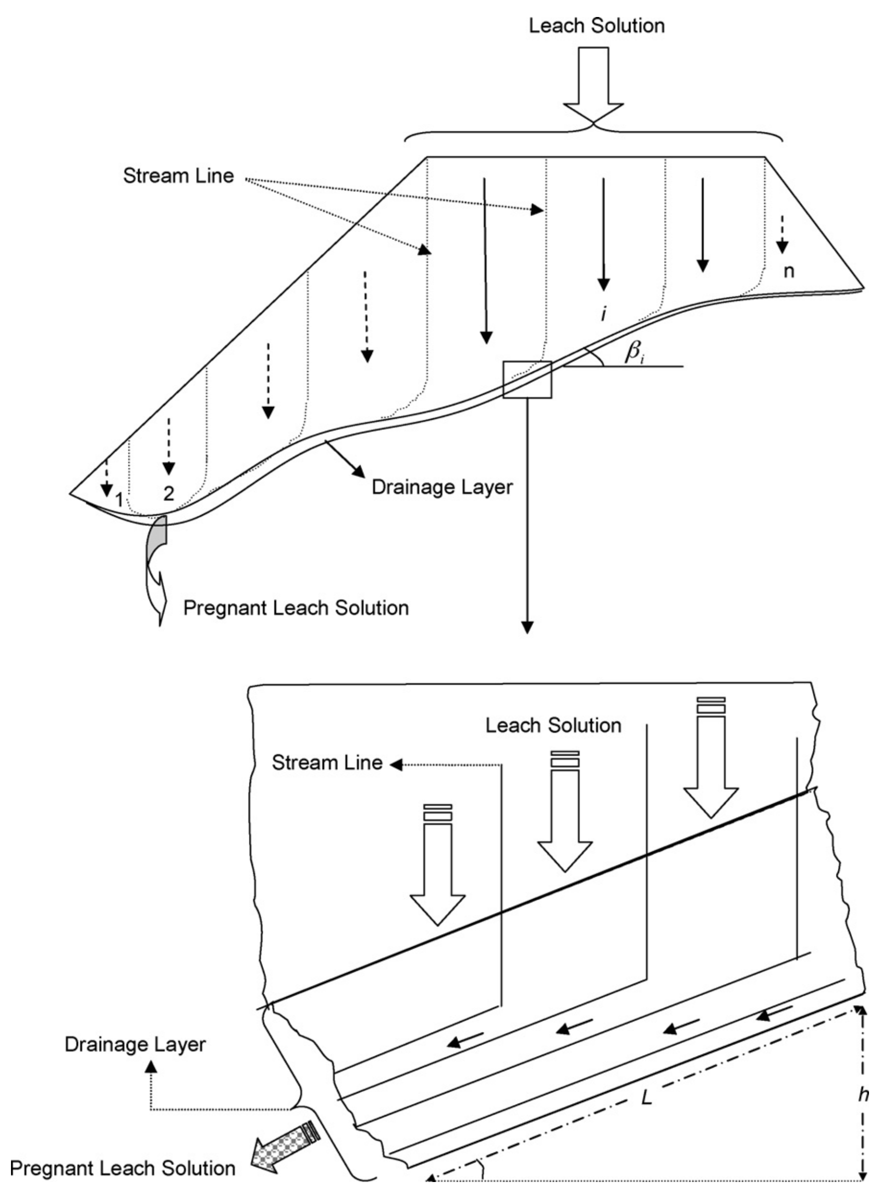

Fig. 2. Assumed flow pattern within the heap structure.

long term permeability for the drainage layer, K_{La} the laboratory coefficient of permeability for the drainage layer, F_S the factor of safety for thickness design of the gravelly drainage layer, RF_{PC} the reduction factor due to particulate clogging, RF_{CC} the reduction factor due to chemical clogging, and RF_{BC} is the reduction factor due to biological clogging.

$$q_h = Q_t = q_l + q_p \quad (2)$$

In which, Q_t, q_l and q_p are the total inflow, PLS inflow and inflow due to seasonal precipitation per square meter of heap surface area, respectively. As well, it should be noted that the reduction factors (RF_{PC}, RF_{CC}, RF_{BC}) vary between 1 and 2 [6].

3. Internal diameter computation of the slotted polyethylene pipes

The leach solution is usually directed towards the floor of the basin via the gravelly layer along the valley walls as shown in Fig. 3. However, due to high acid levels, the gravelly layer alone does not sufficiently drain the entire PLS out of the heap. Therefore, slotted polyethylene pipes are placed on the valley floor, parallel to the valley axis, beneath the gravelly layer. Type, number and internal diameter of the slotted polyethylene pipes for each heap depends on the site slopes, permeability of the gravelly layers, required drainage capacity, and size of the heap structure and topography of the site. Generally, in copper mines, a single polyethylene pipe is placed along the base of each valley as an auxiliary form of drainage in conjunction with the gravelly layer. Peripheral grooves, each with a length of $l = \pi d/3$ (where d is the internal diameter of the polyethylene pipe), are made along the length of the polyethylene pipes (Fig. 4) in order to increase the total inflow. Therefore, the total inflow can readily flow through the upper half of the pipes perimeter. It can be seen in Fig. 4 that the asymmetric slots are chosen such that $\theta = 60°$ thus allowing the total inflow to flow through the upper half perimeter of the pipe. This pipe is used to increase the drainage capacity, preventing an increase in the acid levels of the heap. The internal diameter of the polyethylene pipes should be designed such that the acid inflow from the valley walls is

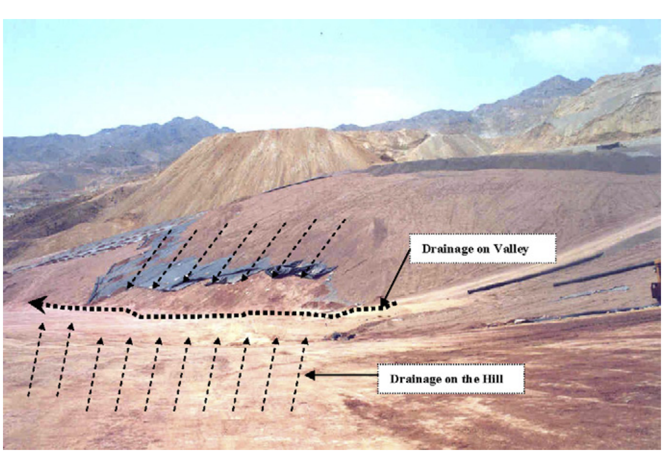

Fig. 3. Direction of the flow within the gravelly layer as well as the polyethylene pipes at Sarcheshmeh copper mine.

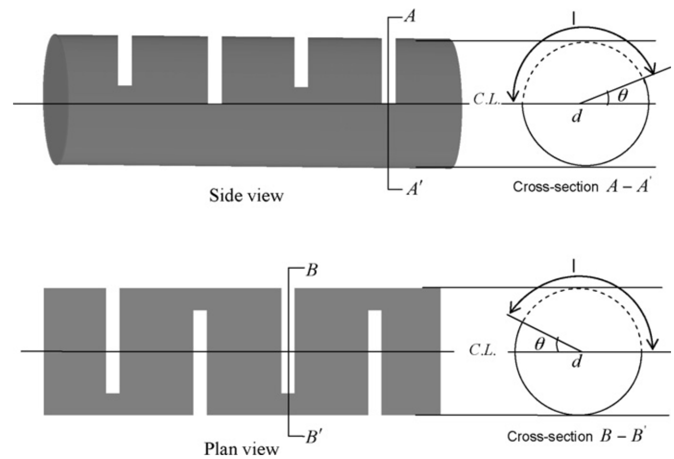

Fig. 4. Side and plan view of the slotted polyethylene pipes within a heap structure.

completely drained out of the heap. The initial cross-sectional area of the polyethylene pipes laid along the base of the valley is circular. However, during the construction of the heap leaching structure, due to an increase of the overburden pressure of the copper oxide waste rock, cross-sectional deformation causes a change in the amount of total discharge from the drainage system [3]. In order to evaluate this deformation, two cases are taken into consideration, in which the first is a theoretical assumption used solely for comparative purposes:

(I) The polyethylene pipes are not embedded within soils, while subjected to uniform vertical pressure.

In this case, the circular cross-section will uniformly deform into an ellipse. The original perimeter is maintained, while the overall cross-sectional area is reduced (Fig. 5).

(II) In practice, the polyethylene pipes are embedded within copper oxide waste rock and are subjected to both overburden and lateral pressures.

In this case, considering a uniform vertical pressure (assuming the vertical pressure is greater than the horizontal pressure), the cross-sectional deformation is not uniform (the pipe appears crumbled under pressure over time), thus the reduction in the overall cross-sectional area will be much more than that considered in case I, while the perimeter remains unchanged (Fig. 6).

Deformation of the pipe that takes place within a heap leaching structure is the same as that described in case II. In this paper

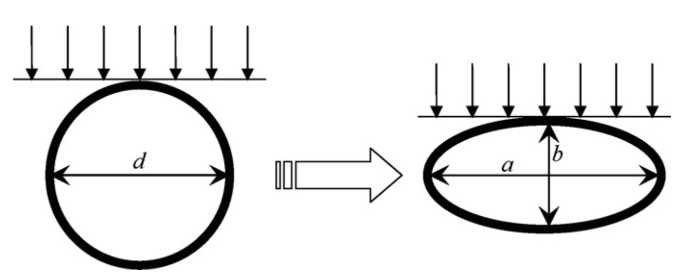

Fig. 5. Idealized deformed shape of a circular pipe subjected to a uniaxial compressive loading.

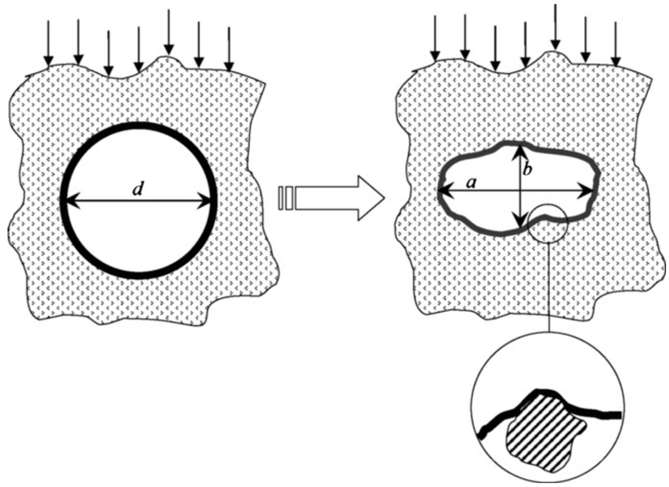

Fig. 6. Assumed deformed shape of the circular pipe within a heap structure.

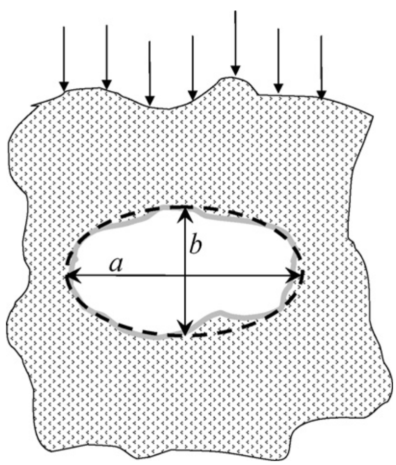

Fig. 7. Idealized deformed shape of the circular pipe within a heap structure.

the discharge is determined assuming that the deformed pipe is circumscribed within an ellipse (Fig. 7). Therefore, considering the non-uniformly deformed pipes, it is assumed that the total inflow passes through 50% of the pipe's cross-sectional area [7]. Therefore, in this case an effective wetted cross-sectional area of flow (A_w) and a wetted perimeter (P_w) is considered as follows (Fig. 8):

$$A_w = 0.5A_e = 0.125\pi ab \tag{3}$$

$$P_w = 0.5P_c = 0.5\pi d \tag{4}$$

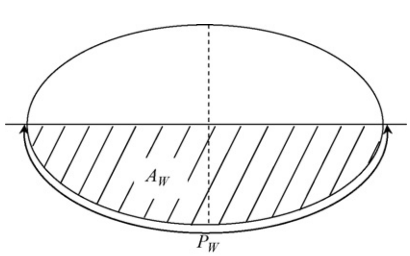

Fig. 8. Effective wetted cross-sectional area of flow A_w and the corresponding wetted perimeter P_w.

In which, A_e is the cross-sectional area of the ellipse, P_c the perimeter of the circle, a the major diameter of the ellipse, and b is the minor diameter of the ellipse.

Using Manning's equation [8], the liquid discharge can be obtained as follows

$$Q_p = VA_w = \frac{1}{n}\left(\frac{A_w}{P_w}\right)^{2/3} i^{1/2} \tag{5}$$

Substituting Eqs. (3) and (4) into Eq. (5) and taking $n = 0.01$, for a polyethylene pipe [8], we have

$$Q_p = (12.457)\left(\frac{(ab)^{5/3}}{d^{2/3}} i^{1/2}\right) \tag{6}$$

Assuming that

$$\eta = \frac{d}{a} \tag{7}$$

$$\xi = \frac{d}{b} \tag{8}$$

Substituting Eqs. (7) and (8) into Eq. (6) gives

$$Q_p = (12.457)\frac{1}{(\eta\xi)^{5/3}} d^{8/3} i^{1/2} \tag{9}$$

Taking $\eta\xi$, to be the deformation correction factor CF_M yields:

$$Q_p = (12.457)\frac{1}{CF_M{}^{5/3}} d^{8/3} i^{1/2} \tag{10}$$

where Q is the pipe discharge, i the pipe gradient (%), and d is the pipe diameter (mm).

Assuming that the total inflow to the heap through the gravel is drained via this layer in conjunction with the pipes, the total outflow may be determined to be

$$Q_p + Q_G = (q_l + q_p)L_v L_D \tag{11}$$

In which, Q_G is the discharge through gravelly layer, L_v the length of valley, L_D the distance between apexes of the two sides of the valley.

The following equation is then obtained given that the gravelly drainage layer used was previously designed for per unit width based on Giroud's equation:

$$Q_G = (q_l + q_p) \times L \times 1 \tag{12}$$

Combining Eqs. (10)–(12), the adequate internal diameter of the slotted polyethylene pipes which will be used in each wall as well as floor of the valley can be calculated as follows

$$d = \left\{\frac{1}{12.457}\frac{1}{i^{1/2}} CF_M^{5/3}(q_l + q_p)(L_v L_D - L \times 1)\right\}^{3/8} \tag{13}$$

Given that the correction factor, CF_M, is dependent on the diameter of the polyethylene pipes, it is necessary to first choose a base internal diameter for calculation purposes. Then using Eq. (13), the theoretical internal diameter is computed. If this matches the base diameter, it will be chosen as the adequate internal diameter; otherwise, a new correction factor based on this computed internal diameter must be chosen in order to obtain

Table 1
Correction factors for deformation of the polyethylene pipes (based on overburden soil)

Soil pressure (kPa)	Deformation correction factor, CF_M			
	Soil compaction = 78%		Soil compaction = 88%	
	Pipe diameter = 180	Pipe diameter = 160	Pipe diameter = 160	Pipe diameter = 110
200	1.03	1.09	1.01	1.01
400	1.06	1.15	1.02	1.02
600	1.07	1.19	1.03	1.03
800	1.08	1.23	1.04	1.04
1000	1.11	1.3	1.05	1.05
1200	1.14	1.37	1.05	1.05
1400	1.18	1.6	1.05	1.06
1600	1.2	1.7	1.06	1.07
1800	1.25	1.9	1.07	1.09
2000	1.3	2	1.1	1.1

a new internal diameter. This procedure must go on until the final computed diameter and the corresponding correction factor match. Finally, the theoretically computed internal pipe diameter is rounded up to the nearest actual internal pipe diameter available on the market which will then be used to design the auxiliary drainage layer in the heap structure.

Based on the information provided [3], along with the use of Eq. (4), CF_M has been calculated for various pipe diameters under a range of pressures and presented in Table 1.

Given the data obtained in the above table, it can be concluded that the lower and upper limits for the deformation correction factor are $1 < CF_M < 2$.

4. Case study of heap structure 2 at Sarcheshmeh copper mine

The lifespan of heap structure 1 at Sarcheshmeh copper mine terminated in 2002. Concurrent to the completion of the hydrometallurgy process of heap 1, the construction of heap structure 2 in an area of approximately 230,000 m^2 covering three valleys (nos.1–3), commenced and was ready for use by 2003 [9]. Fig. 9 illustrates the topographic map of the location of heap structure 2 at Sarcheshmeh copper mine after installation of the geomembrane.

The modified Giroud and Manning equations found earlier in this paper were used to determine the thickness of the gravelly drainage layer as well as the internal diameter of the slotted polyethylene pipes in order to design an adequate drainage system for heap structure 2. Hence, the thickness of the gravelly drainage layer was calculated via Eq. (1). Since, this thickness varies with respect to each valley wall due to base rock slope changes the most critical section of the heap was selected for the overall structure. In this case it can be certain that the height of acid will not increase above admissible levels.

It was found from the topographic map (Fig. 9) that the south wall of valley no. 2 was the most critical section in the heap which is used for the determination of the thickness of the gravelly drainage layer. The geometrical and hydraulic characteristics used for this design are presented in Table 2 and the thickness of the gravelly drainage layer is calculated via Eq. (1) as follows

$$K_{Lt} = \frac{0.01}{1.5 \times 1.5 \times 2} = 2.22 \times 10^{-3}\,\mathrm{mS^{-1}},$$

$$\lambda = \frac{2 \times 10^{-6} + 5.14 \times 10^{-8}}{2.22 \times 10^{-3} \times \tan^2 10} = 2.97 \times 10^{-2},$$

$$j = 1 - 0.12 \exp\left[-\left(\log\left(\frac{8 \times 2.97 \times 10^{-2}}{5}\right)^{5/8}\right)^2\right] = 0.94,$$

$$H_{\mathrm{allowable}} = 0.94 \times \left(\frac{\sqrt{1 + 4 \times 2.97 \times 10^{-2}} - 1}{2\cos 10/\tan 10}\right) \times 130 \times 1.7 = 100\,\mathrm{cm}$$

Thus, the overall design thickness of the gravelly drainage layer for heap leaching structure 2 is suggested to be $H_{\mathrm{allowable}} = 100$ cm. This layer cannot sufficiently drain the entire heap leaching structure on its own, therefore slotted polyethylene pipes are used as a form of auxiliary drainage to ensure that the total inflow is adequately drained out of the heap. Based on Eq. (13), the internal diameters of these pipes were calculated independently for each valley, then, the closest diameter available on the market was chosen for actual usage. The parameters required for the calculation of the internal diameter of these slotted polyethylene pipes are presented in Table 3. In this project,

Table 2
Geometrical and hydraulic characteristics of the southern valley wall 2 used to determine the thickness of the gravelly drainage layer for heap leaching structure 2 at Sarcheshmeh copper mine

RF_{PC}	2
RF_{CC}	1.5
RF_{BC}	1.5
K_{La} (ms^{-1})	0.01
L (m)	130
q_l ($\times 10^{-6}\,m^3\,S^{-1}\,m^{-2}$)	2
q_p ($\times 10^{-8}\,m^3\,S^{-1}\,m^{-2}$)	5.14
β (°)	10
F_S	1.7

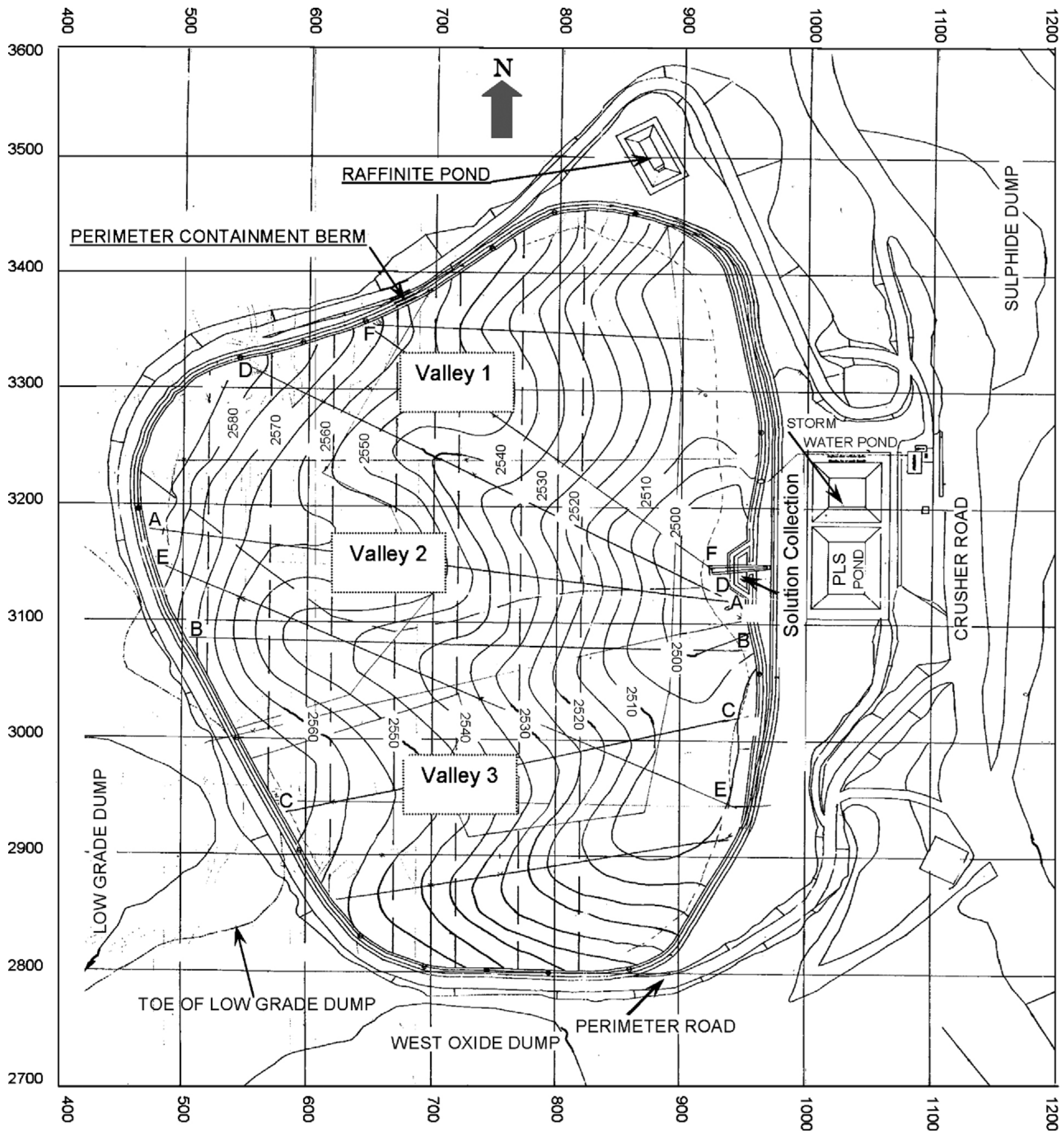

Fig. 9. Topographic illustration of heap structure 2 at Sarcheshmeh copper mine after installation of the geomembrane.

Table 3
Geometrical and hydraulic characteristics used to determine the diameter of the polyethylene pipes for heap leaching structure 2 at Sarcheshmeh copper mine with correction factor CF_M

Valley	Parameter							
	CF_M	i (%)	q_l ($\times 10^{-6}$ m^3 S^{-1} m^{-2})	q_p ($\times 10^{-8}$ m^3 S^{-1} m^{-2})	L_v (m)	L_D (m)	d (mm)	d_A (mm)
1	1.3	17	2	5.14	300	150	247	250
2	1.3	14	2	5.14	300	150	255	250
3	1.3	26	2	5.14	150	100	174	180

Table 4
Geometrical and hydraulic characteristics used to determine the diameter of the polyethylene pipes for heap leaching structure 2 at Sarcheshmeh copper mine without correction factor CF_M

Valley	Parameter						
	i (%)	q_l ($\times 10^{-6}$ m^3 S^{-1} m$-^2$)	q_p ($\times 10^{-8}$ m^3 S^{-1} m$-^2$)	L_v (m)	L_D (m)	d (mm)	d_A (mm)
1	17	2	5.14	300	150	209	210
2	14	2	5.14	300	150	216	220
3	26	2	5.14	150	100	147	150

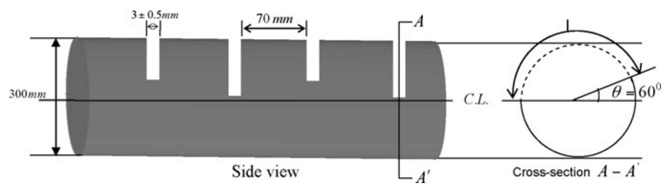

Fig. 10. Side view of the slotted polyethylene pipes used in heap structure 2 at Sarcheshmeh copper mine.

an appropriate correction factor CF_M was found from Table 1 by considering an overburden pressure of 1200 kPa (equivalent to 60 m overburden layer thickness) at 88% compaction. This correction factor was used to determine the internal diameter of the slotted polyethylene pipes. An example of this calculation for valley no. 1 is shown below

$$d = \left[\frac{1}{15.556} \times \frac{1}{0.17^{1/2}} \times 1.3^{5/3}((2 \times 10^{-6} + 5.14 \times 10^{-8}) \times (300 \times 150 - 130))\right]^{3/8} = 0.247\,\text{m} = 247\,\text{mm}$$

However, if deformation is not taken into account, the resulting internal pipe diameters are smaller than that obtained in Table 3. Therefore, the combined drainage system will not drain the total inflow which results in a severe increase of acid levels in the heap structure. Calculations for these internal pipe diameters, without CF_M, are presented in Table 4. The schematic side view diagram of the slotted polyethylene pipes used in the heap is shown in Fig. 10. The particle size distribution along with the related envelopes of the gravels and the construction of heap structure 2 at Sarcheshmeh copper mine are shown in Figs. 11 and 12, respectively.

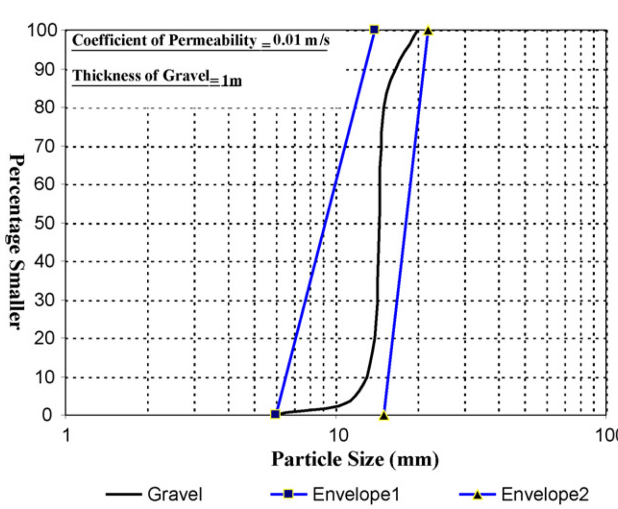

Fig. 11. Particle size distribution and envelopes related to gravelly drainage layer of heap structure 2 at Sarcheshmeh copper mine.

Fig. 12. Site view of the heap structure 2 along with construction of the gravelly drainage layer at Sarcheshmeh copper mine.

5. Conclusion

The investigation in this paper led to the following concluding remarks:

1. The main task of the drainage system is to transfer total inflow from the heap leaching structure towards the designated basin.
2. The PLS flows through the gravelly layer freely parallel to the natural slope of the heap base rock.
3. The average of the highest seasonal precipitation must be taken into account for the calculation of the total inflow for drainage system design purposes.
4. It has been found that, slight modification of Giroud's equation enables determination of the thickness of the gravelly drainage layer for the heap structure as demonstrated in this paper.
5. The most critical slope section was selected for the calculation of appropriate gravelly drainage thickness for the overall heap, ensuring that pore acid pressure will not exceed permissible levels.
6. The slotted polyethylene pipes are deformed due to over burden pressures, causing a reduction in the cross-sectional

area which results in an increase in the pore acid pressure within the heap.

7. Manning's equation alone does not provide adequate pipe cross-sectional area to suit the transfer of the additional inflow.
8. In this paper, CF_M has been added to Manning's equation to account for the deformation factor thus providing the maximum discharge from the polyethylene pipes.
9. In this paper by combining Manning and Giroud's equations a modified equation is obtained (Eq. (13)) which enables the calculation of adequate polyethylene pipe diameter to be used as a form of auxiliary drainage within the heap structure.
10. The thickness of the gravelly drainage layer for heap leaching structure 2 at Sarcheshmeh copper mine has been calculated to be 1 m and the internal diameter of the slotted polyethylene pipes are 250 mm for valley nos. 1 and 2 and 180 mm for valley no. 3 when the CF_M correction factor is used.

Acknowledgements

The authors would like to sincerely thank M. Torabi, consultant at the Sarcheshmeh Copper Centre for Research and Development, who provided support for the data required and encouragement throughout the investigation.

As well, considerable appreciation is expressed to Ms. F. Majdi as editor and Mrs. M. Majdi for proof reading of the manuscript.

Finally, the financial support of Khavar Tunnel Engineering Inc., throughout preparation of this paper is greatly appreciated.

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