EXPERIMENTAL MODELS OF METAL LEACHING FOR SCALING-UP TO THE FIELD

Part 1: Similitude Concept for Testing of Metal Leaching from Waste Rock Dumps

Part 2: Confirmation from the Field Data

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NRC’s ARD-ML Research

Vision:
- To contribute to the Canada’s world-leading ARD-ML research
  - A Canadian hub
  - A center for ARD-ML data analysis
  - A center for scaling up testing to the field

Mission:
- To generate core/key knowledge and technologies for predicting and preventing ARD-ML and transfer them to Canadian companies
NRC’s ARD-ML Research

Target Clients
Primarily Canadian consulting companies who provide technical services to mining companies

Who gets benefits from the research

- The public in terms of reduced water pollution;
- Consulting companies in terms of improved global competitiveness
- Mining companies in terms of reduced cost and liability

NRC’s employees: 3,900
Research centers: over 20 across Canada

We do **not** compete with the Canadian Industry
Experimental models vs. the real field

Real Field

Rain-Water/snow-melt
Infiltration rate Q

Waste Rock Dump

Drainage chemistry C

\[ C = f(q_1, q_2, q_3, q_4, \ldots) \]

Experimental Models

Water Infiltration rate Q

A sample of waste
rock dump

Drainage chemistry C

\[ C = f(q_1, q_2, q_3, q_4, \ldots) \]
The problems with the experimental models

Problems

- Samples ≠ Population
- How to scale-up experimental results to the field?

Solutions

- Statistically sufficient number of samples; Mixing
- Make the experimental models similar to the field

But, what do you mean by similar?
Summary

1. A similitude concept is proposed here for designing the smaller-scale metal-leaching testing models. Based on the concept, the smaller-scale testing models are similar to the field when \( \left( \frac{Q}{k \lambda B} \right)_{Lab} = \left( \frac{Q}{k \lambda B} \right)_{Field} \), the similarity condition, one has, \( \left( \frac{C}{C_e} \right)_{Lab} = \left( \frac{C}{C_e} \right)_{Field} \).

Q: infiltration rate
k: kinetic constant of metal leaching
\( \lambda \): wet surface area within a unit volume of rocks
B: vertical depth of a waste rock dump or a column-leach cylinder
C: Concentration of a metal in drainage water
\( C_e \): Saturation concentration of a metal in drainage water

2. In terms of overall trend the concept is in agreement with the 30 years of ARD-ML monitoring data from Equity Silver mine site.
Part 1: Similitude Concept for Scaling-up smaller-scale metal leaching testing results to Waste Rock Dumps
Geometrical similarity of triangles allows for scaling up

\[
\text{Area} = f(a, b, c)
\]
\[
\text{Area} = a^x b^y c^z, \quad (x + y + z = 2)
\]
\[
\text{Area} = a^{2-y-z} b^y c^z
\]
\[
\text{Area} = a^2 \left(\frac{b}{a}\right)^y \left(\frac{c}{a}\right)^z
\]
\[
\frac{\text{Area}}{a^2} = f\left(\frac{b}{a}, \frac{c}{a}\right)
\]

When geometrical similarity holds, that is, \( \frac{b}{a} = \frac{b}{a} ; \frac{c}{a} = \frac{c}{a} \)

One has, \( f\left(\frac{b}{a}, \frac{c}{a}\right) = f\left(\frac{b}{a}, \frac{c}{a}\right) \)

So, one has, \( \frac{\text{Area}}{a^2} = \frac{\text{Area}}{a^2} \)
**Make experimental models similar to the field**

**Step 1: List the significant quantities**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Symbol</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metal ion concentration</td>
<td>C</td>
<td>ML$^{-3}$</td>
</tr>
<tr>
<td>Water infiltration rate through a unit horizontal surface</td>
<td>Q</td>
<td>LT$^{-1}$</td>
</tr>
<tr>
<td>Wet surface area within a unit volume of rocks</td>
<td>$\lambda$</td>
<td>L$^{-1}$</td>
</tr>
<tr>
<td>Kinetic constant for metal leaching</td>
<td>$k$</td>
<td>LT$^{-1}$</td>
</tr>
<tr>
<td>The depth through which water flows</td>
<td>$\beta$</td>
<td>L</td>
</tr>
<tr>
<td>Saturation concentration</td>
<td>$C_e$</td>
<td>ML$^{-3}$</td>
</tr>
</tbody>
</table>

**Kinetic constant for metal leaching**

\[
\frac{dM}{dt} = -Ak(C - Ce)
\]
Make experimental models similar to the field

Step 2: Reduce the number of arguments

\[ C = f(Q, \lambda, \beta, k, C_e) \]

\[ C = f\left(\frac{Q}{\lambda}, \beta, k, C_e\right) \]

\( \frac{Q}{\lambda} \): amount of water flowing through the surfaces of a unit volume of rocks within a unit time

The Field

Rain-Water/snow-melt
Infiltration rate \( Q \)

Waste Rock Dump

Wet surface density: \( \lambda \)
Dump depth: \( \beta \)
Kinetic constant: \( k \)
Saturation concentration: \( C_e \)

Metal concentration \( C \)

\[ C = f\left(\frac{Q}{\lambda}, \beta, k, C_e\right) \]
Make experimental models similar to the field?
Step 3: Further reduce the number of arguments by Dimensional Analysis

Buckingham π theorem

\[ C = f \left( \frac{Q}{\lambda}, k, \beta, C_e \right) = \left( \frac{Q}{\lambda} \right)^x k^y (\beta)^z C_e^w \]

Using dimensional homogeneity, it gives

\[ ML^{-3} = (L^2 T^{-1})^x (LT^{-1})^y L^z \quad (ML^{-3})^w \]

1 = w
0 = −x − y
−3 = 2x + y + z − 3w

w = 1
y = −x
z = −x

\[ \frac{C}{C_e} = \left( \frac{Q}{k\lambda\beta} \right)^x = f \left( \frac{Q}{k\lambda\beta} \right) \]

One argument only, not four. A big deal!

Where “x” could be any number; f denotes a function of ( ).
Make experimental models similar to the field

Step 4: Similarity condition

\[
\frac{C}{C_e} = f\left(\frac{Q}{k\beta\lambda}\right)
\]

The ML (metal-leaching) similarity condition: make \(\frac{Q}{k\beta\lambda}\) constant, that is,

When the condition is met, \(\left(\frac{Q}{k\lambda\beta}\right)_{Lab} = \left(\frac{Q}{k\lambda\beta}\right)_{Field}\)

one has, \(\left(\frac{C}{C_e}\right)_{Lab} = \left(\frac{C}{C_e}\right)_{Field}\)

In this way, scaling up is done!
An illustrative example: determine the size of rocks in a leach-column testing so that scaling-up condition is met

Assume $k=k$, $Q=Q$, then, in order to make $\frac{Q}{k\beta\lambda}$ unchanged, i.e.,

$$\frac{Q}{k\beta\lambda} = \frac{Q}{k\beta\lambda}$$

One gets,

$$\frac{\lambda}{\lambda} = \frac{\beta}{\beta}$$

Note that $d$ is proportional to $\sqrt{\lambda}$, so one has,

$$\frac{d}{d} = \sqrt{\beta}$$

Assume a waste rock dump’s height $\beta$ and the leach column’s height $\beta$ has the relation $\beta = 0.1\beta$, then, the rock sample to be tested should be ground into smaller size as $d=\sqrt{0.1}d=0.32d$, so that $C=C$. 
The model tells the dependence of $C(\beta)$ upon infiltration rate $Q$ as: 

$$C(\beta) = C_e (1 - e^{-(k\lambda\beta)/Q})$$

Mass conservation:

$$\frac{dc(x)}{dx} = \frac{k}{hv} (C_e - C(x))$$

Boundary Condition: $C = 0$ when $x=0$

Solve for: $C = ?$ When $x=\beta$

$C = C_e (1 - e^{-(k\beta)/(hv)})$, when $x=\beta$

Note that $Q = \lambda hv$, so it can be written as $C = C_e (1 - e^{-(k\lambda\beta)/Q})$

Denote $\ln(1-C/Ce) = y$, and denote $1/Q = x$, so 

$y = -(K\beta\lambda)x$, a straight line on a x-y plane, and its slope: $-(K\beta\lambda)$
Part 2: Conformation of the Models from the ARD-ML Monitoring data of the waste rock dump at Equity Silver Mine, BC, Canada

How to confirm: comparison between the model and the mine-site data

The experimental model gives a dependence of drainage metal concentration $C$ on infiltration rate $Q$

The historical monitoring data of ARD-ML also gives the dependence of drainage metal concentration $C$ on infiltration rate $Q$
The model shows the dependence of metal concentration $C$ upon infiltration rate as:

$$\frac{C}{C_e} = 1 - e^{-(k\lambda\beta)/Q}$$

$$\ln\left(1 - \frac{C}{C_e}\right) = -\frac{(k\lambda\beta)/Q}{Q}$$
Equity Silver Mine

- Houston, BC
- Au, Ag, Cu mine
- 1980-1994 mining operation
- Closed in 1994
- Sulfide mine waste 80 million tons
- Effluent pH 2-3
- About $1.5M/year for effluent treatment
- $5M for the cover in 1994
ARD Ditches and Ponds at Equity Silver mine
The mine-site data shows the dependence of acidity $C$ upon flow rate $Q$ at C7 location on the ARD ditch.

### March from 1998-2017

$$y = -0.4839x - 0.2558$$  
$$R^2 = 0.1559$$

### April from 1998-2017

$$y = 0.9541x - 0.2448$$  
$$R^2 = 0.1544$$

### May from 1998-2017

$$y = -0.9514x - 0.2025$$  
$$R^2 = 0.0334$$

### June 1998-2017

$$y = -0.5764x - 0.1293$$  
$$R^2 = 0.2638$$
The mine-site data shows the dependence of acidity $C$ upon flow rate $Q$ at C7 location on the ARD ditch.
The mine-site data shows the dependence of Cu concentration C upon flow rate Q at C7 location on the ARD ditch.

Flow Rate(Q) VS. Copper (C) at C7
March from 1998-2017

Flow Rate(Q) VS. Copper (C) at C7
April from 1998-2017

Flow Rate(Q) VS. Copper (C) at C7
May from 1998-2017

Flow Rate(Q) VS. Copper (C) at C7
June 1998-2017

y = -1.0941x - 0.0341
R² = 0.9359

y = -0.8243x - 0.2491
R² = 0.1789

y = -1.7451x - 0.0857
R² = 0.7781

y = -0.5277x - 0.0841
R² = 0.7042
The mine-site data shows the dependence of Cu concentration C upon flow rate Q at C7 location on the ARD ditch.

Flow Rate(Q) VS. Copper (C) at C7
- August from 1998-2017
  \[ y = -0.0692x + 0.2175 \]
  \[ R^2 = 0.115 \]

- September from 1998-2017
  \[ y = -0.6557x - 0.0662 \]
  \[ R^2 = 0.5301 \]

- October from 1998-2017
  \[ y = -0.853x - 0.0145 \]
  \[ R^2 = 0.9998 \]
The mine-site data shows the dependence of Iron concentration $C$ upon flow rate $Q$ at C7 location on the ARD ditch.

Flow Rate(Q) VS. Iron (C) at C7
March from 1998-2017

$$y = -0.212x - 0.1757$$
$$R^2 = 0.0729$$

Flow Rate(Q) VS. Iron (C) at C-7
April from 1998-2017

$$y = -0.4584x - 0.1898$$
$$R^2 = 0.0828$$

Flow Rate(Q) VS. Iron (C) at C7
May from 1998-2017

$$y = -0.6296x - 0.1237$$
$$R^2 = 0.0463$$

Flow Rate(Q) VS. Iron (C) at C7
June 1998-2017

$$y = -0.333x - 0.0594$$
$$R^2 = 0.3863$$
The mine-site data shows the dependence of Iron concentration C upon flow rate Q at C7 location on the ARD ditch.
The mine-site data shows the dependence of Mg concentration upon flow rate Q at C7 location on the ARD ditch.
The mine-site data shows the dependence of Mg concentration C upon flow rate Q at C7 location on the ARD ditch.
The mine-site data shows the dependence of Zn concentration \( C \) upon flow rate \( Q \) at C7 location on the ARD ditch.

- **March from 1998-2017**
  \[ y = -0.2103x - 0.18 \]
  \( R^2 = 0.0979 \)

- **April from 1998-2017**
  \[ y = -0.5078x - 0.1066 \]
  \( R^2 = 0.2551 \)

- **May from 1998-2017**
  \[ y = -0.5169x - 0.1442 \]
  \( R^2 = 0.0286 \)

- **June 1998-2017**
  \[ y = -0.5306x - 0.1029 \]
  \( R^2 = 0.3594 \)
The mine-site data shows the dependence of Zn concentration $C$ upon flow rate $Q$ at C7 location on the ARD ditch.

**Flow Rate(Q) VS. Zn (C) at C7**

- **July from 1998-2017**
  - $y = -0.6829x - 0.0927$
  - $R^2 = 0.5287$

- **August from 1998-2017**
  - $y = -0.3844x - 0.1504$
  - $R^2 = 0.2229$

- **September from 1998-2017**
  - $y = -0.2895x - 0.1552$
  - $R^2 = 0.2309$

- **October from 1998-2017**
  - $y = -0.2838x - 0.119$
  - $R^2 = 0.1777$

$Ce$ = Saturation Concentration

$1/Q$ = Flow Rate(Q)
The mine-site data shows the dependence of Al concentration C upon flow rate Q at C7 location on the ARD ditch.
The mine-site data shows the dependence of Al concentration C upon flow rate Q at C7 location on the ARD ditch.
The mine-site data shows the dependence of Ca concentration $C$ upon flow rate $Q$ at C7 location on the ARD ditch.
The mine-site data shows the dependence of Ca concentration C upon flow rate Q at C7 location on the ARD ditch.
The mine-site data shows the monthly variation of $k\beta\lambda$ is in the same trend of the monthly rain-fall+snow-melt
Next steps

1. Improve the accuracy of scaling up by releasing the current assumption that $\lambda$ is a constant. Actually, $\lambda$ becomes larger when infiltration rate goes up.

2. Study seasonal effect on $k$.

3. Re-confirm the improved scaling-up method.

We are looking for collaborators who can provide ARD-ML testing data and/or mine-site monitoring data.