Design project - SIE 2025

Development of a Predictive Tool for the Leaching of Pollutants in Construction Material Deposits

Students:
Alice *Giorgetti*, Lorenzo *Prato*

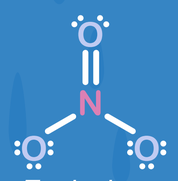
Company: IFEC ingegneria, David *Cordier*
EPFL supervisor: Prof. Meret *Aeppli*, SOIL

Context

Environmental risks associated with the **leaching** of contaminants from solid excavation waste, particularly from tunnel construction activities, such as the excavation of ***Gotthard Road Tunnel***, used as a *theoretical case study.*

- Leaching of pollutants due to water infiltration could lead to contamination of surface and groundwater,

Considered Contaminants



Explosives

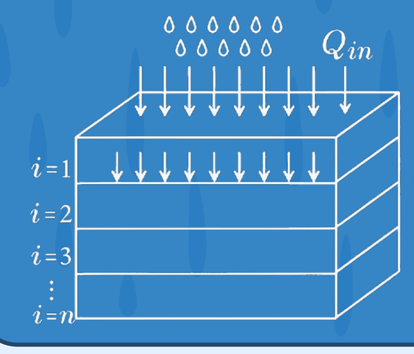
Geogenic

Regulamentary framework:

- Excavated material must meet ADWO[1] limits to be reused, otherwise it goes to Type B-D landfills,
- Landfills must collect, monitor, and treat leachate regularly,
- Leachate discharge is allowed only if it meets legal standards[2].

Goal & Assumptions

Goal: develop a predicitive model for the leaching of inorganic contaminants from excavation material deposits. Particular attention to low solubility contaminants (Arsenic) and high solubility ones (Nitrate).



Assumptions:

1. Water movement within the deposit is considered one-dimensional and vertical,
2. The initial concentration of pollutants in the solid phase is assumed to be constant and homogeneous throughout the deposit,
3. Pollutants do not undergo any physico-chemical transformations

Methods

Precipitation data

Material properties

Infiltration model - Green&Ampt [3]

Parameters:
K_s hydraulic conductivity, ψ suction, $\theta_d = \theta_s - \theta_i$ moisture deficit, θ_s saturated water content, θ_i initial water content.

Potential infiltration rate:

$$f_* = K_s(1 + \frac{\Psi\theta_d}{F})$$

Actual infiltration rate: *f = min(f*, R)*

$$F(t) = \int_0^t f(t)\,d\tau \qquad Z = \frac{F(t)}{\theta_d}$$

➜ Newton's method to obtain F(t)

OUTPUTS: t, f(t), f*(t), F(t) and z(t)

Timestep

Total deposit height

Discretization

- Time-step corresponds to water residence time in one layer
- Linear interpolation of Green & Ampt outputs

OUTPUTS:
- # of layers
- Height of each layer

Contaminant properties

Diffusion model [4]

Release of contaminants governed by diffusion processes, described using **Fick's Second Law**

Cumulative mass of the costituent released in layer i :

$$M_{\text{mass}}^{i=1} = 2 \cdot C_0 \cdot \frac{S}{V} \cdot \left(\frac{D^{\text{obs}} \cdot t_{i=1}}{\pi}\right)^{1/2} [mg/kg]$$

➜ Conversion to aqueous concentration by dividing by WS (water-to-solid ratio)

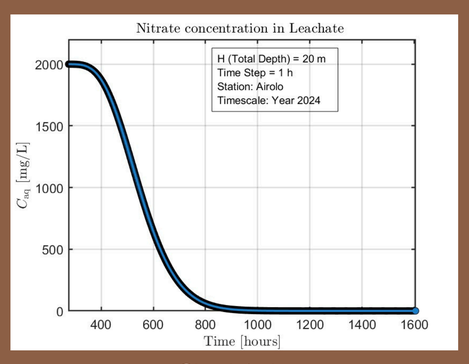
Linear sorption model to describe equilibrium conditions :

$$C_{aq,eq,i} = \frac{(C_0 - M_{\text{mass}}^i)}{k_D}\ [mg/L]$$

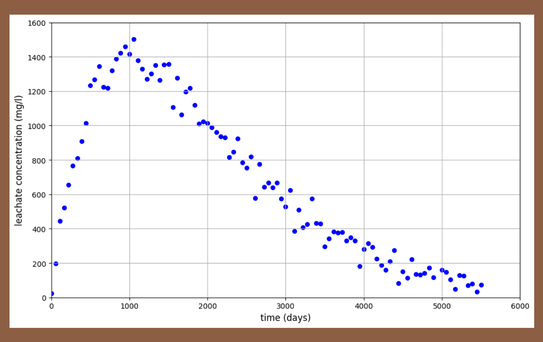
OUTPUT
Concentration of contaminant in leachate [mg/L]

Results and Discussion

Nitrate



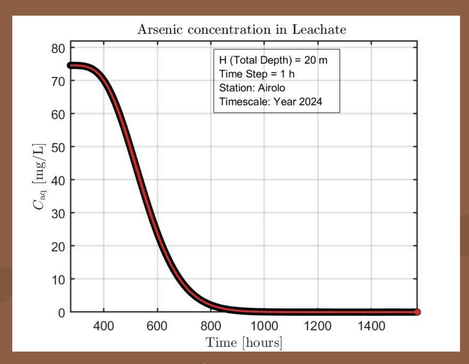
Simulated



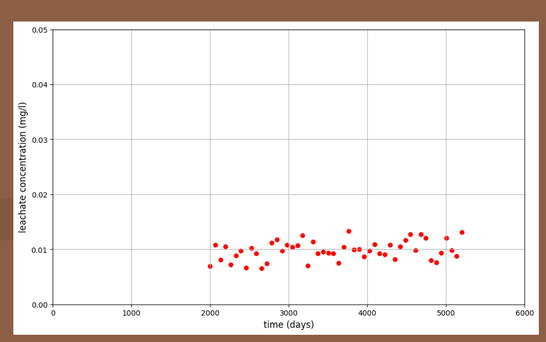
Measured

- Concentration decreases over time due to pollutant depletion in the solid phase
- Higher peak concentration observed,
- Simulated results match measured data in magnitude and decline trend,
- Faster simulated decline due to instantaneous sorption model and overestimated infiltration depth.

Arsenic



Simulated

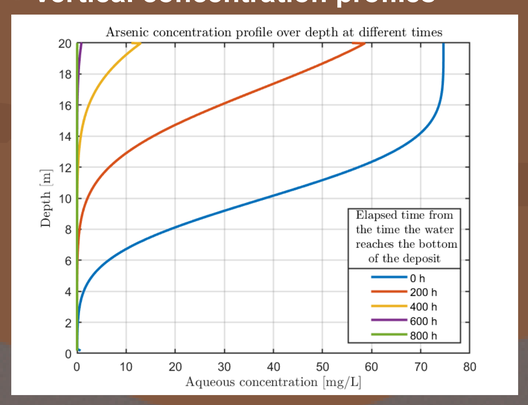


Measured

- Similar temporal evolution to nitrate, driven by rapid establishment of equilibrium conditions,
- Significant discrepancies with measured data,
- Improvements include surface complexation modeling and incorporation of pollutant speciation.

Sensitivity analysis

- **Variation of precipitation input** (different altitudes):
  - Rapid attainment of thermodynamic equilibrium overrides the influence of precipitation on final concentrations,
  - Precipitation affects only the diffusion process, not the time required to reach equilibrium.
- **Variation of time-step (tr)**:
  - Larger time-steps result in slower concentration decay and less precise pollutant dynamics,
  - Smaller tr values yield sharper and more realistic concentration curves.
- **Variation of deposit height (H):**
  - Increasing deposit height delays and prolongs contaminant release (slower vertical perticolation),
  - Peak leachate concentrations remain similar across all heights (rapid solid-liquid equilibrium).
- **Vertical concentration profiles**



  - Top layers quickly flush out,
  - Contaminant fronts shift downward with time. Maximal concentrations remain near the bottom until full rinsing (~800 h).

Conclusion

- The model highlights general trends in contaminant leaching but lacks precision due to oversimplified starting hypotheses: chemical transformations, kinetic sorption processes and environmental variables were excluded,
- Diffusion is the only controlling mechanism, which leads to a rapid attainment of equilibrium for both pollutants. Major limitation for low solubility contaminants,
- Sensitivity analyses confirm the model's strong dependence on timestep and deposit height.

➜The current model is a conceptual prototype and its predictive reliability is low without further refinement,
➜Future development prospectives: Arsenic phisico-chemical parametrisation, time-lagged sorption model, time-scale adjustments, more realistic deposit shape, multidirectional flow.

References
[1] SR 814.600, Waste Ordinance (2015), [online]
[2] SR 814.201, Waters Protection Ordinance (1998), [online]
[3] L. W. Mays, "Water resources engineering", 2nd Edition, 2010.
[4] Kosson et al., Environ. Eng. Sci., 19, 2002. DOI: 10.1089/109287502760079188

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