Athens 2014

2nd INTERNATIONAL CONFERENCE

on Sustainable Solid Waste Management

IMPACT OF LEACHATE FILTRATION ON SLOPE FAILURE POTENTIAL OF LANDFILL SIDE WALLS

Damjan Ivetić - divetic@hikom.grf.bg.ac.rs

dr Nenad Jaćimović

University of Belgrade

Faculty of Civil engineering

Content of the presentation

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- Mathematical model / Governing equations
- Problem domain definition
- Numerical model
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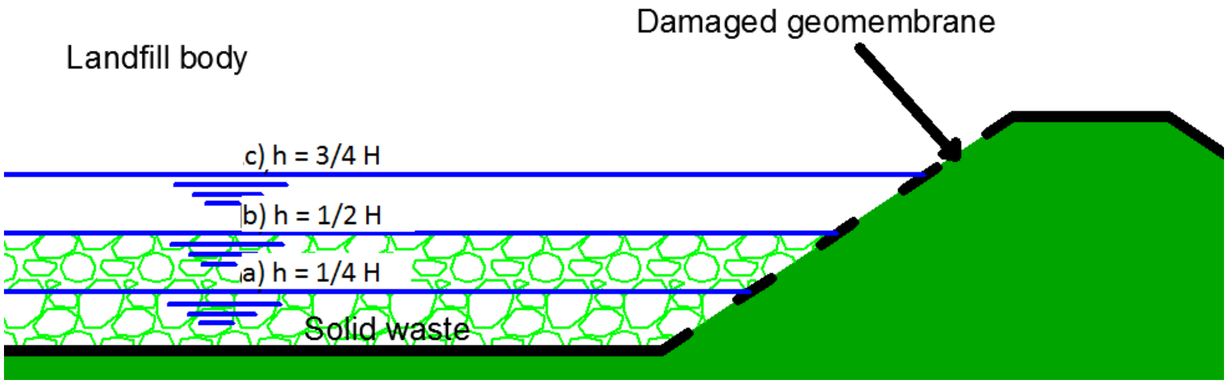


Why are we analyzing this issue?

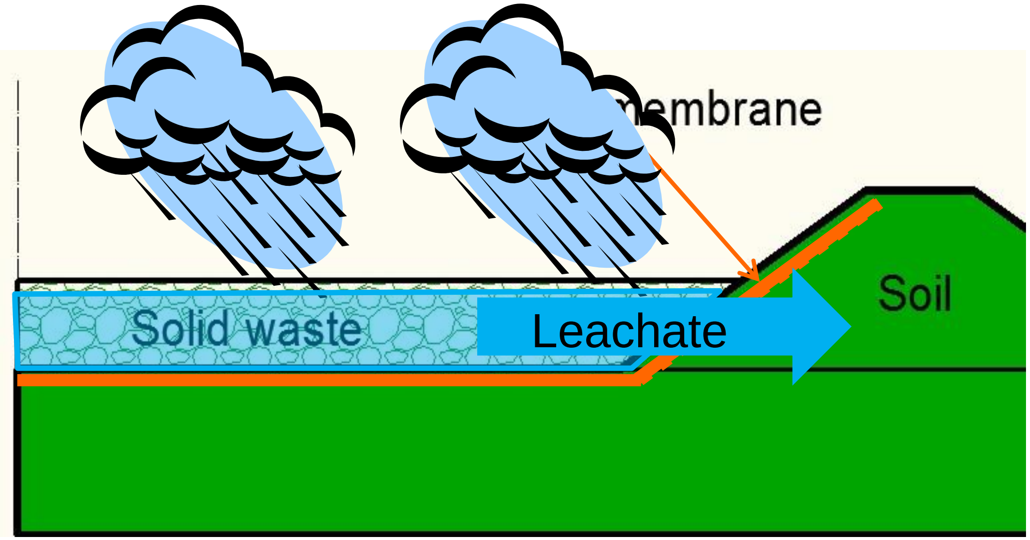
- Organized solid waste disposal:

High income countries	Low and middle income countries
Sanitary landfills	Sanitary landfills
SW Incineration	…
Separation and recycling	(around 84% of the global pop. World Bank 2012)
…	

- Different aspects of sanitary landfill design and exploitation have been examined and improved in past but…
- There are still potential hazards that require attention

Why are we analyzing this issue?

- We are addressing the issue of leachate filtration through porous walls of landfills.
- Leachate is generated from the waste itself and by precipitation events (daily cover **is not** applied)



- Drainage system - out of order
- Heavy precipitation – (Serbia, Bosnia, Croatia 2014)
- Geomembrane – poorely built will detoriate
- Gravity drives the leachate through porous wall
- **Seepage and buoyancy forces – shear slope failure?**

Mathematical model / Governing equations

- Two issues:

1.) Steady state 2D filtration 2.) 2D poroelastic analysis

1.) Saturated / Unsaturated flow through porous media

Darcy's law

$$q = \frac{Q}{A} = -K\frac{dh}{dl}$$

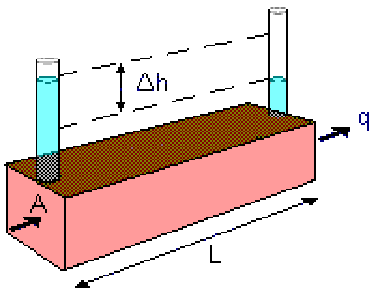
h - fluid head/potential

$\frac{dh}{dl}$ - potential gradient

K - hydraulic conductivity

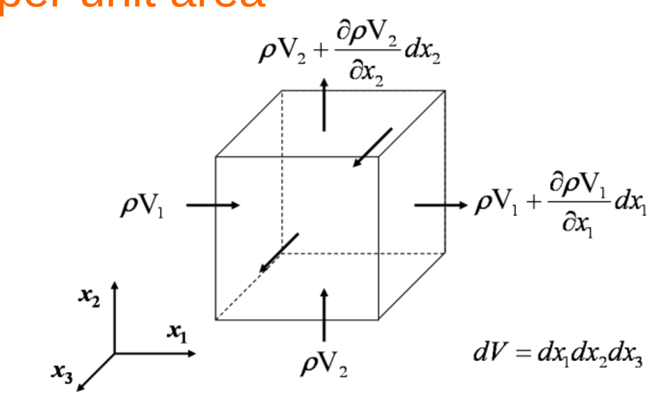
Q - flow rate

q - flow rate per unit area



Laplace's equation

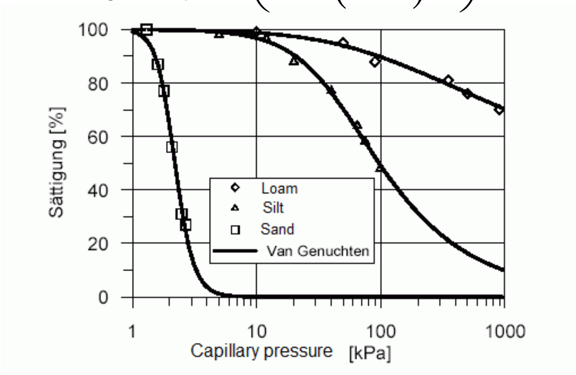
$$\frac{\partial}{\partial x}\left(-K_x\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(-K_y\frac{\partial h}{\partial y}\right) = 0$$



Mathematical model / Governing equations

Soil water characteristic curve $\Psi - \theta_w$ (van Genuchten, 1980)

$$\theta = \frac{\theta_w - \theta_r}{\theta_s - \theta_r} = \left(\frac{1}{1 + (\alpha \Psi)^N} \right)^M$$



θ - reduced saturation

θ_w - water content for a particular soil

θ_r - irreducible saturation

θ_s - saturated water content

Ψ - capillary pressure

α, N, M - model's parameters

coupled with **relative permeability model** (Mualem, 1976)

$$K_w(\theta_w) = k_{rw}(\theta_w) K$$

$$k_{rw} = \sqrt{\theta} \left(1 - \left[1 - \theta^{1/M} \right]^M \right)^2$$

k_{rw} - relative permeability

K_w - unsaturated hydraulic conductivity

Mathematical model / Governing equations

2.) 2D poroelastic analysis – Plane strain

Hooke's law constitutive model

$$\varepsilon_{xx} = \frac{1}{E}\left[\left(1-\nu^2\right)\sigma'_{xx} - \nu\left(1+\nu\right)\sigma'_{yy}\right]$$

$$\varepsilon_{yy} = \frac{1}{E}\left[\left(1-\nu^2\right)\sigma'_{yy} - \nu\left(1+\nu\right)\sigma'_{xx}\right]$$

$$\varepsilon_{yx} = \frac{1+\nu}{E}\sigma'_{yx}$$

Terzaghi's effective stress concept

$$\sigma'_{ij} = \sigma_{ij} + \alpha p \delta_{ij}$$

Effective stress equilibrium

Seepage body forces

$$\frac{\partial \sigma'_{xx}}{\partial x} + \frac{\partial \sigma'_{yx}}{\partial y} = \alpha \rho_w g \frac{\partial h}{\partial x}$$

$$\frac{\partial \sigma'_{yy}}{\partial y} + \frac{\partial \sigma'_{yx}}{\partial x} = (\rho_t - \alpha \rho_w) g + \alpha \rho_w g \frac{\partial h}{\partial y}$$

Finally unknown displacements….

$$\frac{E}{2(1+\nu)}\nabla^2 u_x + \left[\frac{\nu E}{(1-2\nu)(1+\nu)} + \frac{E}{2(1+\nu)}\right]\cdot\left(\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_y}{\partial y \partial x}\right) = \rho_w g \frac{\partial h}{\partial x}$$

$$\frac{E}{2(1+\nu)}\nabla^2 u_y + \left[\frac{\nu E}{(1-2\nu)(1+\nu)} + \frac{E}{2(1+\nu)}\right]\cdot\left(\frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_x}{\partial x \partial y}\right) = \left(\rho_t - \rho_w\right) g + \rho_w g \frac{\partial h}{\partial y}$$

Problem domain definition

1.) Steady state 2D filtration

$$\frac{\partial}{\partial x}\left(-K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(-K_y \frac{\partial h}{\partial y}\right)=0$$

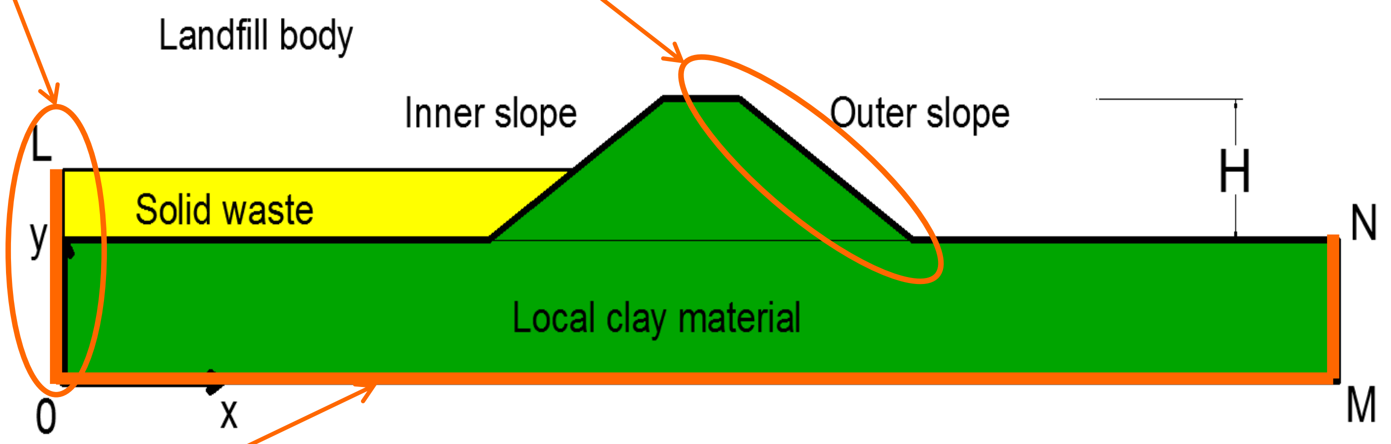
Boundary condition obtained through iterations

$$h(x_{RB},0)=0$$

$$h(x_{RB},y_{RB})=y_{RB}$$

Boundary condition fixed

$$h(x_{LB},y_{LB})=h_L$$



no flow boundary

Another set is used for the poroelastic analysis

Problem domain definition

1.) 2D poroelastic analysis – Plane strain

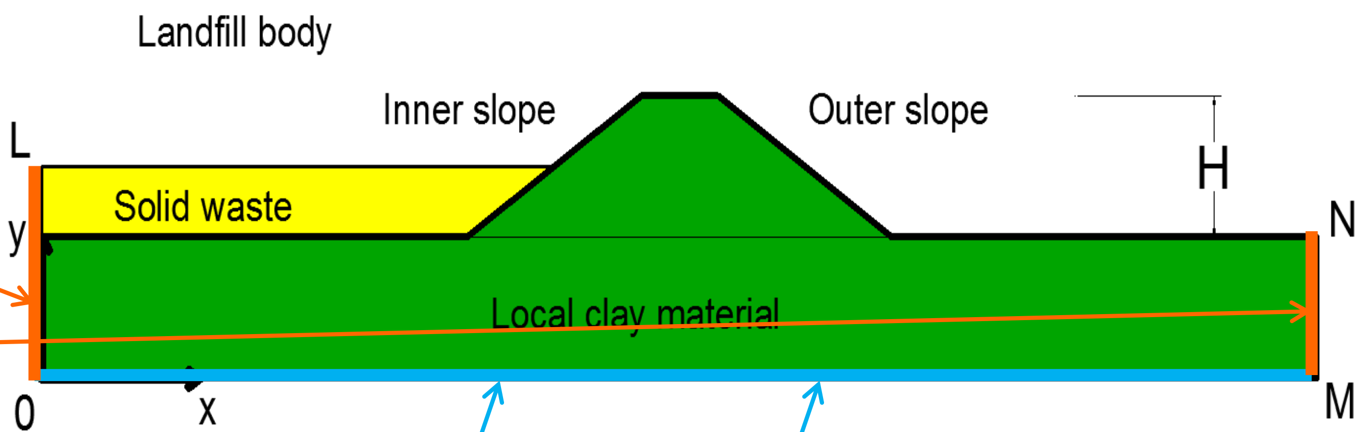
$$\frac{E}{2(1+\nu)}\nabla^2 u_x + \left[\frac{\nu E}{(1-2\nu)(1+\nu)} + \frac{E}{2(1+\nu)}\right]\cdot\left(\frac{\partial^2 u_x}{\partial x^2} + \frac{\partial^2 u_y}{\partial y \partial x}\right) = \rho_w g \frac{\partial h}{\partial x}$$

$$\frac{E}{2(1+\nu)}\nabla^2 u_y + \left[\frac{\nu E}{(1-2\nu)(1+\nu)} + \frac{E}{2(1+\nu)}\right]\cdot\left(\frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_x}{\partial x \partial y}\right) = (\rho_t - \rho_w) g + \rho_w g \frac{\partial h}{\partial y}$$

Horizontal displacements restricted

$u_x(0, y) = 0$

$u_x(x_M, y) = 0$



Both horizontal and vertical displacements restricted

$u_x(x, 0) = 0$ $u_y(x, 0) = 0$

Numerical model

- We employ two FE codes with quadrilateral elements:

2D steady state filtration → 2D poroelastic analysis → **Shear failure potential Φ distribution**

$$-\frac{\sigma_1 - \sigma_3}{\sigma_1 + \sigma_3} = \frac{|\tau'_{\max}|}{-\sigma_m} = \sin\phi = \Phi$$

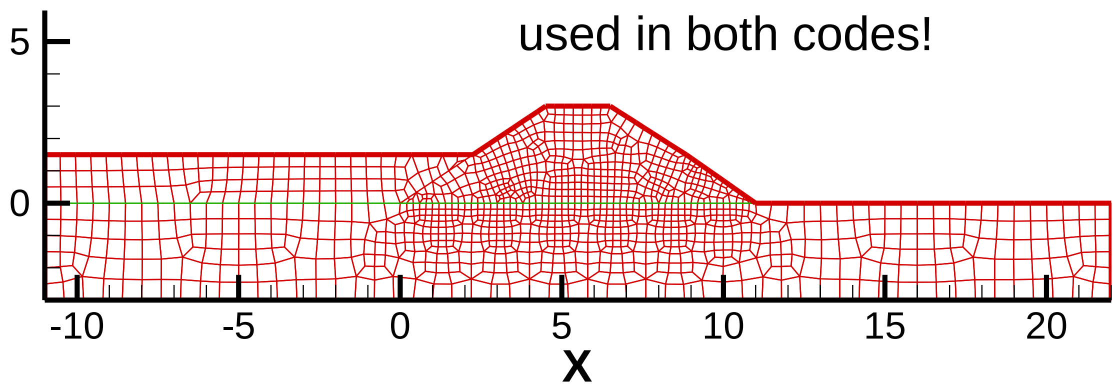
σ_1, σ_3 - principal stresses

τ'_{max} - max shear stress

σ_m - mean n. stresses

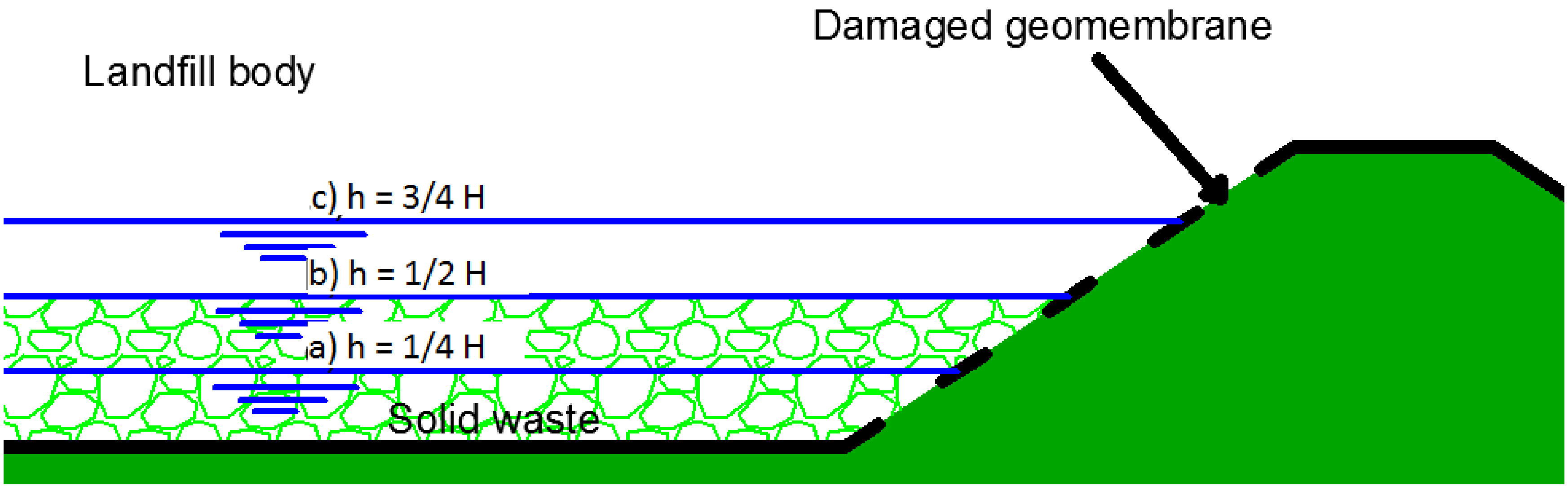
ϕ - angle of internal friction

Same FE mesh is used in both codes!



Results

- Nondimenzionalization of the variables
- Three scenarios investigated and compared to dry or normal operating conditions…



- Outer slope toe of the wall is the critical area…

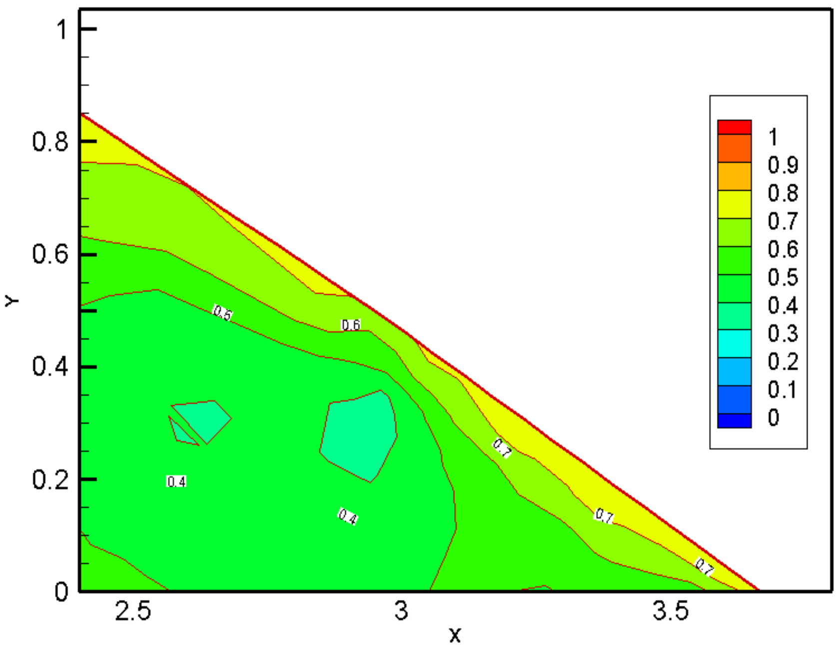
Results

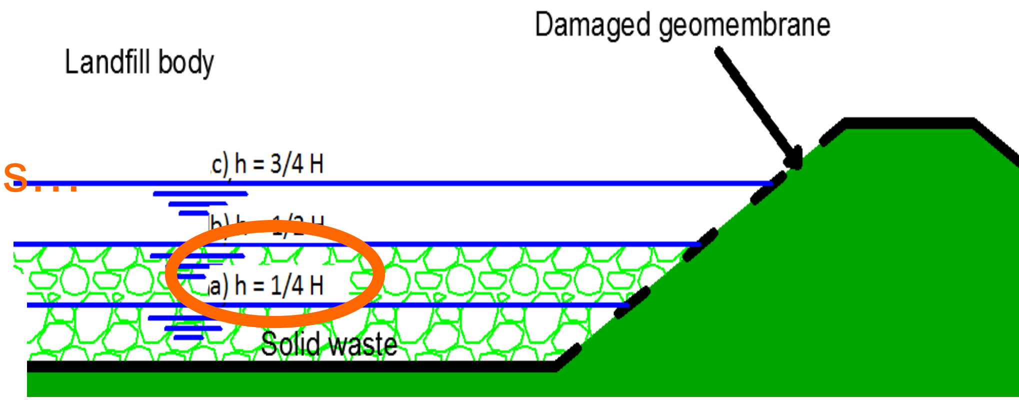
- Solid waste parameters for filtration analysis similar to gravel!

	Parameters for elastic displacement analysis					
Material	Dry density	Saturated density	Poisson's ratio	Young's modulus		
	ρ_{td}	ρ_{ts}	v	E		
	[kg/m^3]	[kg/m^3]	[/]	[MPa]		
Local clay	1600	2000	0.3	50		
Solid waste	770	1000	0.33	1		
	Parameters for groundwater flow analysis					
Material	Hydraulic conductivity x	Hydraulic conductivity y	Residual w. content	Saturated w. content	Model par.	Model par.
	K_x	K_y	θ_r	θ_w	α	n
	[m/s]	[m/s]	[/]	[/]	[/]	[/]
Local clay	0.0000001	0.00000001	0.19	0.4	0.8	1.3
Solid waste*	0.0001	0.00001	0	0.23	2	2.9

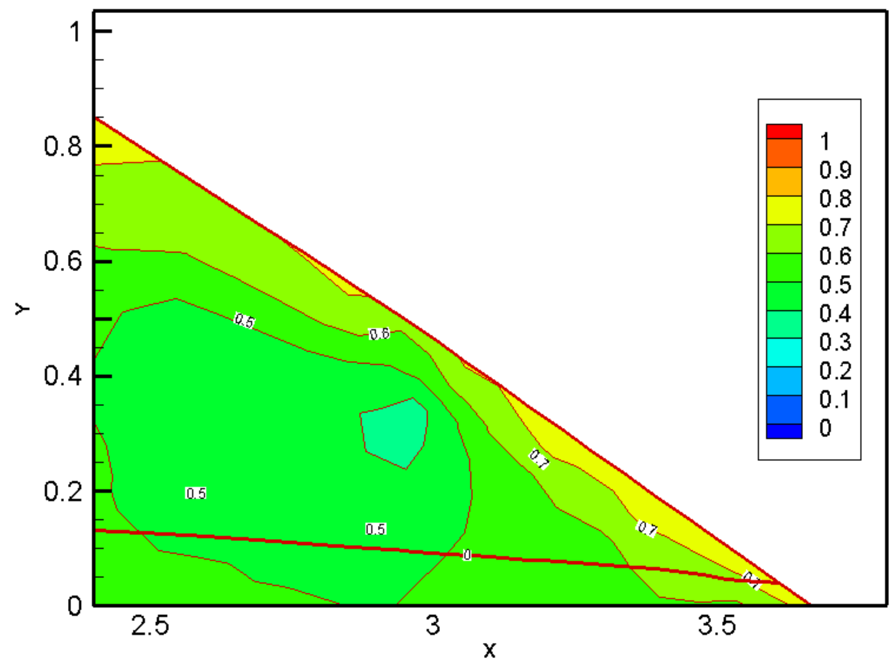
Results

Dry or normal operating conditions…



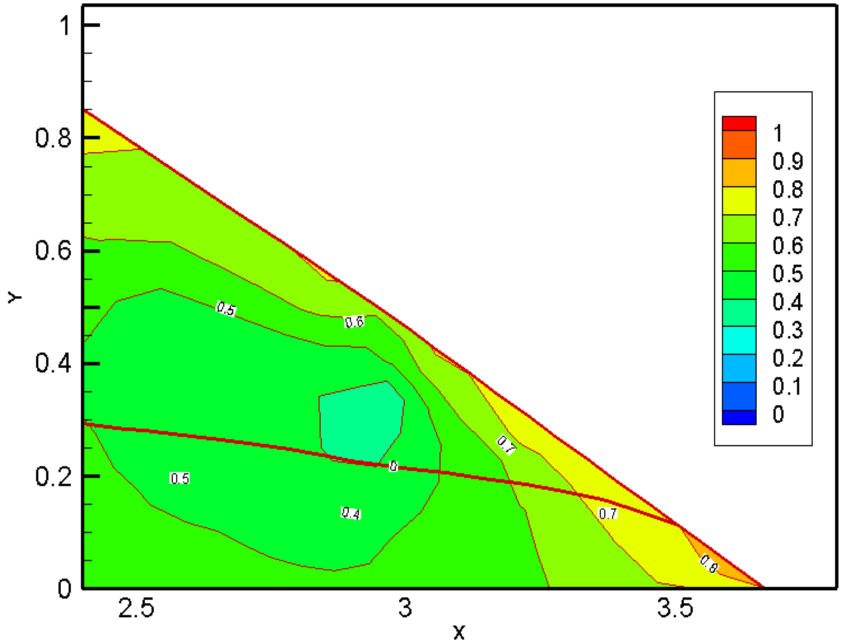


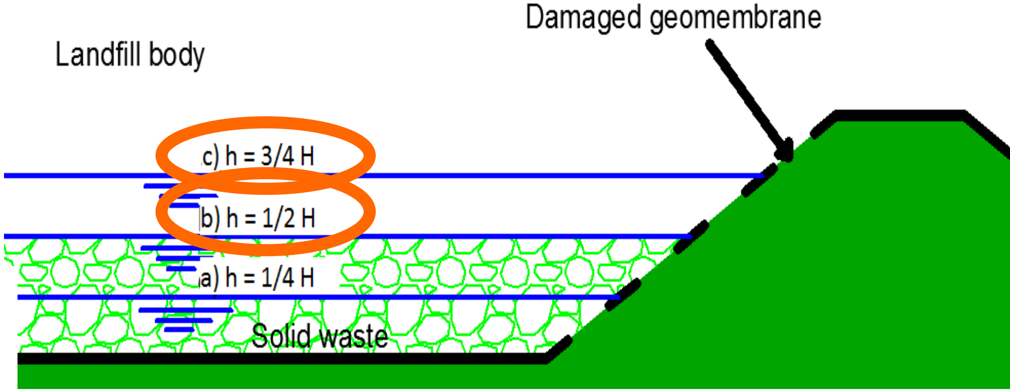
Scenario a) h= ¼ H…



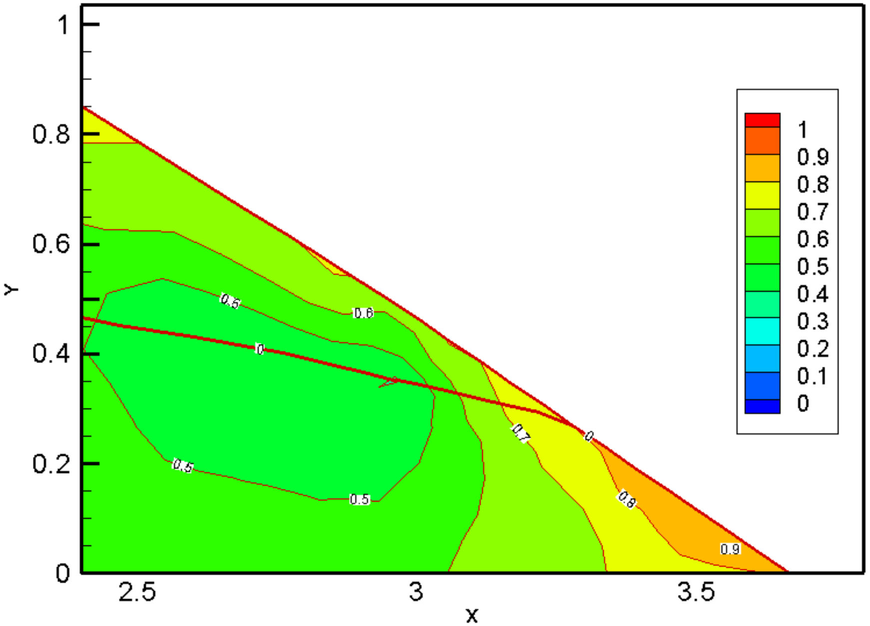
Results

Scenario b) h= ½ H…





Scenario c) h= ¾ H…



Conclusions

- A numerical model for simulation of leachate flow in saturated and unsaturated porous media coupled with elastic displacement analysis was developed.
- We assumed that porous landfill walls are elastic and investigated the effects of leachate filtration for three scenarios $h = \{\frac{1}{4} H, \frac{1}{2} H, \frac{3}{4} H\}$ on the shear slope failure potential Φ
- Most significant effects were observed at the outer slope toe where the maximum increase of Φ was about 30%.
- Since leachate usually contains a variety of the contaminants, our intention is to extend developed model by including contaminant transport analysis and investigate potential negative impacts on the environment.

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