Landfill hydrogeology: impacts and challenges

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Outline

- A brief history of landfill
- Importance of managing water: why hydrogeology matters, both within and at the boundaries of the landfill
- Inside the landfill: dependence of hydraulic conductivity on density or vertical stress
- Anisotropy due to waste structure and daily cover
- Effect of gassing
- Preferential flow
- Flushing out contaminants
- Challenges for the future

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A brief history of landfill

In the beginning…

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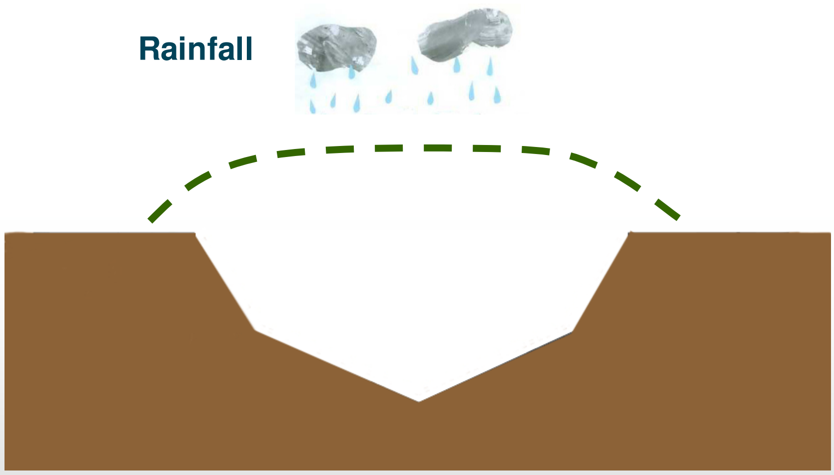
….was the open dump



Waste Composition 1892 to 2002

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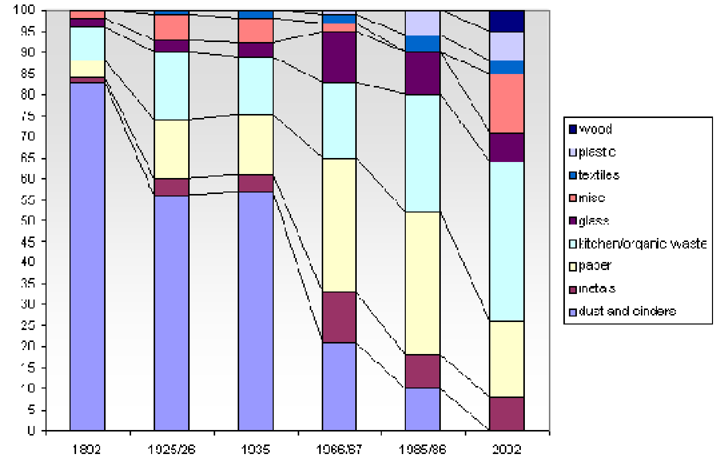

Source: Waste Watch

Landfill processes: influenced by waste composition

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- Leachate generation
- Flushing of contaminants
- Degradation
- Gas generation
- Settlement

Emission of landfill gas (CH_4 + CO_2) as waste degrades

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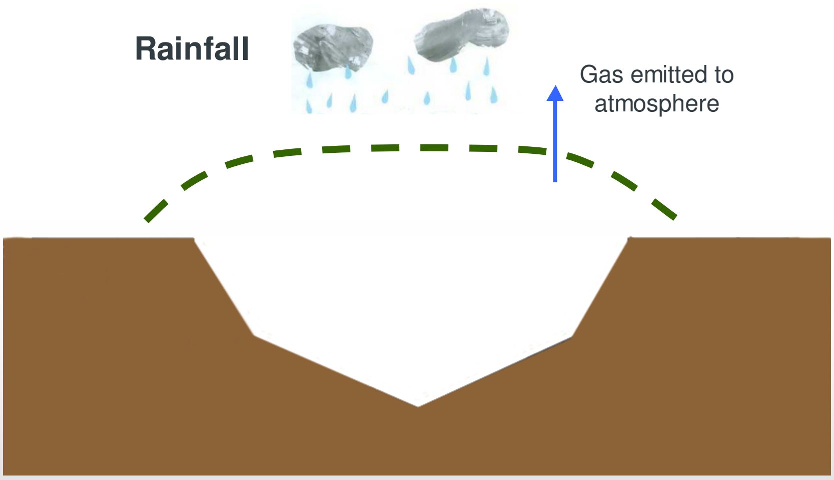

Loscoe explosion

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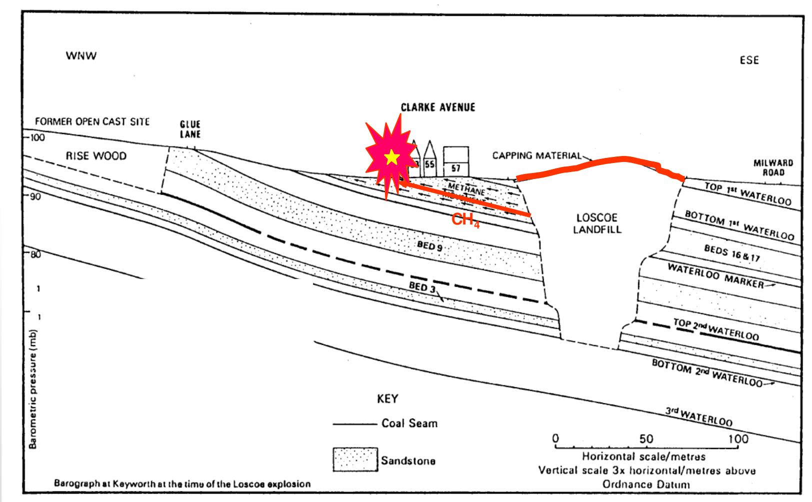

Loscoe explosion

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The engineered landfill

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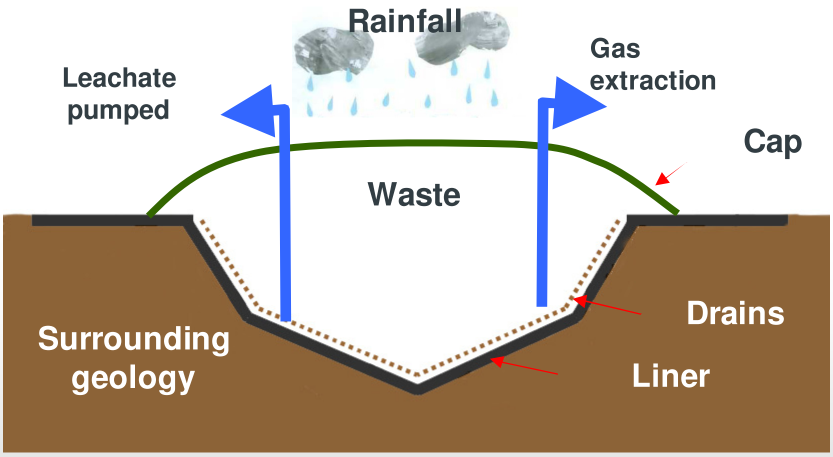

Sustainable development

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- "meets the needs of the present without compromising the ability of future generations to meet their own needs"

Our Common Future, 1987

Sustainable landfill?

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- The contents of the landfill must be managed so that outputs are released to the environment in a controlled and acceptable way
- The residues left in the site do not pose an unacceptable risk to the environment, and the need for aftercare and monitoring should not be passed on to the next generation
- Future use of groundwater and other resources should not be compromised

The Role & Operation of the Flushing Bioreactor, CIWM, 1999

Completion

- The landfill has reached a stable state, in hydraulic equilibrium with the surrounding environment with contaminant release at a rate that will not damage the receiving environment
- Degradation has substantially stopped
- Settlement has stopped
- Gas generation has stopped
- Leachate is non-or minimally polluting
- Mobile recalcitrant contaminants have been washed out

Landfill processes and completion

MOISTURE CONTENT

Rainfall, Irrigation, Groundwater intrusion, Leachate collection, Recirculation, Surface vegetation, Cover and liner material

BIOLOGY

Nutrient microbes, seeding, Temperature, pH buffering

LANDFILL STABILISATION

REFUSE COMPOSITION

Density,Particle size, Pre-treatment, Compaction, Permeability

CHEMISTRY

Oxygen, Hydrogen, Sulphate, Toxics, Metals, Ambient temperature, Pressure, Gas recovery, Air Intrusion, Industrial waste co-disposal

El-Fadel *et al*, Journal of Waste Management & Research, 1999

Landfill processes: the role of liquid

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- Water content
  - encourages microbial degradation: >35% water content needed for methanogenesis
- Water flow
  - transports seed bacteria and nutrients for anaerobic degradation
  - flushes out non-degradable contaminants
- Both processes essential for "completion"

The engineered landfill: engineered features degrade over time

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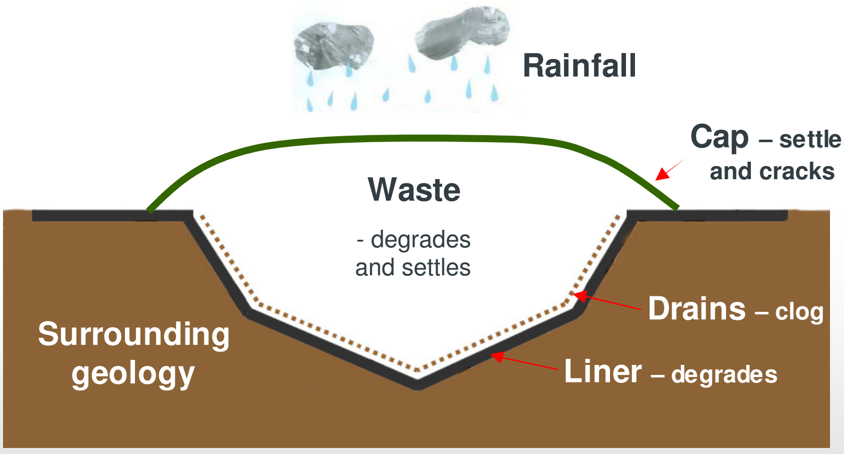

The engineered landfill: geotechnical failure modes

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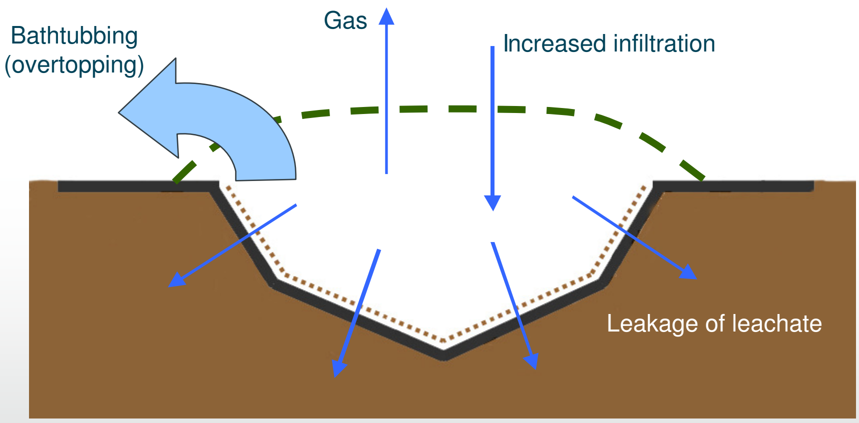

Sustainable landfill?

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- The open dump offers no control
  - leachate may attenuate naturally
  - fugitive methane gas emissions unacceptable
- Engineered features will eventually degrade and therefore just buy time
- Must use that time actively to degrade and reduce the pollution potential of the waste

Sustainable landfill?

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- Landfills are generally not actively managed to accelerate degradation and remove contaminants
- On the basis of current practice, landfills will take hundreds of years to reach a stable, non-polluting state (Hall et al, 2004)
- Need active leachate circulation / flushing, plus gas extraction, to reduce completion times
- Need to know about (bio-mechanical) hydrogeological properties of the waste
- Also about hydrogeology of caps, drains and liner systems and interactions with the environment

Hydraulic conductivity of waste: measurements

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- Large scale tests to investigate the effects of
  - waste pre-treatment
  - compression
  - gassing
  - waste structure

Pitsea compression cell

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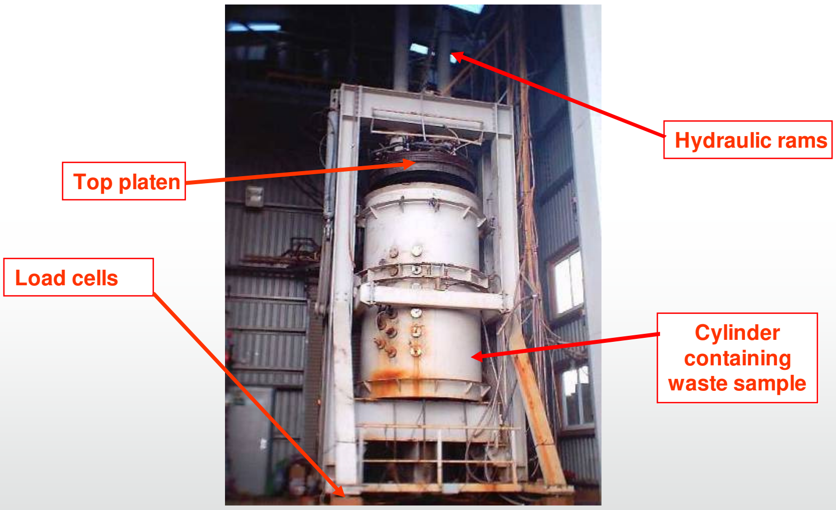

Pitsea compression cell

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Pitsea compression cell

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Pitsea compression cell

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Domestic waste samples tested

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- DM3: fresh, unprocessed
- PV1: fresh, pulverized and passed through a 150 mm screen and heavy fines (including some putrescibles) removed
- DN1: fresh, partly sorted and tumbled in a Dano drum
- AG1: 25 years old, partly degraded, mixture of soil, crude waste and pulverised waste, recovered from a landfill (depth < 5 m)

Typical waste assay (DM3)

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CATEGORY ASSAY%

Size mm	Wt %	Paper Card	Plastic film	Dense Plastic	Tex-tiles	MC	MNC	Glass	Fe	nFe	Putres	<10 mm
160+	39.0	62.7	4.0	7.1	10.5	14.0	-	0.8	0.7	-	-	-
160-80	26.4	35.4	6.8	7.5	4.4	18.5	1.3	7.0	7.7	2.1	9.3	-
80-40	15.2	30.2	6.3	8.4	1.3	5.3	5.0	9.2	5.4	3.2	25.8	-
40-20	10.0	1.8	0.7	3.4	0.8	4.2	10.9	21.6	1.1	1.2	44.2	-
20-10	4.5	6.0	0.2	1.5	-	5.6	5.6	27.8	-	0.5	52.9	-
<10	4.9	-	-	-	-	-	-	-	-	-	-	100
Total	100.0	39.8	4.4	6.4	5.5	11.8	2.4	7.0	13.2	3.2	1.2	4.9

Water content (Wc_{wet}) of refuse = 34%

Waste composition

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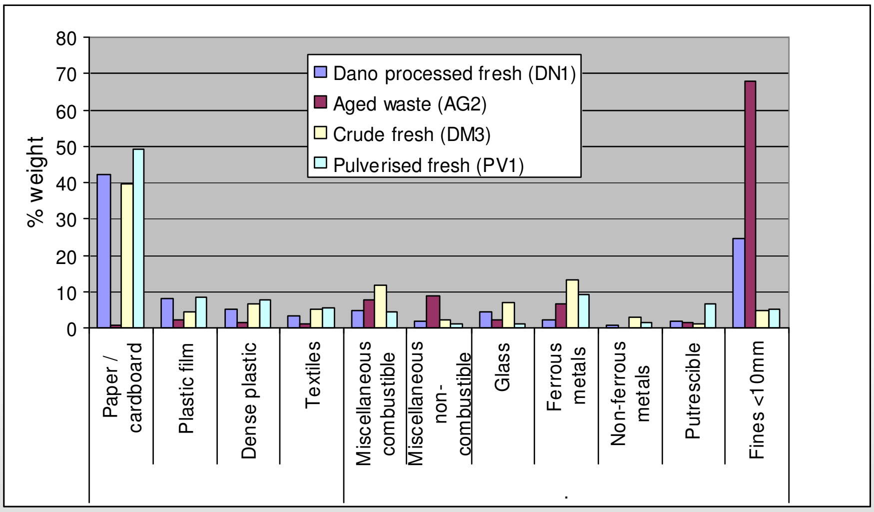

Results: hydraulic conductivity *vs* vertical stress

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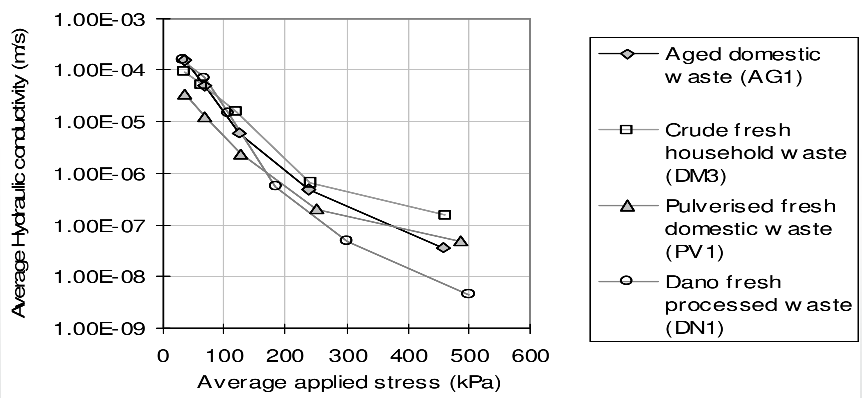

Findings: k *vs* effective stress

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- Single correlation between vertical hydraulic conductivity and vertical effective stress in first loading
- Differences in k resulting from particle size reduction and waste degradation are less significant, but appear to become greater at higher vertical effective stresses (spread of just > one order of magnitude in k at a stress of 500 kPa).

Hydraulic conductivity *vs* dry density

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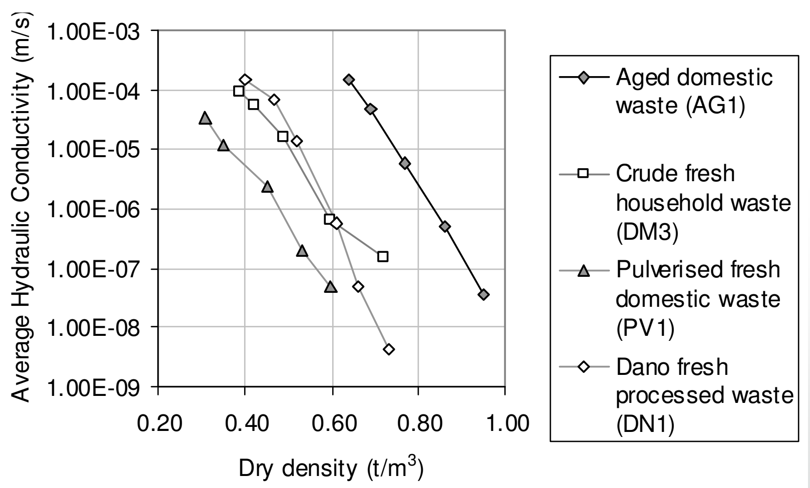

Findings: k *vs* density

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- There are individual correlations between vertical hydraulic conductivity and dry density for each waste type, with an essentially linear relationship between the logarithm of the vertical hydraulic conductivity and the dry density

Hydraulic conductivity k *vs* drainable porosity

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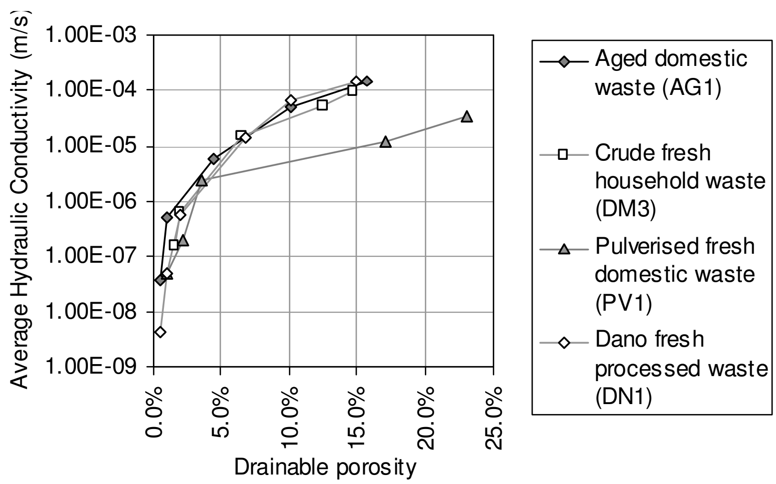

Findings: k *vs* drainable porosity

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- Single correlation between the vertical hydraulic conductivity and the drainable porosity of the waste
- Unsurprising, as drainable porosity represents a measure of the size and degree of connectivity of the voids, both of which will have a major influence on the bulk hydraulic conductivity
- Unlike the vertical effective stress, the drainable porosity is a difficult parameter to estimate *a priori* for design purposes, so the correlation between vertical hydraulic permeability and vertical effective stress is of more practical use

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Practical application:

Vertical flow through a landfill to a basal drainage blanket

Vertical flow through a landfill to a basal drainage blanket

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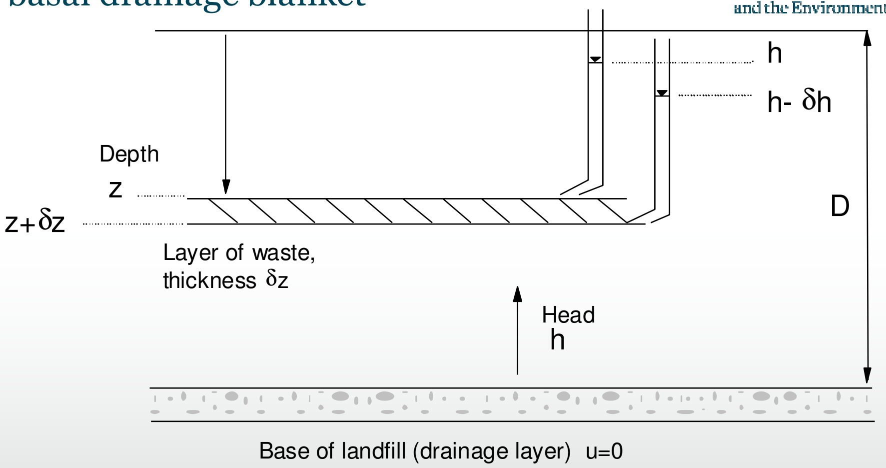

Analysis

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The changes in vertical total stress $\delta\sigma_v$, pore water pressure δu and vertical effective stress $\delta\sigma'_v$ that take place over the depth increment δz are:

$\delta\sigma_v = \rho_{sat}.g.\delta z$ $\quad \delta u = \rho_w.g.(\delta z\text{-}\delta h)$ $\quad \delta\sigma'_v = \delta\sigma_v - \delta u$

From Darcy's Law, $(q/A) = k.i = k.(\delta h/\delta z)$

$\Rightarrow \delta h = (q/A).(1/K).\delta z$

The saturated density ρ_{sat} and hydraulic conductivity k may be related to the vertical effective stress (in kPa):

Variation in waste density with vertical effective stress

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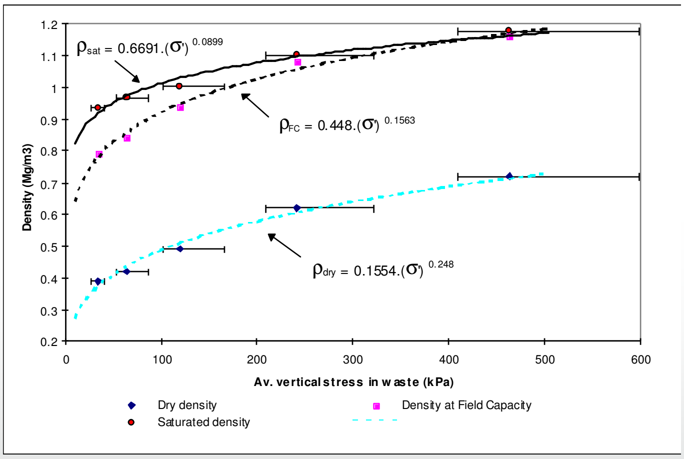

ρ_{sat} (Mg/m³) = 0.6691 × $(\sigma'_{v'})^{0.0899}$

Hydraulic conductivity *vs* vertical stress (Powrie & Beaven, 1999)

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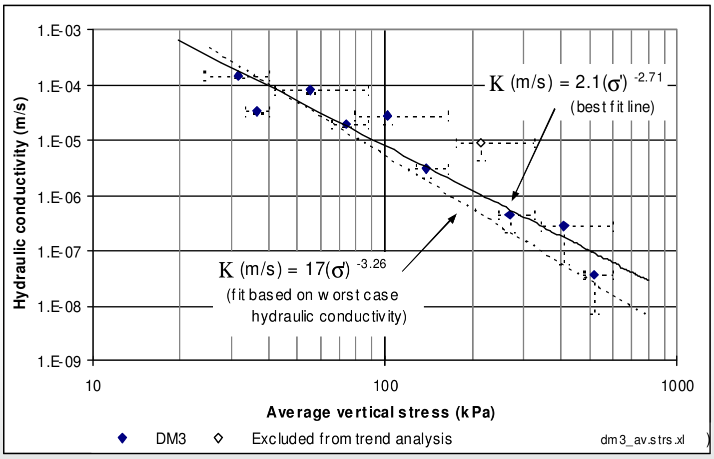
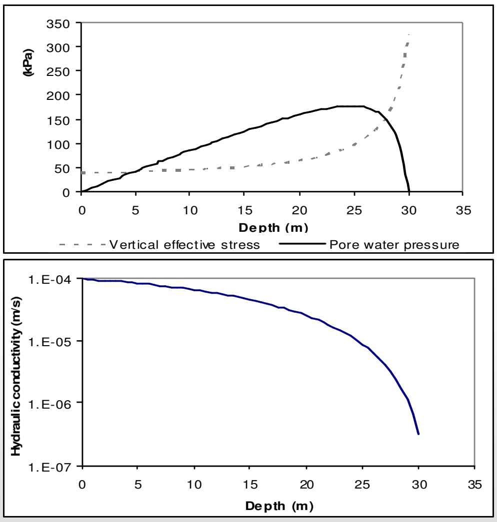


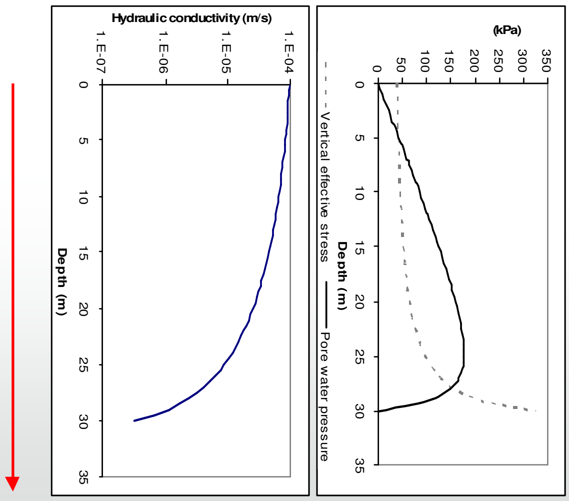
k (m/s) = 2.1 × $(\sigma'_{v'})^{-2.71}$

Pore pressure, k and vertical effective stress *vs* depth



Pore pressure, k and vertical effective stress *vs* depth

Depth



Observations and Implications

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- Pore pressures within the body of the waste are near hydrostatic over the top ~70% of the landfill, even though there is zero pressure in the drain
- If you want to measure leachate heads for licensing purposes, they must be measured at the point where it matters (e.g. on the base)
- Use piezometers with a discrete, defined response zone for measuring leachate pressure

Reduction in k due to gas accumulation; shredded domestic waste

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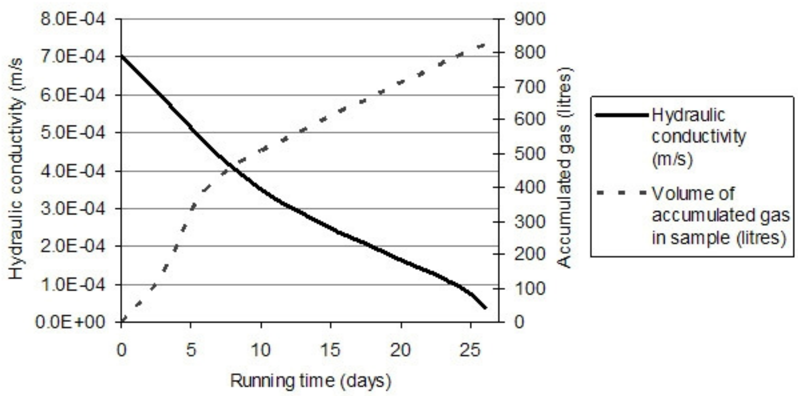
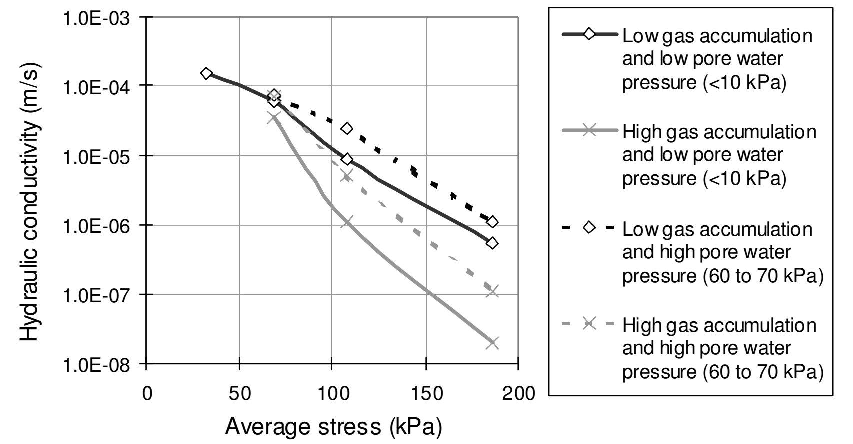


Effects of gas generation



Findings: effect of gas generation on k

- Gas accumulation could reduce the hydraulic conductivity by between one and two orders of magnitude
- At elevated pore water pressures, compression of the trapped gas will reduce its impact

Tracer tests to investigate preferential flow paths

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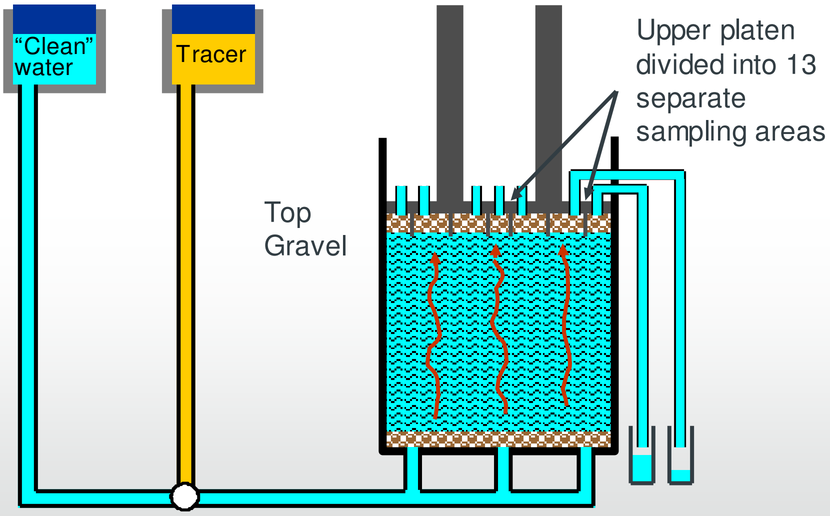

Initial conditions

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• Waste volume	=	3.44 m^3
• Total porosity	=	32.3
• Water content of waste	=	1,112 litres
• Drainable porosity	~	2 %
	=	70 litres
• Upward flow rate	~	5 litres/hour
• HRT	~	9 days

Tracer addition

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- Lithium tracer used (added as LiBr)
- Background concentration of Li in waste ~ 0.18 mg/l
- Concentration of lithium added in tracer ~ 26.2 mg/l
- Total volume used ~ 615 litres

Tracer addition and flushing

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- First 300 litres of tracer in 4 days
- Flow stopped for 20 days
- Final 315 litres of tracer in 1 day
- Clean water flush started
- 3,385 litres added over following 70 days

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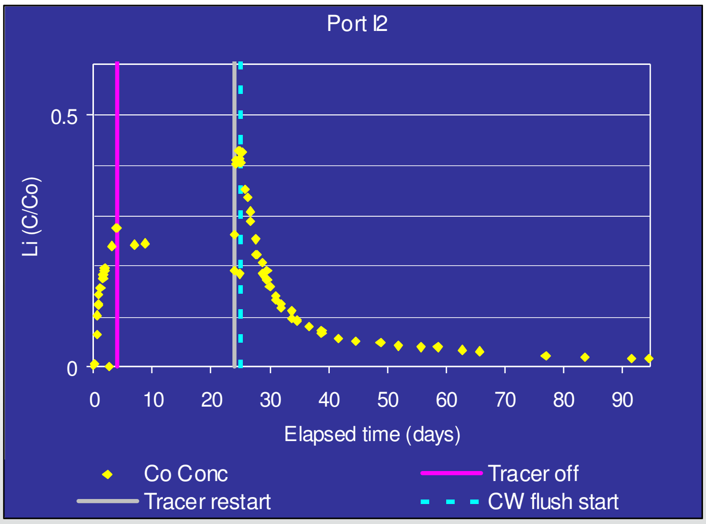

Analyses of tracer results using DP-pulse (Professor John Barker)

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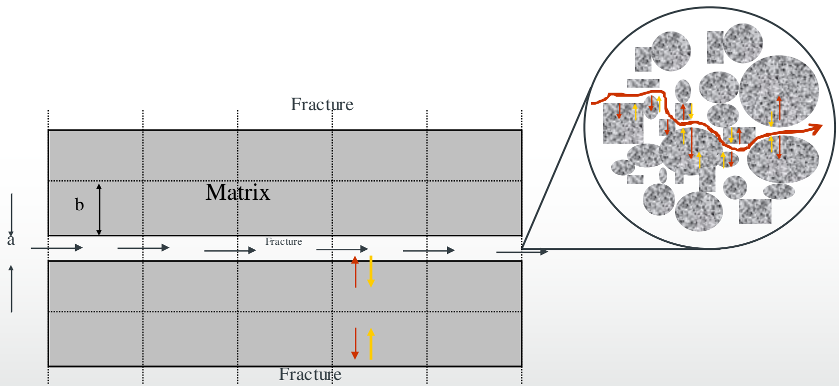

Comparison of fitted model with test cell data

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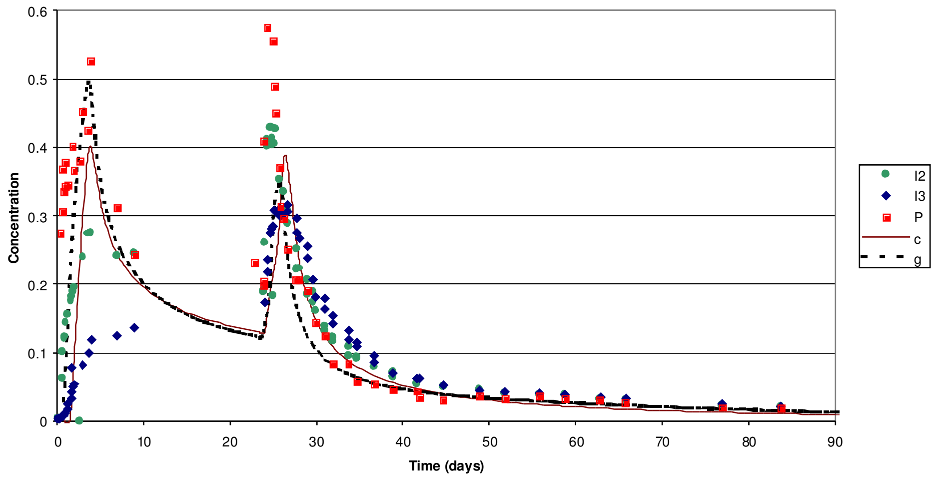

Findings: tracer tests

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- Very rapid breakthrough times indicative of flow in "channels"
- Diffusion into and out of a matrix evident
- Structure of waste likely to be a controlling influence for gas and liquid flow

Layering in waste and daily cover

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Landfill: the future

The EU landfill Directive

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- Aims to reduce the amount of biodegradable waste going to landfill to 35% of 1995 amounts by 2016 (2020 in the UK)
- Requires pretreatment of biodegradable wastes prior to landfill
- Aims to reduce fugitive greenhouse gas emissions

"Post LFD" wastes

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- Current options for treatment of wastes prior to disposal are mostly either thermal and mechanical/biological treatment (MBT)
- Wastes will be mainly ash and MBT residues, plus air pollution control (APC) residues and filter cakes
- Markets for some of these, but not others
- Ash, APC and filter cake residues biologically inert
- MBT wastes still bioactive to some extent

Incinerator residues

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Incinerator bottom ash

Air pollution control residues

Filter cakes

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Filter cake in inorganic tip face

MBP residues

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60 mm MBP waste

Impact of LFD on future landfill management

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- MBT residues will generate gas, but probably not enough to make active gas extraction commercially worthwhile
- Incinerator ashes will be biologically inert, but contaminated: flushing will be an important mechanism of reducing the pollution potential

Field data on flushing of incinerator ash: short term model fit

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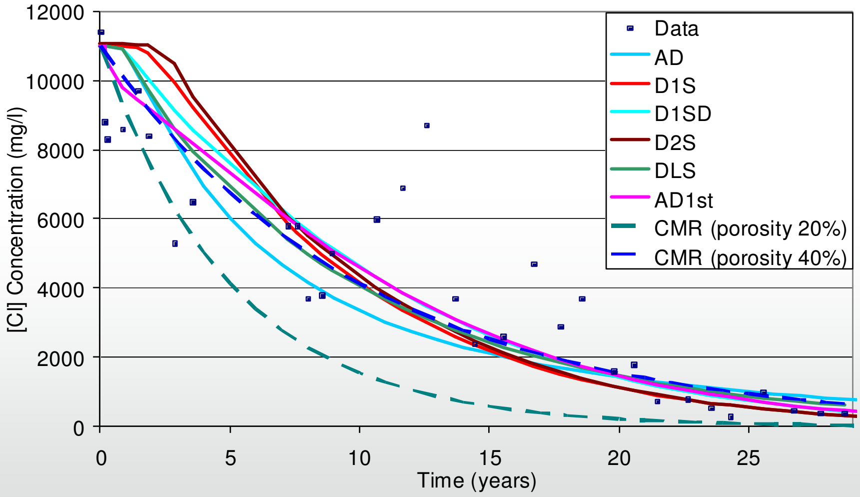

Data from Hjelmar and Hansen, 2004

Field data on flushing of incinerator ash: long term model fit

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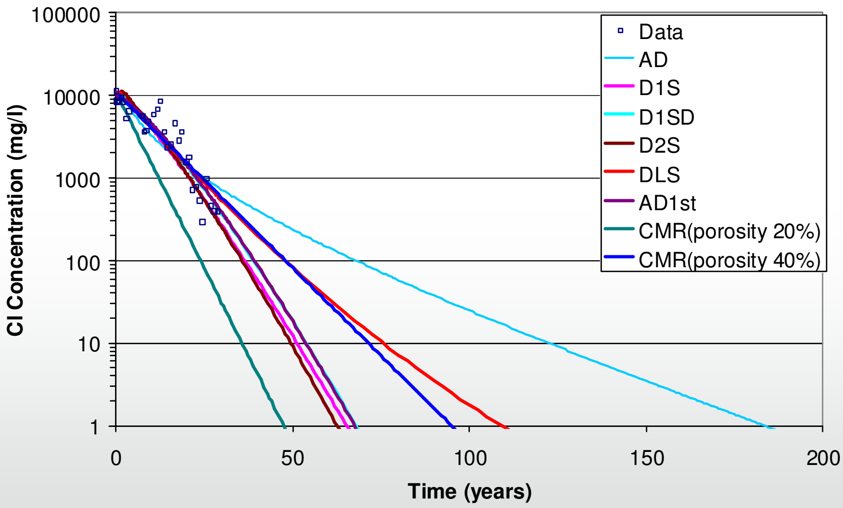

Data from Hjelmar and Hansen, 2004

Challenges – historic landfills

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- For practice, acceptance of spatial variability of waste hydraulic conductivity in landfills (especially with stress/depth), anisotropy and gassing - essential to understand patterns of leachate head
- Better understanding of the mechanism of gas generation and its effects on hydraulic conductivity
- Better characterisation of waste structure and how it will affect flushing

Challenges – future landfills

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- Stabilisation of ash and filter cakes will be primarily by flushing
- Need to develop reliable flushing models to predict late-time behaviour
- MBT residues will gas gently: need to understand and model gas generation and flow at a variety of gas contents/distributions
- For practice, sites receiving either type of residue will still need to be managed

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Papers

- Hydraulic properties of household waste and their implications for fluid flow in landfills. W Powrie & R P Beaven. *Proceedings of the Institution of Civil Engineers (Geotechnical Engineering)* **137**(4) 235-247, October 1999
- The sustainable landfill bioreactor – a flexible approach to solid waste management. W Powrie & J P Robinson. In *Sustainable solid waste management in the Black Sea region* (eds B Nath *et al*), Kluwer Academic Publishers, 2000
- Modelling the biochemical degradation of solid waste in landfills. J K White, J P Robinson & Q Ren. *Waste Management* **24**, 227-240, April 2004
- Modelling the compression behaviour of landfilled domestic waste. A P Hudson, J K White, R P Beaven & W Powrie. *Waste Management* **24**, 259-269, April 2004
- Modelling flow to leachate wells in landfills. A A Al-Thani, R P Beaven & J K White. *Waste Management* **24**, 271-276, April 2004
- Installation of horizontal wells in landfilled waste using directional drilling. S E Cox, R P Beaven, W Powrie and D Cole. *American Society of Civil Engineers Journal of Geotechnical and Geoenvironmental Engineering* **132** (7), 869-878, July 2006
- Operation and performance of horizontal wells for leachate control in a waste landfill. W Powrie, S E Cox & R P Beaven. Accepted for publication in *American Society of Civil Engineers Journal of Geotechnical and Geoenvironmental Engineering*

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