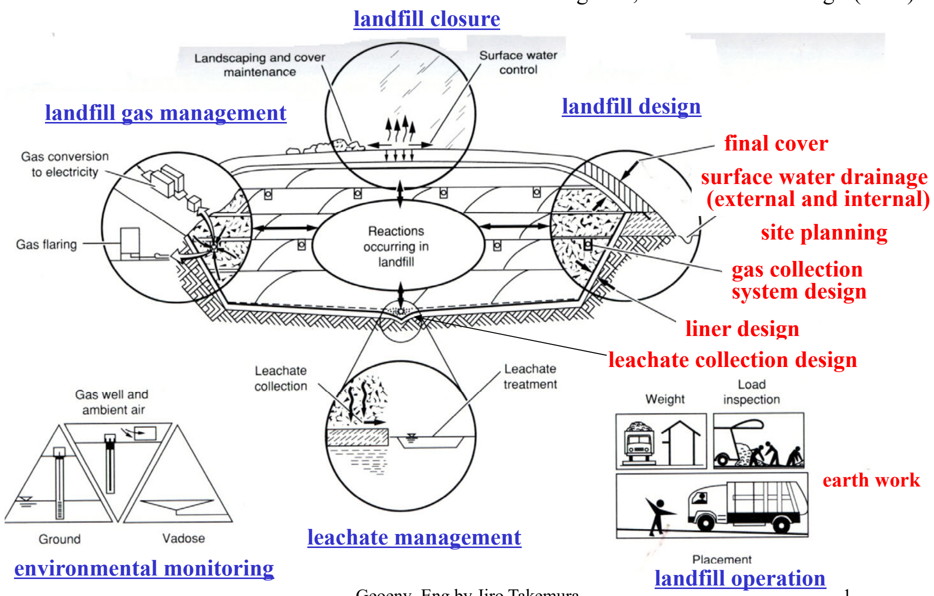
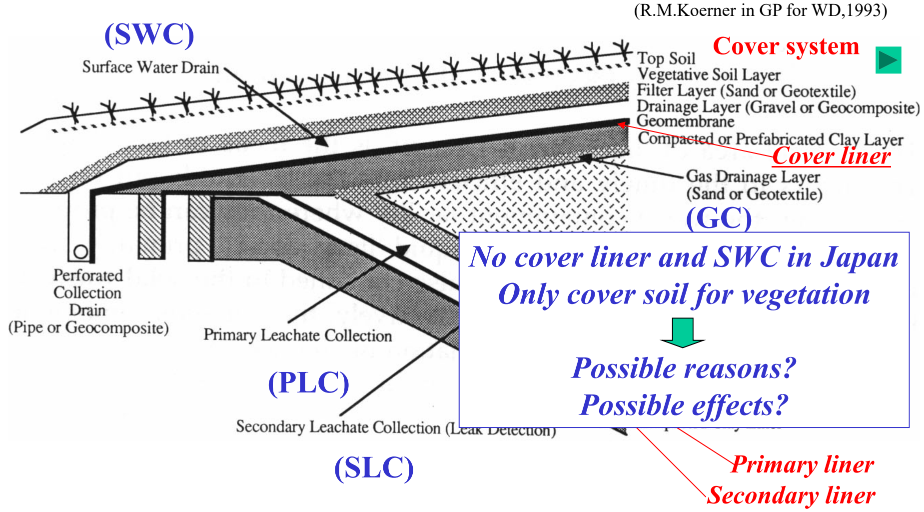
Definition sketch for landfill operation and processes:
G. Tchobanoglous , H. Theisen & S. Vigil (1993)



Various drainage layers in liquid management in solid landfill facility

(R.M.Koerner in GP for WD,1993)



No cover liner and SWC in Japan
Only cover soil for vegetation

Possible reasons?
Possible effects?

Surface Water Collection and Removal System
- Cover System -

Functions of cover system

- raise ground surface elevation in low lying areas;
- minimize the amount of runoff of precipitation;
- promote controlled runoff of whatever precipitation is remaining;
- separate the waste from plants and animals;
- prevent migration of perched leachate out of waste on side slopes;
- limit infiltration of precipitation into the waste; and
- **control release of gas from the waste**.=>CDM and Energy recover

The USEPA: the prime element in the final cover is to keep water out of the contaminated material.

Reduction of leachate and chance of its release to the surrounding.

4. Landfill Liner System

One of the major concerns with landfill of waste

uncontrolled release of leachate from landfill:

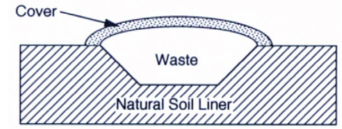
Leakage of leachate containing pollutants may cause *contamination of ground water and surface water, giving serious impacts to public health and environment.*

Function of landfill liner system:
to eliminate or minimize the impact of this concern.

Geotechnical engineer can contribute to this part to a great extent.

4.1 Types of liner for landfill

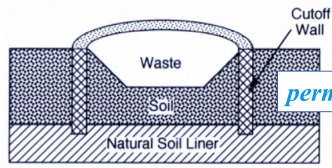
(a) natural soil liner



- Old landfill
- For new LF, very uniform, massive, and well characterized stratum, like marine clay (offshore or onshore LF)

p42

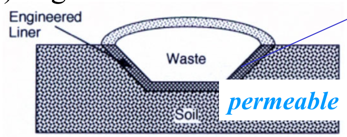
(b) vertical cutoff wall+natural soil L.



permeable

Containment and remediation of contaminated site

(c) engineered liners



permeable

Possible components in ELs
- compacted clay liners (CCL)
- geomembrane liners (GM)
- geosynthetic clay liner (GCL)

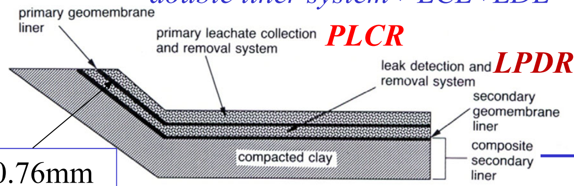
  or
- composite liners (GM+CCL)

Minimum liner requirements of the USEPA: Daniel (1993)

RCRA

(a) for hazardous waste landfills:

double liner system+ LCL+LDL



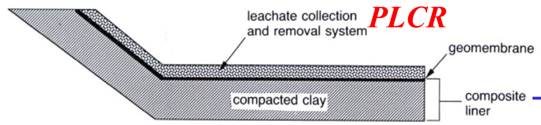
detecting in 24hrs

0.76mm thickness

0.9m thickness with $K < 1\times10^{-9}$m/s

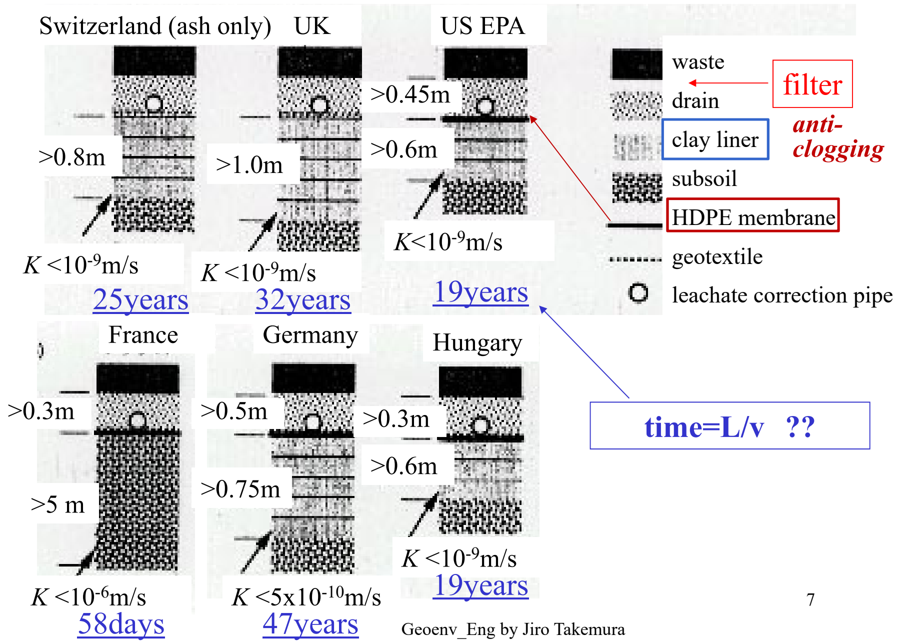
(b) for non-hazardous waste landfills:

single liner system+LCL



0.6m thickness with $K < 1\times10^{-9}$m/s

Liner system of non-hazardous landfill in various countries



time=L/v ??

Minimum standards of liner system in Japan

WMPCL

less permeable subsoil

t > 5m

$K < 10^{-7}$m/s$=8.6\times10^{-3}$m/d

579days

compacted clay + geomembrane

t >0. 5m

$K < 10^{-8}$m/s

579days

asphalt concrete + geomembrane

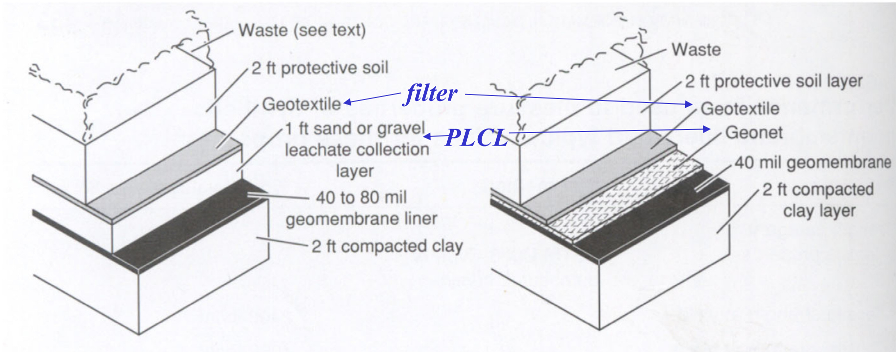
t > 0.05m

$K < 10^{-9}$m/s

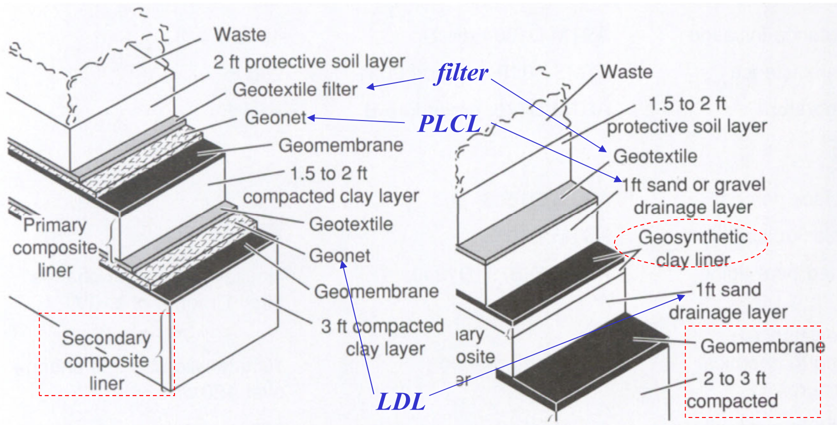
579days

geomembrane+ geotextile geomembrane

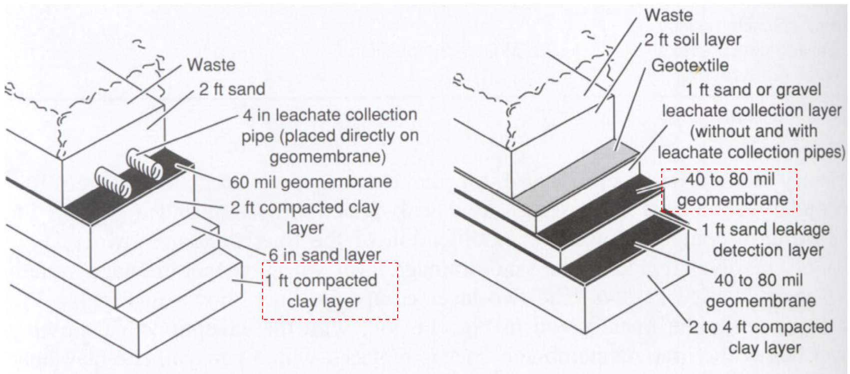
Typical landfill Liners
-**single** composite barrier types-



Typical landfill Liners
-double composite barrier types-

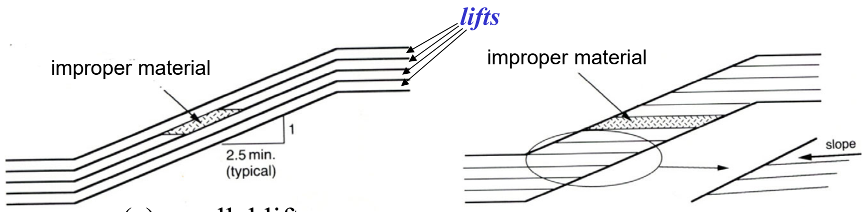


Typical landfill Liners
-double composite barrier types-



Compacted clay liners

Compacted clay liners are constructed primarily from **natural soil** materials, although the liner may contain processed material such as ***bentonite*** or synthetic materials, like polymers. Clay liners are constructed in layers called **lifts**.



(a) parallel lifts

not steeper than 2.5-3 on 1 (H to V)

(b) horizontal lifts

Side slopes constructed with (a) parallel and (b) horizontal lifts

Requirements of compacted liner

Objectives of compaction: **remolding chunks (clods)** of soil into **homogeneous mass** that is free from large, continuous interclod void. => **Low hydraulic conductivity: < 10^{-9}m/s**

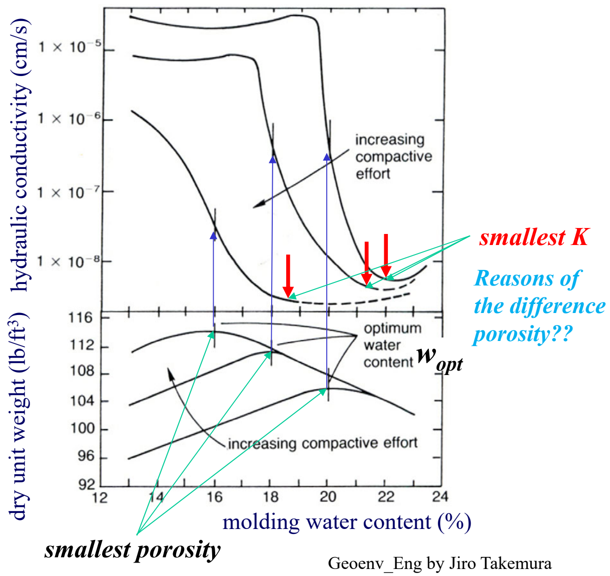
Major influences on the hydraulic conductivity in compaction process:

1) **water content**: *wet side of optimum water content* (***w_{opt}***),
2) **method of compaction**: *kneading type compactive energy*
3) **compactive effort**:

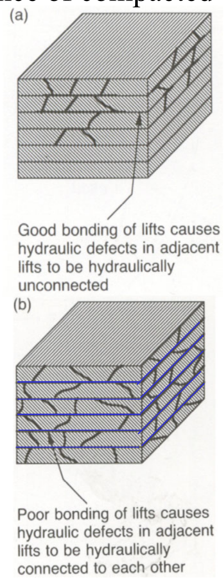
homogeneity, *avoiding* ***crack*** *and* ***large void***

In the determination of the design water content, the compactive energy, variation of W/C and C/E in the construction, and the relevant factors (shear strength, desiccation) should be considered.

Effect of W/C and energy of compaction on K Daniel (1993)



Effect of bonding of lifts on the performance of compacted CL



Materials for compacted clay liners

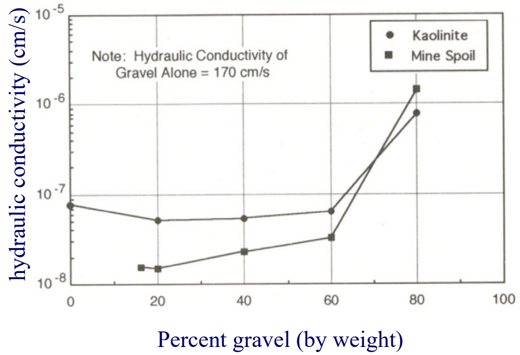
Minimum requirements for most soil liner materials recommended by Daniel (1993):

percentage fines (<75μm):	> =20-30%
plasticity index:	>=7-10%
percentage gravel (> 4.76mm)	<=30%
maximum particle size:	25-50mm

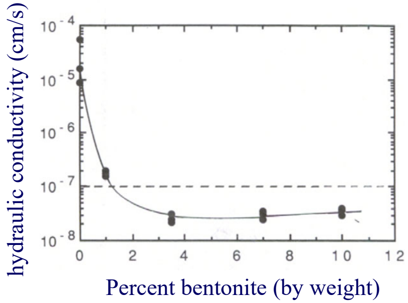
Adding bentonite to the liner material can lower ***K*** as much as several orders of magnitude.

Effect of gravel and bentonite on *K*

lab test results not field



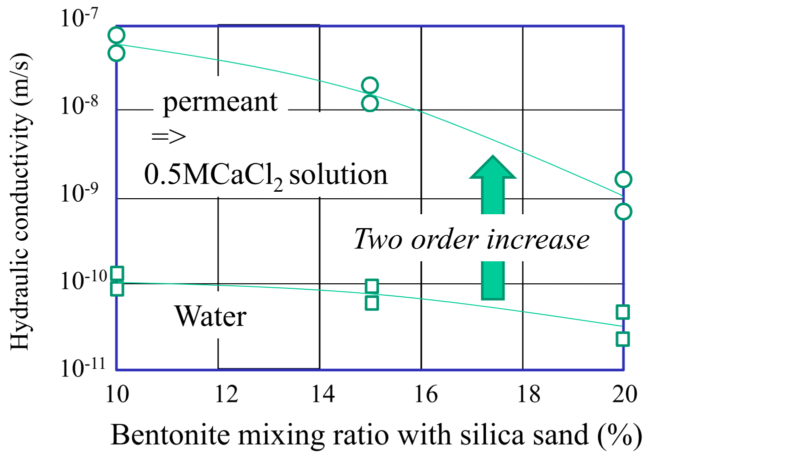
Effects of percent gravel in clay on hydraulic conductivity: by Shelley (1991) in Daniel (1993)



Effects of percent bentonite on hydraulic conductivity: Daniel (1993)

Compatibility of bentonite mixture

Stern and Shackelford (1998): ASCE JGGE,124(3)



Construction procedures of compacted clay liners

Processing:

breaking down clods of the soil; sieving out stones and rocks; moistening the soil and incorporating additive if required

uniform condition of the soil is essential!!

Surface preparation: securing **good bonding** between lifts

surface of the previous compacted lift should be rough, like *Proctor* test.

Soil replacement: Soil is placed in ***loose*** lift, less than about 230mm.

Compaction:

Heavy, footed compactors with large feet that fully penetrate a loose lift of soil is ideal. Static compaction is preferred than dynamic.

Weight of compactor: ***heavy*** for dry soil with firm clods;

not heavy for relatively wet soil with soft clods.

Construction procedures of compacted clay liners (cont.)

Protection: After compaction of a lift, soil must be protected from **desiccation** 乾燥 and **freezing** 凍結, by temporary cover, periodical moistening, smooth-rolling the surface.

Quality control: in situ hydraulic test using ***test pad***.

Other factors affecting the quality of CCL

Chemical attack by waste:

Acids and bases can dissolve solid in soil, forming channels.

Neutral, inorganic liquids may affect the diffuse double layer.

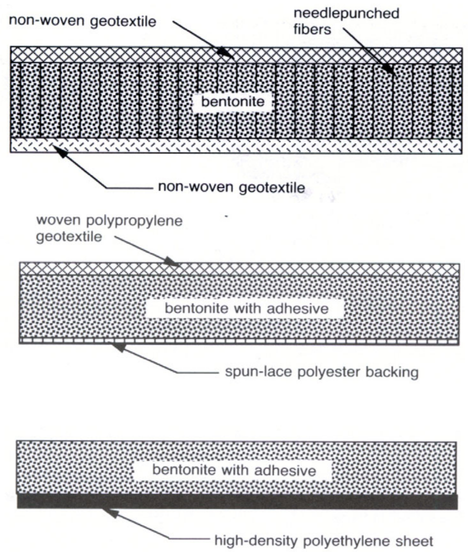
Most **organic chemicals** have high hydraulic conductivity and causes clay particle to flocculate, and the soil to shrink and crack, but not the case for dilute organic liquid.

Geosynthetic Clay Liner (GCL)

GCL: a thin layer of clay sandwiched between geotextile or glued to a geomembrane. *Factory made. Containing bentonite about 5kg/m^2.*

Very thin: t<10mm,
but
Hydraulic conductivity:
$10^{-10} \sim 10^{-12}$m/s

GCL can function as composite liner(CL).



Self-sealing at overlaps betw. panels.

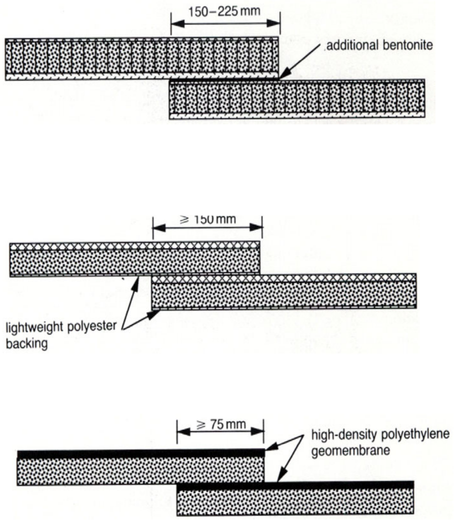
hydration of clay makes the clay swell

↓

sealing the overlap automatically
no chemical seaming of joint

↓

rapid installation



After installation, GCL must be covered immediately.

Uneven swelling caused by rain storm leads improper seal.

Advantage and disadvantage of GCLs

Advantage:

-rapid installation with lightweight construction equipment, which avoid puncture of geomembrane underlain;
-installation with dry conditions, thus not vulnerable to damage from desiccation during construction;
-reliability of quality by factory made production;
-not producing water upon loading (water due to consolidation may be misinterpreted as leakage in detection layer).

Disadvantage: general lack of experience
-vulnerability of a thin GCL to puncture;
-questionable composite behavior;
-less leachate attenuation capacity than thick layer;
-questions about stability of hydrate bentonite.

Comparison of GCLs with CCLs Daniel (1993)

compacted clay liner (CCL)	geosynthetic clay liner (GCL)
thick (0.6-1.5m)	thin (<10mm)
field construction	manufactured
hard to build correctly	easy to build (unroll and place)
impossible to puncture	possible to damage and puncture
constructed with heavy equipment	light construction equipment cane be sued
often requires test pad at each site	repeated field test date not needed
site-spec data on soils needed	manufactured product; data available
large leachate attenuation capacity	small-leachate attenuation capacity
relatively long containment time	shorter containment time
large thickness takes up space	little space is taken
cost is high variable	more predictable cost
soil has low tensile strength	higher tensile strength
can desiccate and crack	can't crack until wetted
difficult to repair	not difficult to repair
vulnerable to freeze/thaw damage	less vulnerable to freeze/thaw damage
performance is highly dependent upon quality of construction	hydraulic properties are less sensitive to construction variability
slow construction	much faster construction
consolidation produces water	no water production due to loading

Installation of GCL & GM

http://www.cetco.com/lt/Resources/Akwaseal%20Pond%20Liner%20Installation%20Guidelines.pdf

Deployment of GCL

Welding of geomembranes (GM) http://www.geomembrane.com/thermal_welding/index.html

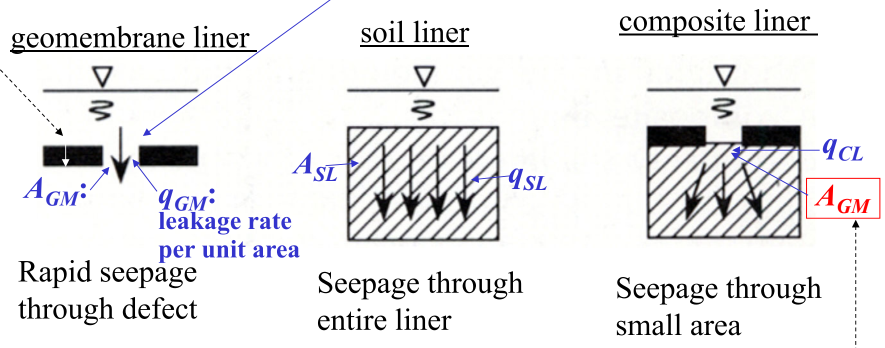
Bentonite powder

Seaming detail of GCL
CETCO Design & Installation Guide (2009)

4.2 Seepage through liners

permeation through intact GM is minor than that through the defect of GM

defects in geomembrane cannot be avoid



$q_{GM} >> q_{CL}$? q_{SL}

$A_{SL} >> A_{GM} = A_{CL}$

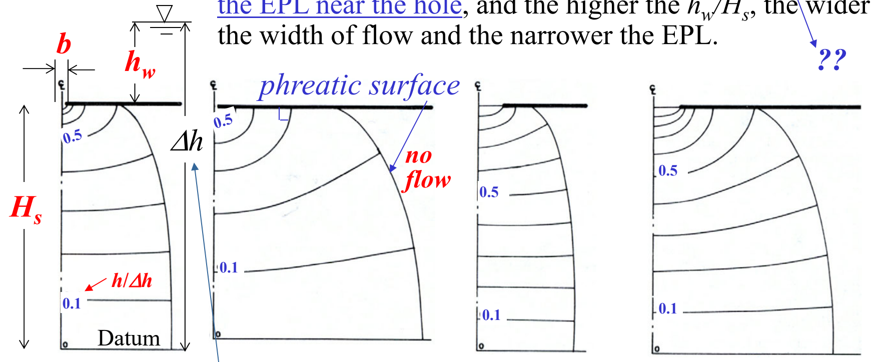
total leakage rate through liner

$Q_{GM} >< Q_{SL} >> Q_{CL}$

hydraulic contact

Typical equipotential lines for leakage through a composite liner(CL) due to a geomembrane hole for two-dimensional in perfect contact betw. GM and CL- numerical work by Faure(1979) in Giroud, Bonaparte (1989)

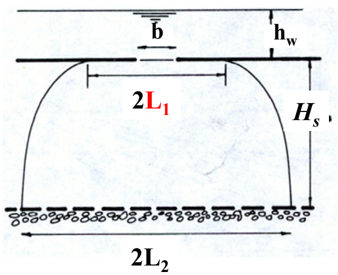
From continuity condition, the smaller b/H_s, the narrower the EPL near the hole, and the higher the h_w/H_s, the wider the width of flow and the narrower the EPL. ??

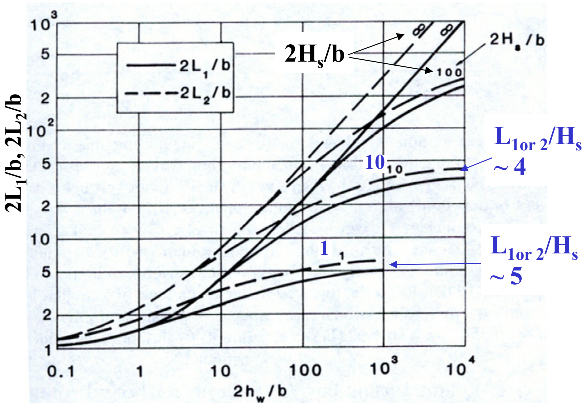


(a) b/H_s=0.02, h_w/H_s=1
(b) b/H_s=0.02, h_w/H_s=3
(a) b/H_s=0.2, h_w/H_s=1/3
(a) b/H_s=0.2, h_w/H_s=1

for what condition ??

Lateral extent of the phreatic surface limiting flow in soil layer due to a hole of geomembrane numerical work by Faure(1979) in Giroud, Bonaparte (1989)





As h_w increases, $2L_1/b$ and $2L_2/b$ increase, whereas L_1/H_s and L_2/H_s reach a liming value about 5. $L_{1or2}/H_s = (2L_{1or2}/b)/(2H_s/b)$

=> The lateral extent of flow zone can be large compared to the hole size, but **not more than a few times the thickness of the soil liner**.

Rate of leakage through a composite liner due to a geomembrane hole for two-dimensional in perfect contact betw. GM and CL-
based on numerical work by Faure(1979) in Giroud, Bonaparte (1989)

$$Q^* = C_F K_s (H_s + h_w) \quad (1)$$

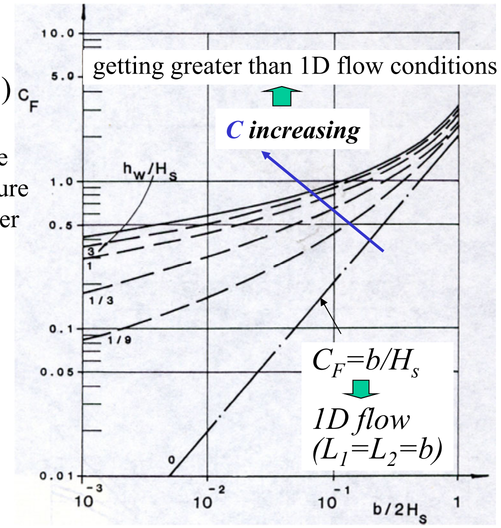
Δh

Q^*:leakage rate per unit length in the direction perpendicular to the figure
K_s:hydraulic conductivity of clay liner

$$Q^* = bK_s i_t \quad (2)$$

i_t: hydraulic gradient in the clay very near to the defect
$i_t = C(H_s+h_w)/H_s$

$$C_F = Cb/H_s \quad (3)$$

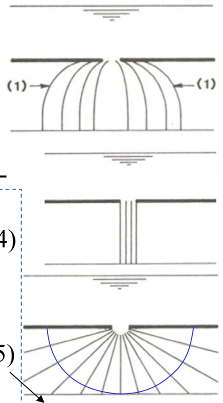


Comparison of various assumptions regarding leakage rate through composite liners

by Faure(1979) in Giroud, Bonaparte (1989)

(a) realistic case

$$Q^* = C_F K_s (H_s + h_w) \quad (1)$$



(b) 1D vertical flow

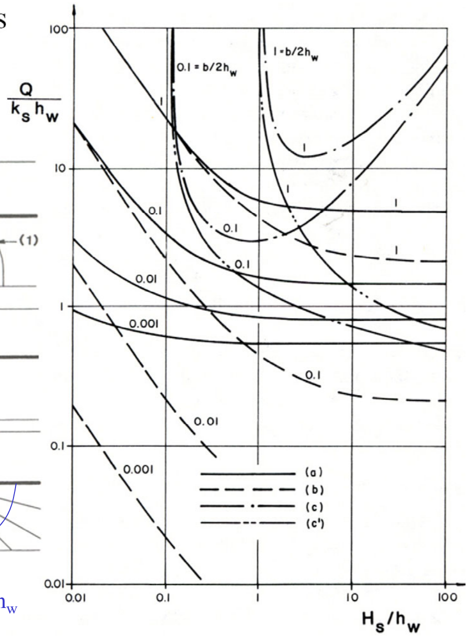
$$Q^* = K_s b (H_s + h_w) / H_s \quad (4)$$

(c) (d) radial flow

(c) $$Q^* = \frac{\pi K_s (H_s + h_w)}{\ln(2H_s / b)} \quad (5)$$

(c') $$Q^* = \frac{\pi K_s h_w}{\ln(2H_s / b)} \quad (6)$$

too big for large H_s/h_w



Rate of leakage through a composite liner due to a geomembrane hole for three-dimensional in perfect contact betw. GM and CL

Approximate solutions of Q (leakage rate) from circular hole (diameter: *d* or area: *a*)

(a) 1D vertical flow lower:lower bound solution

$$Q = K_s a (H_s + h_w) / H_s \quad (7)$$

(b) radial flow:upper bound solution

$$Q = \frac{\pi K_s (H_s + h_w) d}{1 - 0.5d / H_s} \quad (8)$$

too big for small d/H_s, which is the case for the most practical conditions. For a fixed d, Q increase with increasing H_s.

approximate solution

inconsistent with common sense!!

$$Q = \frac{\pi K_s h_w d}{1 - 0.5d / H_s} \quad (9) \rightarrow Q = \pi K_s h_w d$$

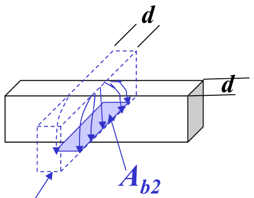
(c) realistic case: second approximation solution

$$Q^* = C_F K_s (H_s + h_w) \quad (1)$$

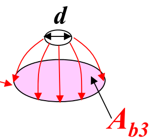
Using the chart for C_F by Fraue for 2-D case and modifying eq.(1) by replacing in Q*(which is equal to Q/length) the length of slot by the perimeter πd of the circular hole, *not d*.

$$Q = \pi C_F K_s (H_s + h_w) d \quad (10)$$

What's the physical mean of π ?



Cross section of 2D flow



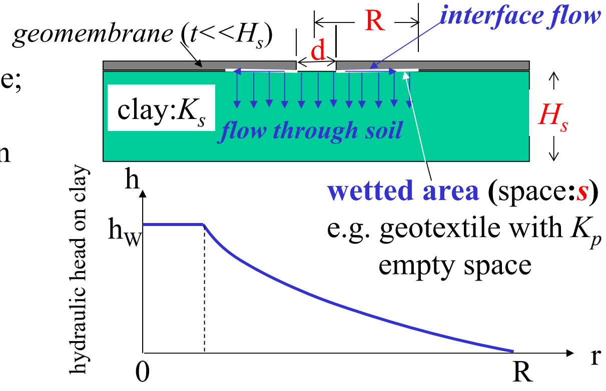
3D flow through circular hole

3 D analysis with interface flow on leakage through a CL due to a geomembrane hole for poor contact betw. GM and CL

Fukuoka (1985) , Brown et al.(1987) in Giroud, Bonaparte (1989)

Assumption 1:
- **circular** membrane hole;
- **radial** interface flow.
  (axisymmetric condition with one variable ***r***)

Assumption 2:
- constant space ***s***



radius from the center of circular hole

wetted area (space:***s***)
e.g. geotextile with K_p
empty space

Transmissivity:

for geotextile: $\theta = K_p s \quad (11)$

for empty space: $\theta = \frac{\rho g s^3}{12\eta} \quad (12)$

Newton's viscosity law to flow betw. two smooth panel:ρ,η: density and viscosity of liquid

The flow rate related to **interface flow**: $\boldsymbol{Q_i}$

$$Q_i = KiA = \theta iB \quad (13)$$

($A \rightarrow sB$)

i: hydraulic gradient
A,B: area and width of flow

For the axisymmetric radial flow:

$$i = -dh/dr \quad (14)$$

$$B = 2\pi r \quad (15)$$

Interface radial flow rate at radius r: $\boldsymbol{Q_r}$ **(=** $\boldsymbol{Q_i}$**)**

$$Q_r = -2\pi r\theta dh/dr \quad (16)$$

h:hydraulic head on top of the clay

Assumption 3:

- flow through the clay is vertical: ***1D flow***

The rate of flow through clay: Q_s

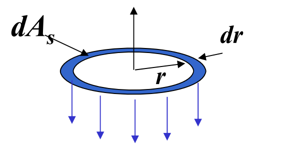
$$\Delta Q_s = K_s i_s \Delta A_s \quad (17)$$

i_s:vertical hydraulic gradient
ΔA_s: cross-sectional area of the flow

i_s is function of r, because h varies radially.

$$i_s = \frac{h+H_s}{H_s} \quad (18)$$

$$dA_s = 2\pi r dr \quad (19)$$



The flow rate in the clay at r: $\boldsymbol{dQ_s}$

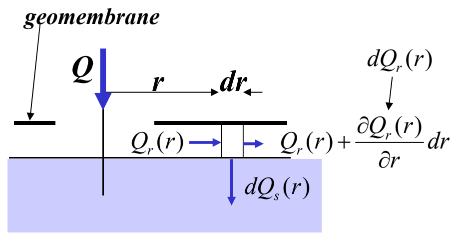
(18)(19)=>(17) $dQ_s(r) = 2\pi r K_s \dfrac{h+H_s}{H_s} dr \quad (20)$

From the mass conservation:

$$dQ_s(r) + dQ_r(r) = 0 \quad (21)$$

differentiating (16)

$$dQ_r(r) = -2\pi r\theta\left(\frac{1}{r}\frac{dh}{dr} + \frac{d^2h}{dr^2}\right) \quad (22)$$



From (20)(21)(22):

Differential equation on the flow problem:

$$\frac{1}{r}\frac{dh}{dr} + \frac{d^2h}{dr^2} = \frac{K_s}{\theta}\left(1 + \frac{h}{H_s}\right) \quad (23)$$

This can be solved using Bessel function, but too complicated.

Assumption 4:

for what occasions??

- the vertical hydraulic gradient i_s=1, which is acceptable for $h_w << H_s$.

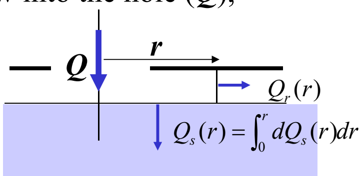
(i_s=1 cannot be substituted into (23), because it cannot satisfy MB in a small element)

From i_s=1and mass conservation to the flow into the hole (***Q***),

$$Q = Q_r(r) + Q_s(r) \quad (24)$$

$$Q = \pi R^2 K_s \quad (25)$$

$$Q_s(r) = \pi r^2 K_s \quad (26)$$



(16)(25)(26) => (24)

$$\frac{dh}{dr} = \frac{K_s}{2\theta}\left(r - \frac{R^2}{r}\right) \quad (27)$$

Integrating (27) with B.C. $h= 0$, at $r=R$

$$h = \frac{R^2K_s}{4\theta}\left[2\ln\frac{R}{r} + \left(\frac{r}{R}\right)^2 - 1\right] \quad (28)$$

relationship betw. h_w and R:

$$h_w = \frac{R^2K_s}{4\theta}\left[2\ln\frac{2R}{d} + \left(\frac{d}{2R}\right)^2 - 1\right] \quad (29)$$

Which is the most difficult to evaluate??

Using (29) $\boldsymbol{R}$ is obtained from given $\boldsymbol{h_w}$, $\boldsymbol{d}$, $\boldsymbol{K_s}$, $\boldsymbol{\theta}$ and Q can be estimated from (25).

Transmissivity given by eq.(11) and (12) depends on many factors.

Space ***s*** of empty gap between GM and clay depends

-rugosity (level of wrinkle of geomembrane),

-stiffness of GM,

-normal stress on GM.

back calculation using eq(12) and (29)

K_s (m/s)	s (mm)
10^{-6}	0.15
10^{-7}	0.08
10^{-8}	0.04
10^{-9}	0.02

Brown et al. (1987) gave the recommended value of ***s*** (right table) from lab column tests (D=0.6m, low normal pressure), which depends on soil type, especially on $\boldsymbol{K_s}$.

Then Q and R is given as functions of h_w, a, K_s.

$$Q = 0.7a^{0.1}K_s^{\ 0.88}h_w \qquad (30)$$

$$R = 0.5a^{0.05}K_s^{\ -0.06}h_w^{\ 0.5} \qquad (31)$$

half empirical equations: Q=m³/s, a=m², K_s=m/s, h_w=m, R=m, d=m

Upper bound solution (Maximum case)

Flow rate through GM defect without CL given by Bernoulli's eq.

$$Q = C_B a\sqrt{2gh_w} \qquad (32)$$

C_B: dimensionless coefficient depend on the sharpness of the edge of aperture, for sharp edge C_B=0.6

from (32) and (25)

$$\pi R^2 K_s = 0.6a\sqrt{2gh_w} \qquad (33)$$

hence

$$R = 0.44a^{0.5}(2gh_w)^{0.25}K_s^{\ -0.5} \qquad (34)$$

for circular hole

$$R = 0.39d(2gh_w)^{0.25}K_s^{\ -0.5} \qquad (35)$$

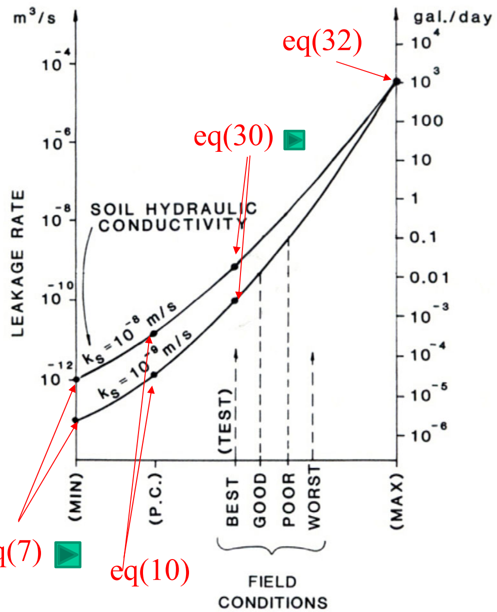
Q=m³/s, a=m², K_s=m/s, h_w=m, R=m, d=m

Trail calculation about the leakage rate: **Giroud, Bonaparte (1989)**

a=1cm² (d=11.3mm)

H_s=0.9m,

h_w=30mm,

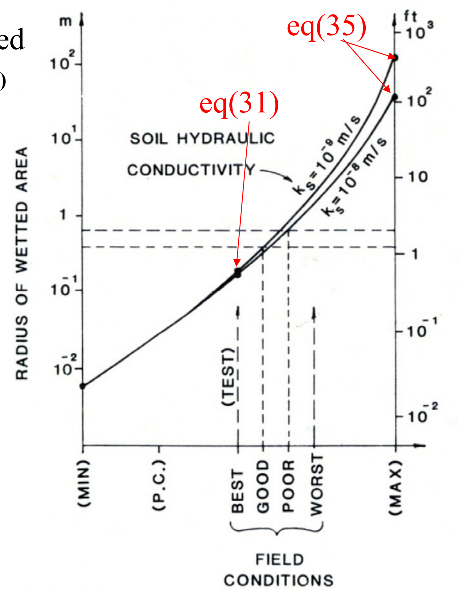


Trail calculation about the wetted area radius: **Giroud, Bonaparte (1989)**

a=1cm² (d=11.3mm)

H_s=0.9m,

h_w=30mm,



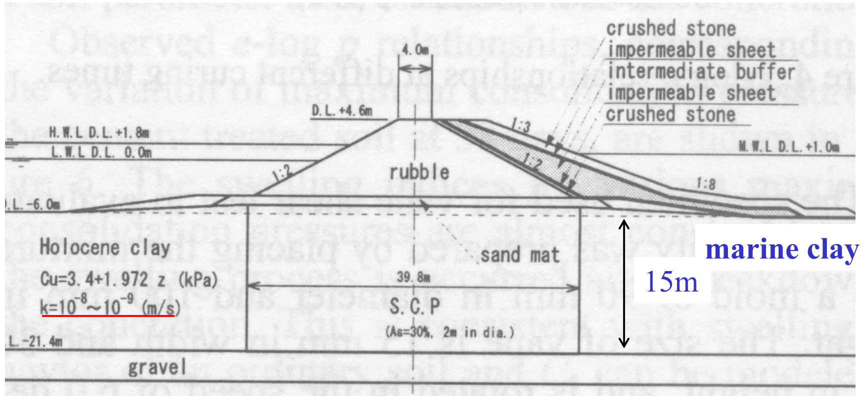
Example calculations of leakage rate:

Giroud, Bonaparte (1989) in Daniel (1993)

Type of liner	leakage rate (L/ha/day) best case	average case	worst case
GM alone	**2,500**	**25,000**	**75,000**
hole /ha	2	20	60
Compact soil alone	**115**	**1150**	**11500**
K_s(m/s)	10^{-10}	10^{-9}	10^{-8}
Composite liner	**0.8**	**47**	**770**
hole/ha	2	20	60
K_s(m/s)	10^{-10}	10^{-9}	10^{-8}
contact	poor	poor	poor

a=0.1cm^2,H_s=0.9m, h_w=0.3m,

Example of onshore waste landfill in Tachibana bay, Japan



In Japanese; requirement for natural clay liner:

***K* < 10^{-7}m/s, thickness > 5m**