

A szennyeződés-terjedési számítások gyakorlati alkalmazása – Az aljzatszigetelő rendszerek egyenértékűsége

Practical application of contaminant transport modeling – The equivalency of barrier-systems

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1 Abstract

Barriers built upon natural and synthetic materials are widely used in environmental engineering since the isolation of different pollution sources is one of the most important issue to avoid extensive contamination in environment or to restrict the penetration of hazardous substances into the intact areas.

From regulatory and waste management aspects the easiest way to control the application is to define the standard barrier types to be used for different waste or contaminant species. In Hungary, the governmental regulation No. 102/1996. controls the problem of barriers for waste disposal. The principle of that regulation is that the wastes are divided into three main groups: municipal wastes, and first and second class hazardous wastes (*Lakatos – Szabó, 1997*). The required barriers in different countries of the world and the recommended hydraulic and geometric parameters are presented on Fig. 1.. (*ISSMFE TC5, 1997*)

The recommended standard barrier types, however, may not often be implemented in practice because of technical or financial reasons. In these cases only construction of such barriers is allowed which has the same or even higher efficiency in isolation than that of the prescribed ones. The approval of barrier replacement might be completed by means of contaminant transport equivalency calculations. The paper presented summarizes the theoretical aspects of transport equivalency and the methods of calculations thereto.

2 Theoretical Considerations

(Principles of Contaminant Transport in Porous Media)

The migration of contaminants consists of four different processes: advection (convection), dispersion, adsorption and degradation (Fig. 2.). The advection is the transport process due to the seepage of the groundwater. The dispersion means the spreading of contaminants caused by local concentration inhomogeneity or seepage velocity. On one hand, the diffusion (contaminant transport due to concentration gradient) results in a spreading. On the other hand, there are some hydrodynamic reasons of this phenomena as well. Both the variation of the pathlines of the transport, the changes of pore diameter and the difference of seepage velocities within the pore; and the large scale inhomogeneity of rock bodies leads to the dispersion of contaminants. However, The three different processes (diffusion, hydrodynamic dispersion and macrodispersion) listed above result in similar effects and that is the reason why they constitute jointly the dispersive transport.

Since the linear adsorption and desorption of contaminant are mostly independent processes, the term of retardation containing both factors is taken into account during the calculations. However the sorption process is usually non-linear, therefore the non-linear adsorption isotherms (Freundlich or Langmuir) have to be used to characterize the sorption side process.

In case of special contaminants, the effect of radioactive decay or biodegradation might be significant (Kinzelbach, 1986). Consequently, the their flux has also significant impact on the net process and neglecting those simultaneous phenomena can deteriorate the reliability of calculations.

The effects of all listed phenomena results in changes of contaminant concentration both in time and space, and it can be mathematically written in the following form, called general as a transport-equation:

$$\begin{aligned}
 R \frac{\partial c}{\partial t} = & \\
 = & D_{xx} \frac{\partial^2 c}{\partial x^2} + D_{yy} \frac{\partial^2 c}{\partial y^2} + D_{zz} \frac{\partial^2 c}{\partial z^2} + D_{yx} \frac{\partial^2 c}{\partial y \partial x} + D_{xy} \frac{\partial^2 c}{\partial x \partial y} + D_{zx} \frac{\partial^2 c}{\partial z \partial x} + D_{xz} \frac{\partial^2 c}{\partial x \partial z} + D_{yz} \frac{\partial^2 c}{\partial y \partial z} + \\
 & + D_{zy} \frac{\partial^2 c}{\partial z \partial y} + D_{xy} \frac{\partial^2 c}{\partial x \partial y} + D_{yz} \frac{\partial^2 c}{\partial y \partial z} - \frac{\partial}{\partial x} \left(\frac{v_x c}{n} \right) - \frac{\partial}{\partial y} \left(\frac{v_y c}{n} \right) - \frac{\partial}{\partial z} \left(\frac{v_z c}{n} \right) - \lambda R c.
 \end{aligned}$$

where c is the concentration, D_{ij} are the elements of the dispersion matrix, v is the pore velocity of seepage, n is the porosity, λ is the degradation coefficient,

R is the rate of retardation, and x, y and z are the axes of the local (Descartes) coordinate system, respectively (*Bear-Verruijt, 1987*).

Since our task was to determine the possible concentrations on the safe side of the barrier, main goal was to solve either analytically or numerically this transport equation. Taking the fact into account that the v seepage velocity is a parameter of the transport equation, first the determination of piezometric head distribution was needed to calculate the seepage velocity field using the Darcy-law.

3 Types of Barrier Equivalency

We call „A” and „B” barrier systems equivalent if the concentrations at the protected side in time are equal presuming that the hydraulic and the concentration gradients are the same. This means that the „B” being an alternative barrier-system might only be used if the calculated concentrations on the protected side are less than the appropriate values using the „A” standard (recommended) barrier-system (*Szabó, 1995*).

Although this description is quite easy and clear, we may face a lot of practical and theoretical problems determining the equivalency. Understanding the problems it is expedient to discuss the types of equivalency.

3.1 The Advective Equivalency (Hydraulic Equivalency)

Two barriers are advectively equivalent if the concentrations on the protected side - due to equal hydraulic and concentration gradient - are equal taking only the advective transport process into consideration. Since the advective term of the transport equation is given as the seepage velocity multiplied by the concentration in the pore volume, the advective equivalency means the hydraulic equivalency as well.

Some calculations on hydraulic equivalency of different barriers are listed in Table 1. It was proved that about 1.5 cm thick GCL (geosynthetic clay liner) is advectively equivalent to 60 cm compacted clay liner, and 7.5 cm thick, multilayered GCL is needed to assure the same hydraulic equivalency with a geomembrane covered by 3x20 cm compacted clay liner. Practically it might be said that an average GCL of about 1 cm thickness is advectively equivalent only to 2x20 cm compacted clay liner.

To calculate the hydraulic equivalency the following formula should be used:

$$\frac{\sum_{i=1}^n M_i}{\sum_{i=1}^n \frac{M_i}{k_i}} = \frac{\sum_{j=1}^m M_j}{\sum_{j=1}^m \frac{M_j}{k_j}}$$

where n and m are the number of layers in the standard and the alternative barrier-system, M_i and M_j are the thicknesses of the layers and k_i and k_j are the hydraulic conductivity values, respectively.

3.2 The Diffusive Equivalency

Two barrier-systems are diffusively equivalent if the concentrations due to diffusion mass transport at identical concentration gradient are equal on the protected side of the barrier. To investigate the diffusive equivalency let us see the analytical solution of the Fick's first law. In a homogeneous medium the change of concentration in time and space is given by:

$$c_i(x, t) = c_{0i} \operatorname{erfc} \frac{x}{2\sqrt{D_i t}}$$

where c_{0i} is the constant concentration of the i contaminant at the polluted side of the barrier, D_i is the effective diffusion coefficient of the pollutant in the medium, and c_i is the concentration at x distance in time t.

If „A” and „B” barriers are diffusively equivalent then the c_i concentrations due to equal c_{i0} concentrations at the same x distance in time t are equal to

$$\frac{x_A}{\sqrt{D_A}} = \frac{x_B}{\sqrt{D_B}}$$

It means that „B” liner is diffusively equivalent to the „A” barrier of x_A thickness if its thickness is

$$x_B \geq \frac{x_A \sqrt{D_B}}{\sqrt{D_A}}. (\text{Kohler} - \text{Heimerl}, 1995)$$

For determination of diffusive equivalency the term of „diffusive conductivity” can be used as well. The diffusive conductivity might be

introduced using a hydraulic analogy. The yield of seeping water per unit area during unit time is calculated by multiplication of the hydraulic gradient and the hydraulic conductivity. Using that analogy the yield of the contaminant (the mass of contaminant transported through a unit area during a unit time) might be calculated by multiplying the concentration gradient and the so called diffusive conductivity. In this case the smaller the diffusive conductivity of the media, the higher is the isolation efficiency. (Müller-Kirchenbauer *et. al.*, 1991)

In Table 2. some measured effective diffusion coefficients and calculated diffusive conductivities are summarized. Investigating the results of the calculations it seems to be obvious that the efficiency of the HDPE geomembrane and the GCL barriers against diffusive transport processes is much lower than that of the compacted clay liners. Depending on the product the HDPE geomembrane of 2 mm thickness or a GCL of 10 mm thickness is equivalent to 5-10 cm compacted clay liner regarding only the diffusive transport.

3.3 Advective-Dispersive Equivalency

The above mentioned calculations of equivalency took only one transport phenomenon into consideration, namely, the advection or the diffusion. For investigation of more complex transport procedure Shackelford (1990) proposed a solution. Shackelford (1990) derived the 1D transport equation's analytical solution (Ogata, 1960) in the following form:

$$\frac{c}{c_0} = \frac{1}{2} [\operatorname{erfc}(z_1) + \exp(z_2) \cdot \operatorname{erfc}(z_3)]$$

where c is the concentration of the solution on the polluted side of the barrier,

$\operatorname{erf}(z) = \frac{1}{\sqrt{\pi}} \int_0^z \exp(-\xi^2) d\xi$, $\operatorname{erfc}(z) = 1 - \operatorname{erf}(z)$ is the standard error function

and its complementer function, $z_1 = \frac{x - v_s t}{2\sqrt{D^* \cdot t}}$, $z_2 = \frac{v_s \cdot x}{D^*}$ and $z_3 = \frac{x + v_s \cdot t}{2\sqrt{D^* \cdot t}}$,

where x is the distance from the surface of the barrier.

Using this method the average transit time of a pollutant in a given barrier media was calculated considering a uniform flow field during a predefined pathline. (If a given concentration of the pollutant on the protected side of the barrier at a given time is allowed, we can calculate the average pathlength in the uniform flow field, which is equal to the required minimal L thickness of

the barrier.). Introducing the dimensionless T_R and P_L parameters we may obtain:

$$T_R = \frac{v_s \cdot t}{R_d \cdot x} = \frac{v_R \cdot t}{x} = \frac{v_R \cdot t}{L} /_{x=L}, \quad P_L = \frac{v_s \cdot x}{D^*} = \frac{v_s \cdot L}{D^*} /_{x=L},$$

$$\text{then} \quad z_1 = \frac{1 - T_R}{2\sqrt{T_R/P_L}}, \quad z_2 = P_L, \quad z_3 = \frac{1 + T_R}{2\sqrt{T_R/P_L}}.$$

Rewriting the analytical solution using the dimensionless parameters (Fig. 3.) the following expression is obtained:

$$\frac{c}{c_0} = \frac{1}{2} \left[\operatorname{erfc} \left(\frac{1 - T_R}{2\sqrt{T_R/P_L}} \right) + \exp(P_L) \cdot \operatorname{erfc} \left(\frac{1 + T_R}{2\sqrt{T_R/P_L}} \right) \right].$$

Thus, the calculation consists of the following steps:

- Determination of the constants of the calculation (I: hydraulic gradient, k: hydraulic conductivity, n: porosity, c: allowable concentration at the protected side of the barrier at time t, c_0 : concentration at the polluted side of the barrier, D^* : effective dispersion coefficient of the pollutant in the investigated barrier, R_d : retardation coefficient),
- Determination of the seepage velocity in the pore volume: $v_s = \frac{k \cdot I}{n}$,
- Estimation of an L (required barrier-thickness) which assures that the c concentration on the protected site is lower at time t then the recommended limiting value,
- Determination the $P_L = \frac{v_s \cdot L}{D^*}$ value,
- Determination of c/c_0 value and from Fig. 3. we determine the T_R value using the previously calculated c/c_0 and P_L values,
- The average transport time of the pollutant can be calculated using $t_I = \frac{T_R \cdot R_d \cdot L}{v_s}$.
- If $t_1 > t$ then the barrier of L thickness is efficient, if not the calculation must be repeated using higher L value.

3.4 The General (Numerical) Equivalency

The presented equivalency calculations, however, have several limitations. The most crucial problems are as follows:

- Not all, but only some of the transport processes are considered;
- The barrier-forming material must be homogeneous (only one layer);
- Linear and monolayer adsorption is supposed (Henry-isotherm, Langmuir isotherm ?) or no adsorption allowed at all;
- Constant concentration at the polluted side of the barrier required;
- Hydraulic gradient, hydraulic conductivity, porosity, effective diffusion or dispersion coefficient for the pollutant in the investigated barrier medium must be constant both in space and time.

For practical calculations these simplifications are too strict, so a new calculation method using the numerical solution of the transport-equation had to be introduced. Using the implicit finite difference method with the Peclet and Courant stability criteria all the above mentioned problems could be eliminated. The barrier is handled as a column of elements, where each element is characterized with its own thickness, hydraulic and transport properties. The mass equilibria of the pollutant due to any transport process is taken into consideration which is represented in the 1D transport-equation.

Using the FD method the effluent concentration vs. time function is calculated for any layer in the barrier-system irrespectively to the varying influent concentration. As a first step, the average seepage velocity in the barrier system is to be calculated. Then, the transport properties of the medium should be determined. As a precondition, the initial concentration distribution in the barrier system, as boundary condition the constant or varying concentration at the polluted side of the barrier is used. The calculation is performed layer by layer, starting with the top layer of the barrier. The concentration vs. time relationship at the bottom of the layer was calculated using the initial and boundary conditions. This concentration distribution in time is the input for the second layer, etc..

For the complete numerical calculation of the equivalency the mentioned procedure must be run two times. At the first time, the calculations should be run using the data of the standard barrier system, and the second time applying the investigated alternative barrier system. The equivalency is proven if the concentration at the protected side of the alternative barrier system is lower than in case of the standard barrier system at the same time interval (Fig.4.).

4 Calculation Methodology of the General Equivalency

Since incompatibility problems may arise between different leachates and barrier-forming media (particularly in case of compacted clays, GCL, geomembranes, geotextiles, etc.) it is highly recommended to perform the numerical equivalency calculations simultaneously for different contaminants. There are six groups of contaminants with rather different behaviour for the different barrier elements which are the following:

- Cations of alkali metals and alkali-earth metals (Na, K, Mg, Ca)
- Anions of halogenides (Cl, Br, I)
- Toxic metals and heavy metals (Sr, Cd, Cu, Ni, Zn, Pb, Fe)
- Chlorinated hydrocarbons (mono and dichloro benzene, carbon tetrachloride, etc.)
- Alcohols and their derivatives (alcohols, aldehydes, ketones)
- Aromatic organic compounds (benzene, xylene, toluene, etc.)

For each group it is recommended to make the calculation using the data of the most hazardous component. The environmental hazard might be estimated using the c/c_0 value (allowed concentration at the protected side/maximal concentration on the polluted side).

The equivalency calculation of any contaminant groups can be omitted if the occurrence of that leachate components is irrelevant. If the leachate composition in the planning phase is not known, a chemical analysis of leachates at similar pollution sources is advised. The general (representative) transport properties of the different contaminant groups for some barrier elements are listed in Table 4.

Using the numerical calculations, the equivalency of standard and alternative barrier systems or their elements can be determined at much higher safety level, because the prescription made only by the hydraulic equivalency does not assure the equivalency if other transport processes are also taking place.

5 Summary

Present paper deals with the problem of equivalency calculations of different complex barrier-systems used in environmental engineering. After a short summary of the transport phenomena and its mathematical formulation, the transport-equation, the types of equivalency were presented. Analytical formulas of equivalency were derived. Since the real problems can not be solved using the analytical solution of the transport equation, a numerical

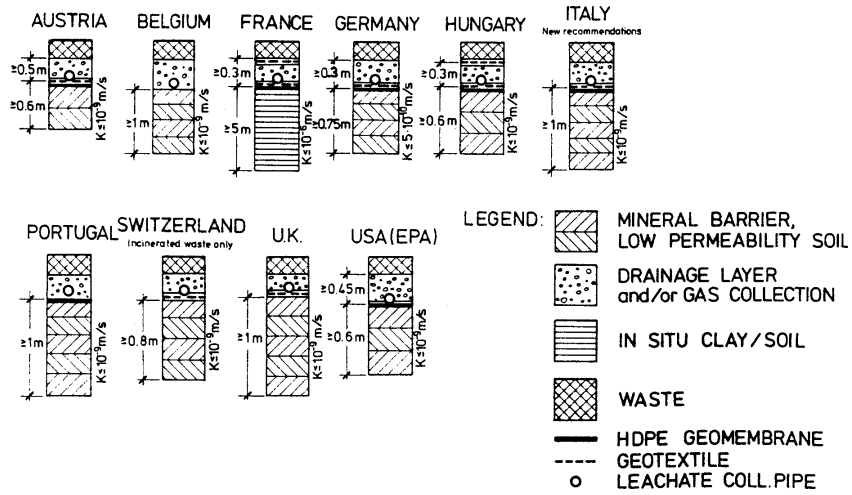
solution is introduced. Finally, a recommendation for complex equivalency calculations is detailed.

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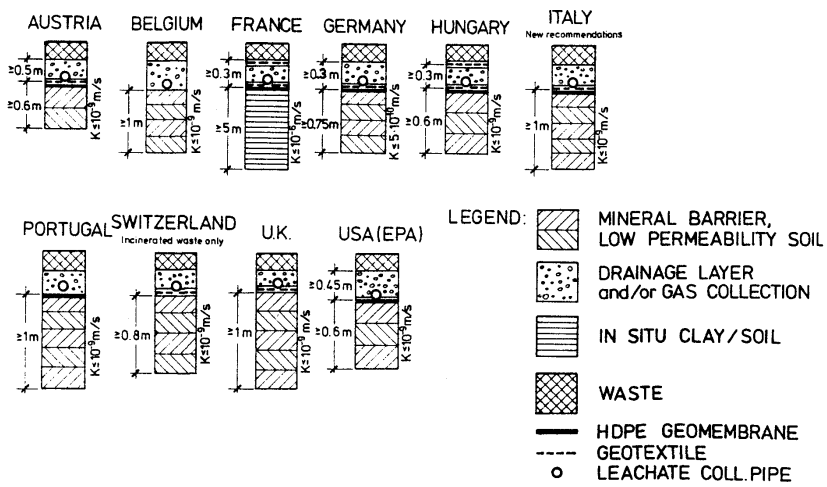


Fig. 1. Bottom lining systems for municipal (a.) and hazardous (b.) wastes from different regulations and recommendations (ISSMFE TC5, 1997)

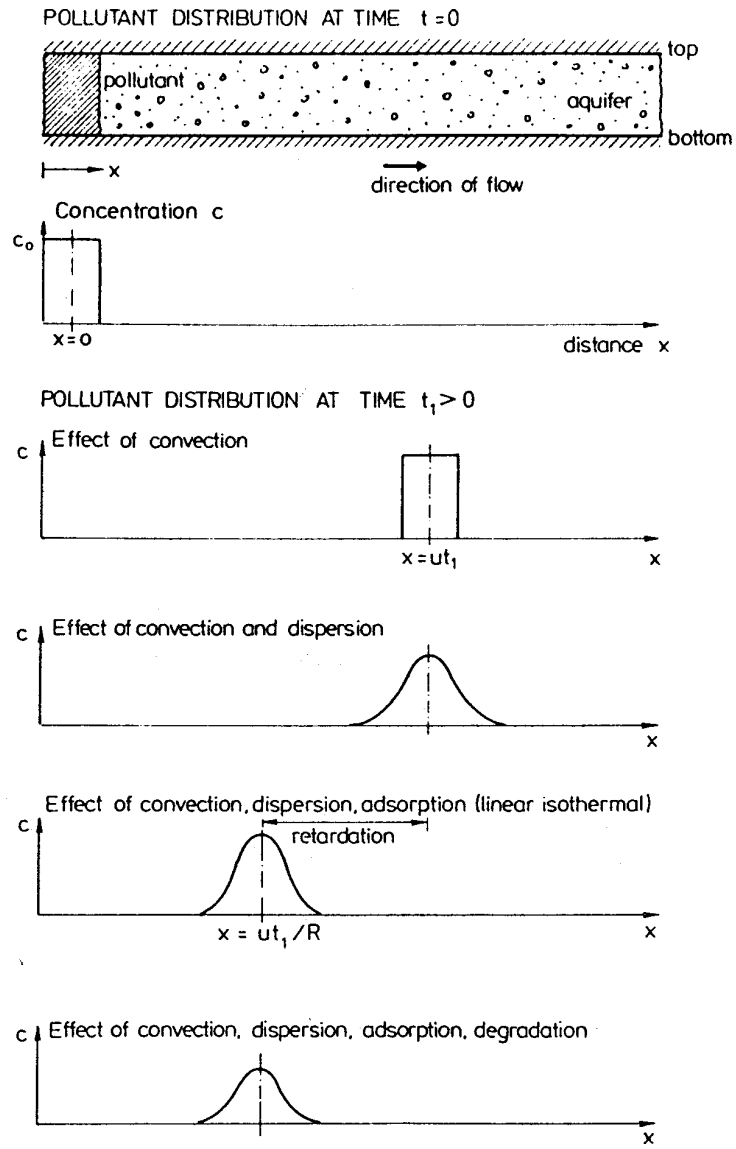


Fig. 2. Schematic of elements of contaminant transport in porous medium (Kinzelbach, 1986)

Table 1.: The hydraulic equivalency of different barrier-forming materials

| Barrier-material | Average hydraulic conductivity [m/s] | Thickness [cm] | Case A [m] | Case B [m] | Case C [m] |
|---------------------------------------|--------------------------------------|----------------|------------|------------|------------|
| Compacted clay liner | 1,00E-09 | 60 | 0,6 | 3,1 | 93 |
| Mixture of sand and 3% bentonite* | 5,00E-07 | (60) | 300 | 1550 | 46500 |
| Mixture of sand and 5% bentonite* | 1,00E-07 | (60) | 60 | 310 | 9300 |
| Mixture of sand and 10% bentonite* | 1,00E-09 | (60) | 0,6 | 3,1 | 93 |
| Mixture of sand and 15% bentonite* | 8,00E-11 | (60) | 0,048 | 0,248 | 7,44 |
| Geomembrane | 8,00E-13 | 0,2 | 0,00048 | 0,00248 | 0,0744 |
| Geomembrane with 5 mm diameter hole** | 4,70E-12 | 0,2 | 0,00282 | 0,01457 | 0,4371 |
| Geomembrane with 1 cm diameter hole** | 9,50E-12 | 0,2 | 0,0057 | 0,02945 | 0,8835 |
| Geomembrane with 2 cm diameter hole** | 1,90E-11 | 0,2 | 0,0114 | 0,0589 | 1,767 |
| GCL (Geosynthetic clay liner) | 2,50E-11 | 1 | 0,015 | 0,0775 | 2,325 |
| Hydraulic asphalt liner | 3,00E-11 | 5 | 0,018 | 0,093 | 2,79 |

Case A: Equivalent thickness [m] with 60 cm thick, $k=10^{-9}$ m/s compacted clay liner

Case B: Equivalent thickness [m] with 60 cm thick, $k=10^{-9}$ m/s compacted clay liner covered by 2 mm HDPE geomembrane

Case C: Equivalent thickness [m] with 60 cm thick, $k=10^{-9}$ m/s compacted clay liner covered by 2x2 mm HDPE geomembrane with drainage layer between

* Average hydraulic conductivity determined by using the experiments of Chapuis (1990)

** Average hydraulic conductivity calculated by using spherical flow field (Oweis-Khera, 1990)

Table 2.: Representative effective diffusion coefficients and diffusive conductivity of some pollutants
(Müller-Kirchenbauer, et. al. , 1997)

| Group of pollutant | Pollutant | Diffusion coefficient | | | Diffusive conductivity | | |
|-----------------------|-----------------------------|--|--|---|---------------------------|------------------------------|--|
| | | In water solution ($\times 10^{-10}$ m ² /s) | Pore-water /clay liner ($\times 10^{-10}$ m ² /s) | Geo- membrane ($\times 10^{-12}$ m ² /s) | Geomem- brane (m/s) | Comp. clay liner (m/s) | Combined barrier system (m/s) |
| Cations | Zn,Cd,Hg,Pb, Ni,Cu,Mn,Na | | | | $\ll 1 \cdot 10^{-15}$ | $3,0 \cdot 10^{-10}$ | $\ll 1 \cdot 10^{-15}$ |
| Anions | Chloride | | | | $\ll 1 \cdot 10^{-14}$ | $1,2 \cdot 10^{-10}$ | $\ll 1 \cdot 10^{-14}$ |
| Alcohols | Metanol | 14,5 | 4,8 | 0,8 | $1,5 \cdot 10^{-12}$ | $2,0 \cdot 10^{-10}$ | $1 \cdot 10^{-12}$ |
| Ketones | Acetone | 10,2 | 3,4 | 0,6 | $8 \cdot 10^{-12}$ | $1,4 \cdot 10^{-10}$ | $8 \cdot 10^{-12}$ |
| | Ethyl-methyl ketone | 9,0 | 3,0 | 0,55 | $9 \cdot 10^{-11}$ | $1,2 \cdot 10^{-10}$ | $5 \cdot 10^{-11}$ |
| Organic acids | Acetic acid | | | 0,15 | $1 \cdot 10^{-12}$ | $0,8 \cdot 10^{-10}$ | $1 \cdot 10^{-12}$ |
| | Propionic acid | | | 0,15 | $5 \cdot 10^{-12}$ | | |
| Esters | Acetic acid-ethylester | 8,4 | 2,8 | 0,15 | $5,5 \cdot 10^{-11}$ | $1,1 \cdot 10^{-10}$ | $4 \cdot 10^{-11}$ |
| Aldehydes | Formaldehyde solution | 17,8 | 5,9 | 0,8 | $5 \cdot 10^{-12}$ | $2,4 \cdot 10^{-10}$ | $5 \cdot 10^{-12}$ |
| Aromatic hydrocarbons | Benzene | 9,0 | 3,0 | 0,2 | $4,5 \cdot 10^{-9}$ | $1,2 \cdot 10^{-10}$ | $1,2 \cdot 10^{-10}$ |
| | Ethylbenzene | 6,8 | 2,3 | 0,2 | | | |
| | Xylene | 7,2 | 2,4 | 0,2 | $1 \cdot 10^{-7}$ | $1 \cdot 10^{-10}$ | $1 \cdot 10^{-10}$ |
| | Toluene | 8 | 2,7 | 0,2 | $2,0 \cdot 10^{-8}$ | $1 \cdot 10^{-10}$ | $1 \cdot 10^{-10}$ |
| | Naphtalene | 7 | 2,3 | | | | |

Table 2.(cont.): Representative effective diffusion coefficients and diffusive conductivity of some pollutants (Müller-Kirchenbauer, et. al. , 1997)

| Group of pollutant | Pollutant | Diffusion coefficient | | | Diffusive conductivity | | |
|--------------------------|----------------------|--|---|---|------------------------|-------------------------------|----------------------------------|
| | | In water solution ($\times 10^{-10}$ m ² /s) | Pore-water /clay liner ($\times 10^{-10}$ m ² /s) | Geo-membrane ($\times 10^{-12}$ m ² /s) | Geomem-brane (m/s) | Compacted clay liner (m/s) | Combined barrier system (m/s) |
| Chlorinated hydrocarbons | Chloroform | 9,2 | 3,1 | 0,25 | $2,0 \cdot 10^{-9}$ | $1,2 \cdot 10^{-10}$ | $1,1 \cdot 10^{-10}$ |
| | Carbon tetrachloride | 8,7 | 2,9 | 0,25 | $2,5 \cdot 10^{-8}$ | $1,2 \cdot 10^{-10}$ | $1,2 \cdot 10^{-10}$ |
| | Trichloro-ethylene | 8,4 | 2,9 | 0,25 | $2,0 \cdot 10^{-8}$ | $1,2 \cdot 10^{-10}$ | $1,2 \cdot 10^{-10}$ |
| | 1,2-Dichloro-ethane | 9,1 | 3 | 0,25 | $2,0 \cdot 10^{-9}$ | $1,2 \cdot 10^{-10}$ | $1,1 \cdot 10^{-10}$ |
| | Tetrachloro-ethylene | 7,6 | 2,5 | 0,25 | $2,0 \cdot 10^{-6}$ | $1 \cdot 10^{-10}$ | $1 \cdot 10^{-10}$ |
| | 1,2-Dichloro-propane | 8 | 2,7 | | | | |
| | Chloro benzene | 8,1 | 2,7 | 0,25 | $5 \cdot 10^{-9}$ | $1,1 \cdot 10^{-10}$ | $1,1 \cdot 10^{-10}$ |
| Saturated Hydrocarbons | Pentane | 8 | 2,7 | 0,2 | $3 \cdot 10^{-7}$ | $1,1 \cdot 10^{-10}$ | $1,1 \cdot 10^{-10}$ |
| | Hexane | 7,2 | 2,4 | 0,2 | $2 \cdot 10^{-6}$ | $1,0 \cdot 10^{-10}$ | $1,0 \cdot 10^{-10}$ |
| | Heptane | 6,6 | 2,2 | 0,2 | $1 \cdot 10^{-5}$ | $0,9 \cdot 10^{-10}$ | $0,9 \cdot 10^{-10}$ |

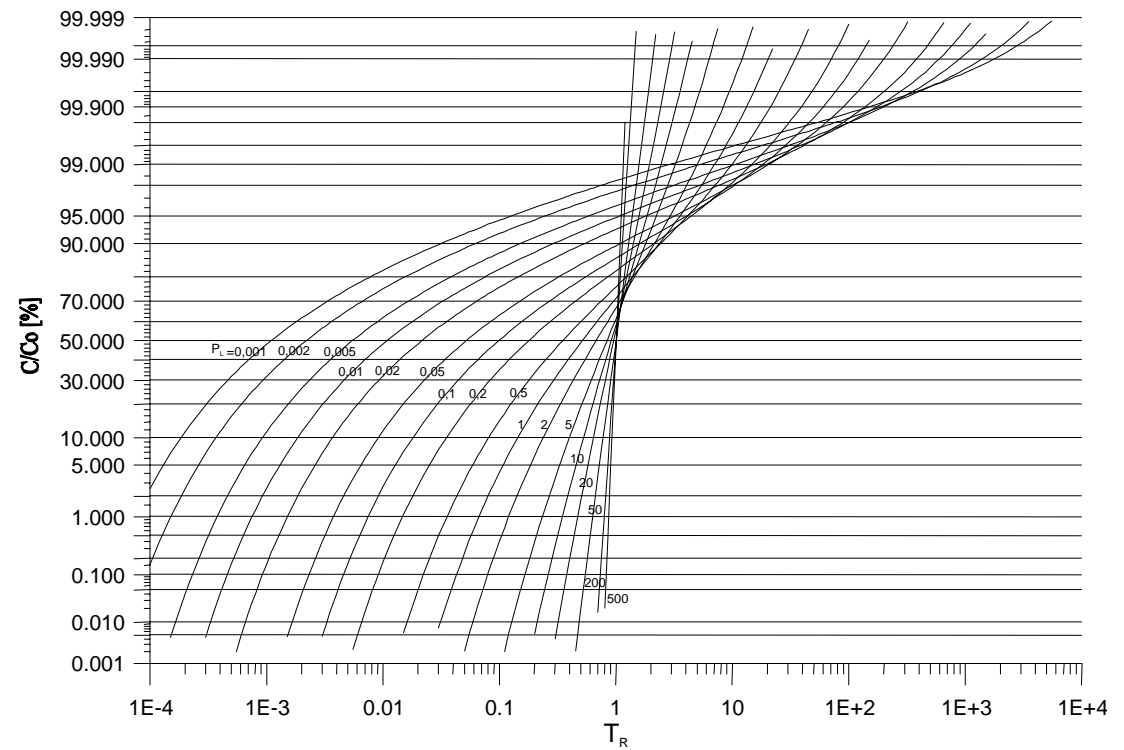


Fig. 3.: The relationship of dimensionless parameters and the relative concentration (Shackelford, 1990)

Table 3.: Diffusive equivalency of geomebrane and compacted clay liners

| Pollutant | Effective diffusion coefficient [$\times 10^{-10}$ m^2/s] | Effective diffusion coefficient [$\times 10^{-12}$ m^2/s] | Equivalent thickness of compacted clay with HDPE geomebrane of 2 mm thickness | Equivalent thickness of HDPE geomebrane with comp. clay liner of 60 cm thickness |
|-------------------------|---|---|---|--|
| | Comp. clay liner | Geo-membrane | [cm] | [mm] |
| Methanol | 4.8 | 0.8 | 4.9 | 0.00167 |
| Acetone | 3.4 | 0.6 | 4.8 | 0.00187 |
| Ethyl-methyl ketone | 3 | 0.55 | 4.7 | 0.00202 |
| Acetic acid | | 0.15 | | |
| Propionic acid | | 0.15 | | |
| Acetic acid- ethylester | 2.8 | 0.15 | 8.6 | 0.00017 |
| Formaldehyde-solution | 5.9 | 0.8 | 5.4 | 0.00110 |
| Chloroform | 3.1 | 0.25 | 7.0 | 0.00039 |
| Carbon tetrachloride | 2.9 | 0.25 | 6.8 | 0.00045 |
| Trichloro ethylene | 2.9 | 0.25 | 6.8 | 0.00045 |
| 1,2-Dichloroethane | 3 | 0.25 | 6.9 | 0.00042 |
| Tetrachloro ethylene | 2.5 | 0.25 | 6.3 | 0.00060 |
| 1,2-Dichloropropane | 2.7 | | | |
| Chlorobenzene | 2.7 | 0.25 | 6.6 | 0.00051 |
| Benzene | 3 | 0.2 | 7.7 | 0.00027 |
| Ethylbenzene | 2.3 | 0.2 | 6.8 | 0.00045 |
| Xylene | 2.4 | 0.2 | 6.9 | 0.00042 |
| Toloene | 2.7 | 0.2 | 7.3 | 0.00033 |
| Naphtalene | 2.3 | | | |
| Pentane | 2.7 | 0.2 | 7.3 | 0.00033 |
| Hexane | 2.4 | 0.2 | 6.9 | 0.00042 |
| Heptane | 2.2 | 0.2 | 6.6 | 0.00050 |

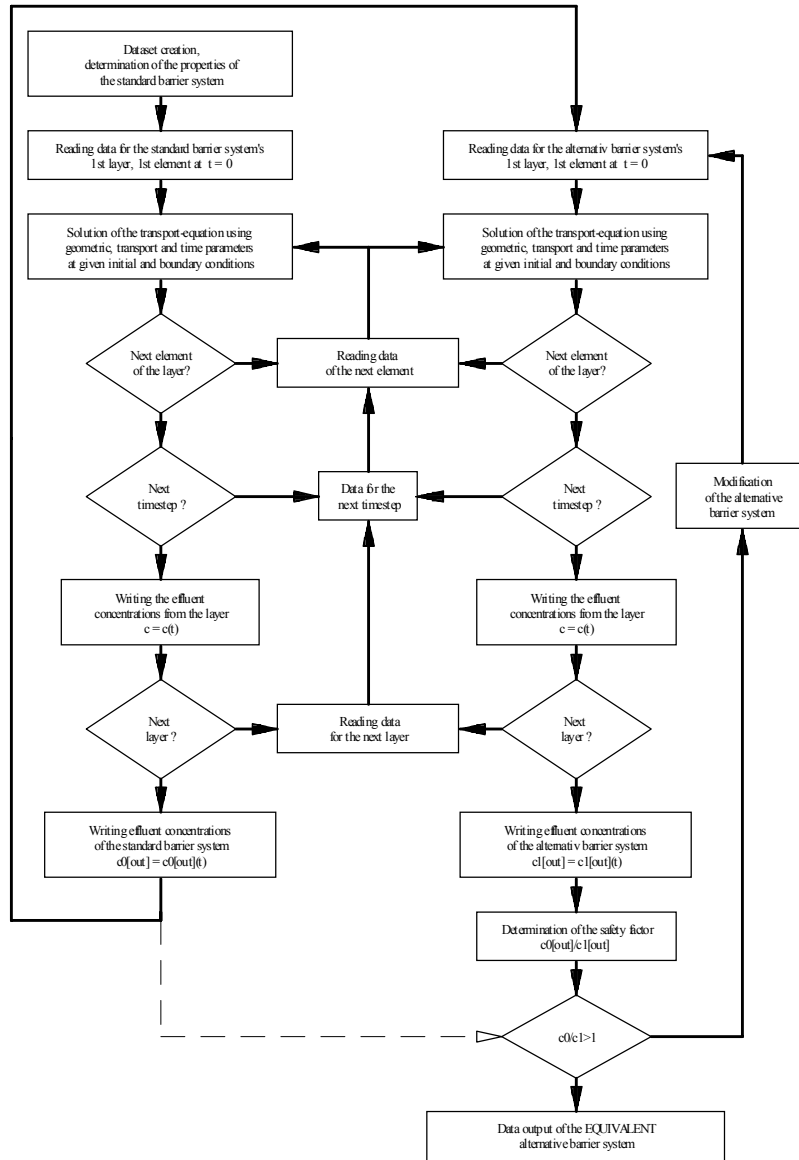


Fig. 4. Flowchart of the numerical equivalency calculation

Table 4.: Representative hydraulic and transport-parameters for calculations of the numerical equivalency

| Property | Representative value | | | |
|--|----------------------------------|-------------------------------|------------------------------|----------------------------------|
| | HDPE geo-membrane | Compacted clay liner | Substratum ¹ | Drainage layer ² |
| hydraulic conductivity [m/s] | 10^{-13} | 10^{-9} | 10^{-8} | 10^{-4} |
| Effective diffusion coefficient [m ² /s] | | | | in saturated conditions |
| 1.group | $2 \cdot 10^{-16}$ | 10^{-10} | 10^{-10} | $5 \cdot 10^{-9}$ |
| 2.group | $3 \cdot 10^{-16}$ | $5 \cdot 10^{-10}$ | $5 \cdot 10^{-10}$ | $7 \cdot 10^{-9}$ |
| 3.group | 10^{-16} | $3 \cdot 10^{-11}$ | $3 \cdot 10^{-11}$ | $5 \cdot 10^{-10}$ |
| 4.group | $2 \cdot 10^{-13}$ | $3 \cdot 10^{-10}$ | $3 \cdot 10^{-10}$ | $6 \cdot 10^{-10}$ |
| 5.group | $6 \cdot 10^{-13}$ | $2 \cdot 10^{-10}$ | $2 \cdot 10^{-10}$ | 10^{-9} |
| 6.group | $2 \cdot 10^{-13}$ | $3 \cdot 10^{-10}$ | $3 \cdot 10^{-10}$ | $6 \cdot 10^{-10}$ |
| Dispersivity [m] (layer thickness[m]) | 0,0001 (0,002) | 0,01(0,2) 0,025(0,6) | 0,08 (3) | thickness dependent ³ |
| „A” parameter of the Langmuir isotherm [mg/kg] | T=0,001 meq/100g ⁴ | T=10 meq/100g ⁴ | T=5 meq/100g ⁴ | T=2 meq/100g ⁴ |
| „K” parameter of the Langmuir isotherm [m ³ /g] | 0,1 | 0,03 | 0,1 | 0,01 |
| λ decay factor [1/s] | 0 | 0 | 0 | 0 |
| n porosity [-] | 0.000001 | .5 | 0.45 | 0.33 |
| n ₀ eff. porosity [-] | 0.000001 | 0.02 | 0.04 | 0.33 |

only at barriers for hazardous waste deposits

only at drainage layers between isolation layers

dispersivity might be determined depending on layer thickness using data from the literature

The parameter in case of contaminant groups 1.-2.-3. might be calculated from CEC (T[meq/100g]) values. A[mg/kg]=M*10*T[meq/100 g], where A is the parameter of the Langmuir isotherm, M is the relative atomic weight. In case of group 4., 5. and 6. the values are to be determined during laboratory measurements.