# PART V

## Coastal, Estuarine and Environmental Problems

CHAPTER 209

# IMPORTANCE OF PERMABILITY IN THE SEDIMENTATION CONSOLIDATION PROCESS

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## ABSTRACT

This paper first presents a literature review of permeability laws. A link between hydraulics and geotechnics formulations is pointed out. Second, reduced permeability expressions are discussed from experimental data available in literature. An extented exponential expression of reduced permeabilty is proposed.


## 1. INTRODUCTION

In coastal engineering, sedimentary transports and harbour silting are governed by the sedimentation-consolidation process.

The current modellings are based on:

- hydraulics laws for very low concentration soils (less than 100 g/l) applicable to sedimentation and using the settling velocity
- soil mechanics laws for high concentration soils (greater than 500g/l) applicable to consolidation and using permeability and effective stress.

Sedimentation-consolidation process is complex. Its settling velocity parametrisation has important limits, because of the lack of distinction between effective stress and permeability influences, and also because of the lack of account of consolidation.

On the other hand, we observe that the flow law is at the core of the confrontation between hydraulics and geotechnics approaches.

It is interesting to use an important flow law parameter : the permeability.

So, the topic of this paper is the analysis and the suitability of the permeability concept with the sedimentation-consolidation process.

We will select a main parameter which will allow us to use sedimentation and consolidation results.

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Then, we will research its evolution with void ratio or with porosity.

## 2. THEORY-BASED LAWS

The origins of these theory-based laws are hydraulics studies issued from settling velocity parametrisation or geotechnics studies issued from permeability parametrisation.

Main parameters are :

- permeability $k$
- hydraulic gradient $i$
- porosity $n$
- void ratio $e$ that is void volume divided by solid volume

$$e = \frac{n}{1 - n}$$

- settling velocity $v_s$
- reduced permeability $k_r$

$$k_r = \frac{k}{1 + e}$$

The reduced permeability is both hydraulics and geotechnics parameter.

Flow law is Darcy's law

First, for very high concentration case, that is for very low void ratio reduced permeability and settling velocity are zero : there is no flow.

Second, for very low concentration case, the process is governed by Stokes' law which links velocity with diameter of grain and viscosity :

$$v_o = \frac{d^2 \gamma'_s}{18\eta}$$

$v_o$ : Stokes' velocity d : diameter

$\gamma'_s$ : unit weight of submerged solids $\eta$ : viscosity

In this case, hydraulic gradient $i_o$ is the ratio between unit weight of submerged mixture and unit weight of water :

$$i_o = \frac{\gamma'}{\gamma_w} = \frac{\gamma'_s}{(1 + e)\gamma_w}$$

$\gamma'$: unit weight of submerged mixture (bulk)

$\gamma_w$: unit weight of water.

So, hydraulic gradient is zero when void ratio is infinite.

In this case, reduced permeability is a constant multiplied by Stokes velocity :

$$k_{ro} = v_o \frac{\gamma_w}{\gamma'_s} = C.v_o \qquad C : \text{constant}$$

So, permeability is infinite and we can see, here, the great interest of a parametrisation by means of reduced permeability which remains finite.

So, we obtain a link between geotechnics and hydraulics, that is between consolidation and sedimentation, by means of reduced permeability.

Most representative theories for modelling sedimentation-consolidation process are Richardson's law and Kozeny's law.

First, the empirical Richardson's law corresponds to the beginning of the phase called hindered settling.

The settling velocity is linked to Stokes' velocity $v_o$ and porosity $n$, which is a function of void ratio ($n=e/(1+e)$):

$$v_s = v_o . n^{4,65}$$

In this case, we deduced reduced permeability $k_r$ as a power law of porosity :

$$k_r = k_{ro} . n^{4,65}$$

Second, Kozeny's law corresponds to a porous media.

Permeability is a fonction of specific are $a$, viscosity and porosity :

$$k = \frac{\gamma_W}{h_k a^2 \eta} \cdot \frac{n^3}{(1-n)^2}$$

It appears the Kozeny's constant $h_k$, which depends on grain shape and tortuosity of the flow between grains.

Usually, $h_k$ equals 4.5.

For spheric grains, we obtain a formulation of reduced permeability with porosity :

$$k_r = \frac{\gamma_W d^2}{36 h_k \eta} \cdot \frac{n^3}{1-n}$$

Using Stokes' reduced permeability, we deduce a new relation between reduced permeability and porosity :

$$k_r = \frac{k_{ro}}{9} \cdot \frac{n^3}{1-n}$$

So, we can compare these 2 theories by means of the formulation of reduced permeability in function of porosity.

So, the reduced permeability $k_r$ is the basic parameter which unables the link between hydraulics and geotechnics.

We compare the results of Kozeny's law and Richardson's law (fig.1)

It appears differencies for values of porosity higher than 90% in the extremal condition of very low concentration $k_r$ remains finite for Richardson's law while $k_r$ is infinite for Kozeny's law.

For porosities lower than 90%, the 2 curves are rather close.

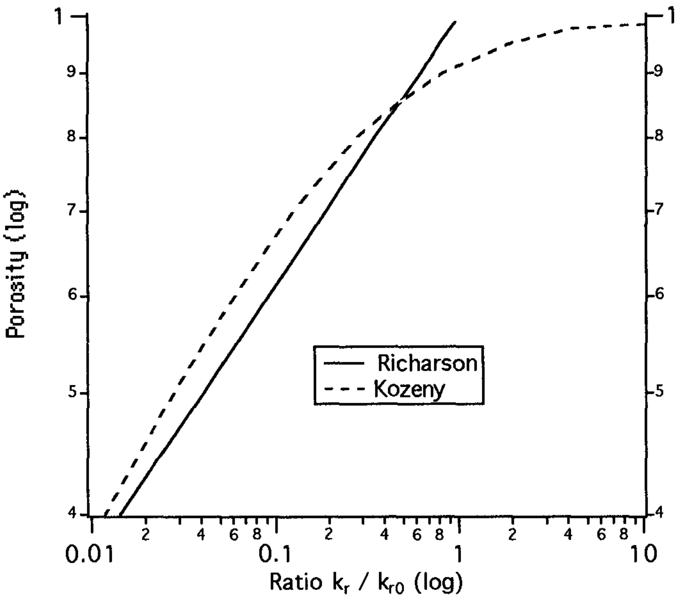


Fig.1 Comparison of Kozeny's and Richardson's laws

So, for the middle concentrated mixtures which are the most interesting, we can consider that the hydraulics analysis of Richardson and the geotechnics analysis of Kozeny give quite similar results.

## 3. INVENTORY OF EXPERIMENTAL LAWS AND CHOICE

The experimental flow laws are numerous in litterature, as every experimenter, according to his speciality and the range of his measurements , looks for a particular shape , both simple and representative which is able to synthesize his values.

So, there is a lot of permeability laws with a lot of parameters.

We propose a methodology consisting in choosing main parameters, such as reduced permeability $k_r$, permeability $k$ and void ratio e and then in translating settling velocity, porosity and concentration in terms of $k_r$, $k$ and e, and at last in gathering different laws to show the links and particular cases.

For this specific work, we are going to propose an original tree-shaped diagram (fig.2) showing the links between the different types of laws.

We are also going to propose new generic laws.

Two main families of experimental laws can be distinguished :

- power laws for reduced permeability in the upper part of this scheme.
- and logarithmic laws for permeability in the lower part of this scheme.

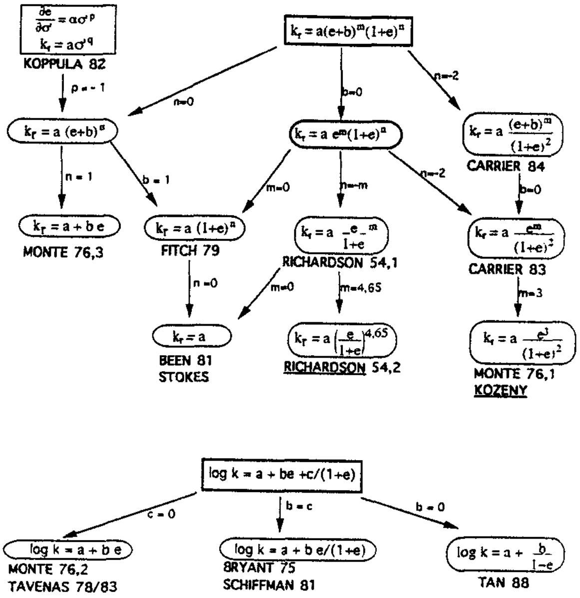


Fig.2: Synthetic arborescent scheme of reduced permeability laws

The name of each parametric constant *a*, *b*, *m*, *n*, is only generic, for instance we have always named *a* the first parametric constant.

Each law is presented with his author and the year of its publication.

For gathering all this laws, we propose new generic laws (in bold). These new generic laws allow a general linkage between all the experimental laws.

In our representation, each stage corresponds to a number of parametric constant. So, we presents 16 laws with 1, 2, 3 or 4 parametric constants.

Once mathematical shapes are compared, we also compare the representative curve of these laws (Fig. 3).

For that, we choose an experimental data set with values of void ratio between 1 and 6 (these values are issued from esperiments on clay ey-silt by YONG, 1982).

We study the 10 previous laws with 1 or 2 parameters.

For each law, we obtain the value of each parameter by means of a best fit method of regression on these experimental data.

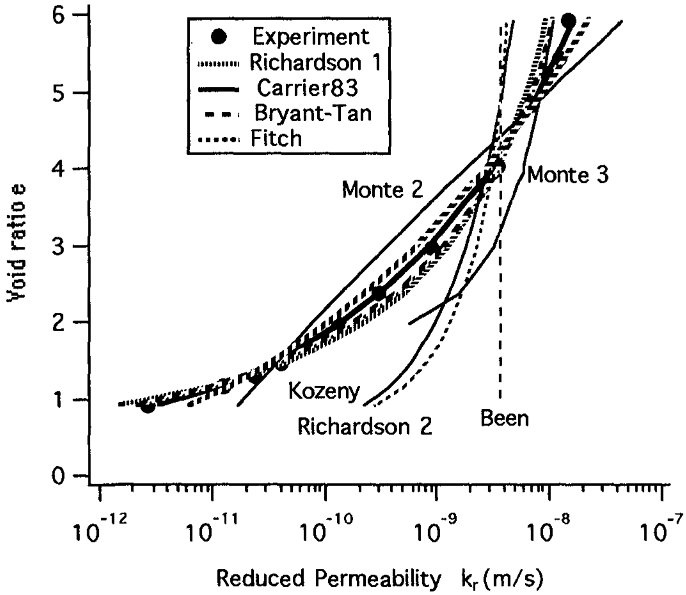


Fig.3:Comparison of reduced permeability laws

In fig.3, experimental values are represented by dots, and each curve corresponds to 1 law.

Corresponding to Stokes'law, BEEN's law is not representative for our problem, neither Richardson 2, Kozeny, Monte 3 laws

We remark that TAN and BRYANT laws give the same curve.

Among these 10 laws, we have written, in the legend, five laws which seem to be representative.

Among these 5 best laws, Carrier's and Richardson 1's laws are the only ones that give a permeability zero where void ratio is zero.

So, we will choose these 2 most representative laws.

To conclude this comparison of curves, we can use 3 criterions :

- representativity
- adequacy with extremal conditions of Stokes with infinite value of void ratio, that is initial sedimentation.
- adequacy with extremal conditions of zero value of void ratio and permeability, that is final consolidaion.

Carrier's law seems to be the most representative, but the law of Richardson 1 with 2 parameters has a better adequacy with the extremal condition of Stokes.

| CRITERIONS | CARRIER'S LAW | RICHARDSON 1'S LAW |
|---|---|---|
| REPRESENTATIVITY | ++ | + |
| STOKES EXTREME (e infinite) | - | ++ |
| $k_r$ = 0 (e=0) | ++ | ++ |

Tab. 1 : Synthesis of comparison of curves.

## 4. VALIDATION

The previous comparison allowed a first sorting of the laws of reduced permeability. These selected laws have to be validated over a much wider range. The bibliographic study reveals a lack of experimental data covering this range (down to a concentration of 50 g/l).

So, we are going to exploit a very large range of cohesive sediment data from differents authors, for values of void ratio between 1 and 50 (concentrations between 1300g/l and 50g/l).

The conversion law of settling velocity into reduced permeability during pure sedimentation is :

$$v_s = \frac{\gamma'_s}{\gamma_w} k_r = 1.65\, k_r$$
$$(\gamma_s = 26.5\ kN/m^3)$$

Figure 4 represents the reduced permeability data in function of void ratio.

Toorman's tests were expressed in terms of settling velocity, they have been continued until the beginning of consolidation, where the relation $v_s$ equals 1.65 $k_r$ is not valid.

So, the previous conversion implies a left shift for the lowest dots of each set.

The regularity of the evolution confirms the concept of continuous process of sedimentation-consolidation.

So, we will keep 2 sets of experimentation data (set1 = Toorman 1 + Pane 1, Set 2 : Toorman 2 + Yong).

Previous figure (fig.4) was interesting but we have no continuous wide-distributed set of measurements.

In order to validate the laws in a wide field, we propose now to synthetise the 2 previous sets of experimentations.

By means of these coherent data sets, we will compare for each set :

- 3 theory-based laws (Richardson 1 and 2 and Kozeny)
- and 2 selected laws (Richardson 1 and Carrier)

Dots are experimental data of set 1 for figure 5 and set 2 for figure 6.

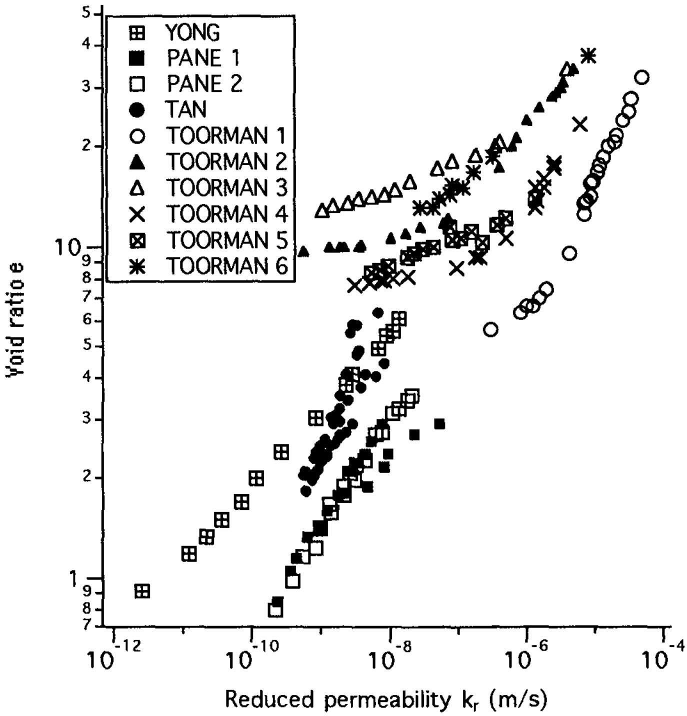


Fig.4: Evolution of experimental reduced permeability with void ratio

These 2 figures show again clearly that the one parameter laws (Richardson 2 and Kozeny) are not convenient.

The curve of Richardson 1 law (here with a power about 20) is not enough representative.

Carrier's law is well representative, and its shape is quasi-linear on this graph.

So, we propose a more simple power-typed law, for the whole range of void ratio between 1 and 50 (or concentration between 50 and 1 300 grains per liter) :

$$k_r = a\,e^{b}$$

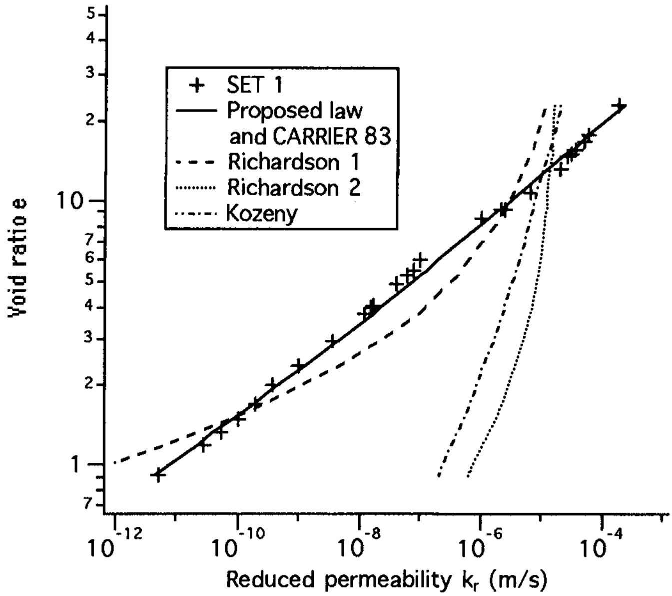


Fig.5: Proposed law and other laws of reduced permeability with Set 1.

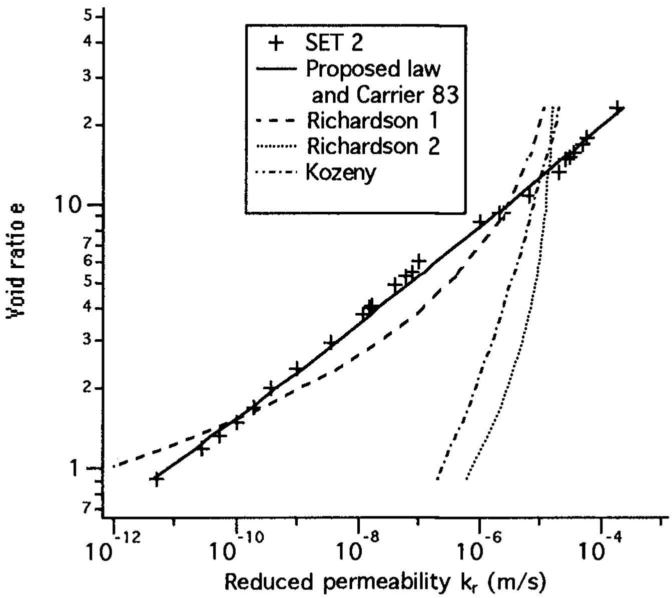


Fig.6: Proposed law and other laws of reduced permeability with Set 2.

## 5. CONCLUSION

The flow law is essential for the modelling of the sedimentation-consolidation process. We have shown the interest of the reduced permeability which links hydraulics and geotechnics.

We have described and compared theory-based laws. We have proposed a tree-shaped synthesis scheme which allows a gathering of laws, which are various as for their origins as for their shapes, and we have proposed new generic laws.

We have achieved a first selection of laws by means of one data set issued from bibliography in which void ratio is between 1 and 6. We have selected two laws, close to the theoretical ones by their shapes.

Then, we have validated by means of extended data sets in which void ratio is between 1 and 50. The position of the dots tends to confirm the continuity of the sedimentation-consolidation process. We have suggested to express the reduced permeability as an exponential law of the void ratio. We have thus extended the validity range of the reduced permeability concept and the concentration field of the modelling.

## 6. ACKNOWLEDGEMENTS

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