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Numerical simulation of double packer tests. Calculation of rock permeability

Carol Braester
Israel Institute of Technology, Haifa, Israel
Roger Thunvik
Royal Institute of Technology

Stockholm, Sweden, June 1982

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POSTADRESS: Box 5864, 102 48 Stockholm, Telefon 08-67 95 40

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ABSTRACT

The permeability of a fractured hard rock formation is usually calculated using the recorded overpressure and the rate of flow during a double packer test. Existing formulae assume that the formation is both homogeneous, and isotropic, and that the borehole is sealed in the region outside the packers, but in practice these assumptions are not fulfilled. The objective of the present investigation is to check the influence on the calculated rock permeability of inhomogeneities, anisotropy and return of flow from the formation into the unsealed part of the borehole by numerical simulation of double packer tests. For this purpose different formations with known permeabilities were considered.

CONTENTS

SUMMARY AND CONCLUSIONS

Packer tests are the most commonly used means of determining fractured hard rock permeability. Double packer tests are extensively used by SGU (Swedish Geological Survey), in the frame of the KBS (Nuclear Fuel Safety) project, to determine the rock permeability at prospective sites for nuclear fuel waste repositories. During such a test, water is injected into the formation in the space between the packers. The applied overpressure and the rate of flow are recorded at quasi-steady state and used for the calculation of the permeability.

Fractured hard rock formations are usually highly inhomogeneous and anisotropic, but permeability is calculated by using formulae assuming homogeneity and isotropy. In addition, the borehole is considered impervious in the region outside the packers, while in fact it is unsealed and pervious.

The aim of the present investigation is to check the effect of deviations from these assumptions on the calculated permeability. For this purpose double packer tests were simulated on synthetic formations, with a priori known permeabilities. The tests were carried out using a numerical flow model, and simulating conditions similar to those appearing in the field.

As in a real packer test, the applied overpressure and the injected rate of flow are used for the calculation of permeability, using formulae assuming homogeneity, isotropy and no flow into the borehole. The calculated permeability is compared with the known permeability in the numerical model.

The only known method with a sound theoretical support, for the interpretation of double packer tests, is the one presented by Dagan (1978). However, one of the most commonly applied formula is Moye´s formula, which is based on a presupposed flow pattern and has no rigorous theoretical foundation. As this is the formula used by SGU, it is of great interest to check its reliability.

In the present investigation results based on Moye´s formula are compared with those obtained by Dagan´s method. It was found that Moye´s formula overestimates the permeability in homogeneous and isotropic formations by 17 %. It may therefore be concluded that Moye´s formula gives a fairly good approximation for most practical purposes.

The numerical simulations worked out in this report are organized in four groups:

(a) The first group deals with homogeneous and isotropic formations.

A first series of runs was caried out with a sealed borehole, in order to compare the results of the present numerical method with those obtained by using Dagan´s (1978) method. The difference between the permeability values calculated by the present numerical method and Dagan´s method is about 5 %.

In a second series of runs an unsealed borehole is considered in order to check the influence of the flow from the formation into the borehole, in the region outside the test section. The effect of the return of flow is often a matter of discussion and controversy.

The present study shows that, if the packer length is 0.30 metres, then about half of the injection rate into the formation is discharged into the borehole. On the other hand, for a given overpressure, the rate of injection is practically unaffected by the flow return. As the injection rate is one of the basic parameters used in the calculation of the permeability, the permeability will be the same as for an ideally sealed borehole.

In the case of an unsealed borehole the permeability calculated by Moye´s formula is overestimated by a factor of 1.4, versus 1.2 in the case of a sealed borehole.

(b) A second group of simulations deals with inhomogeneous isotropic formations.

Two types of inhomogeneities are considered: (i) a region of low permeability near the borehole, and (ii) an inhomogeneity in the vertical section.

The low peremeability region is considered to be caused by a so called "borehole skin" of small thickness. The "skin" effect may be due to mechanical or biological clogging or to a decrease in the fracture width as a result of stress redistribution in connection with the drilling of the borehole. Formulae developed for homogeneous formations, such as Moye´s formula, give values closer to the low permeability of the "skin", than to the real permeability of the formation.

Vertical inhomogeneities are observed in most of the permeability logs performed by SGU. However, the calculated permeability is attributed to the section of investigation of 2 metres, as if it were unaffected by the permeability of the adjacent regions. To evaluate the effect of vertical inhomogeneity, we have investigated a formation with a different permeability in the region between the packers, than in the adjacent regions.

When using Moye´s formula, the permeability of the tested section between the packers may be underestimated as well as overestimated, depending on the permeability of the adjacent region. However, the factor of underestimation or overestimation is relatively moderate (varying from 0.7 to 1.8) even for strongly contrasting permeabilities.

(c) A third group of simulations deals with anisotropic homogeneous formations. Only the effect of anisotropy with the principal directions along the horizontal and the vertical axes is investigated. Anisotropy ratios of 1/10 and 1/100, either of the horizontal to the vertical component or vice versa, are considered.

For a sealed borehole, Moye´s formula gives more or less the value of the horizontal permeability. For an unsealed borehole and lower permeability in the vertical direction, the behaviour is similar to that of a sealed borehole. Higher permeability in the vertical direction affects the calculated permeability only for very large anisotropy ratios (k_v/k_h), of the order of 100.

(d) The last group of simulations deals with discrete media.

Two different settings are considered: (i) a fracture network and (ii) an isolated fracture. The discrete medium considered is one with a relatively high fracture density, which can be treated in principle by the continuum approach.

Good quality rocks are characterized by low fracture density and poor connections between the fractures. In such rocks the section of investigation, between the packers, may be intersected by a single fracture only, poorly connected or completely unconnected to other fractures. The flow through an isolated fracture is two-dimensional, and the flow pattern is thus quite different from the three-dimensional flow pattern presupposed in Moye´s formula.

When investigating a fractured formation one deals with an unknown fracture configuration. In practice, the permeability is calculated by using formulae assuming three-dimensional flow patterns, e.g. Moye´s formula.

Although Moye´s formula is not appropriate for calculating the permeability of an isolated fracture, the results of the present investigation show that it underestimates the permeability of an isolated single fracture only by a factor of about 0.4.

For a fracture with a low permeability region near the borehole the same conclusions as for a homogeneous formation may be drawn.

The results of the present investigation lead to the following conclusions:

- Flow return from the formation into the unsealed region of the borehole outside the packers has no significant influence on the caculated permeability
- For homogeneous and isotropic formations Moye´s formula can be considered a good approximation for most practical purposes.
- Inhomogeneities in the formation in the region outside the packers, have no significant influence on the calculated permeability of the region between the packers.
- In anisotropic formations with the principal directions of the anisotropy along the horizontal and vertical axes, Moye´s formula gives more or less the horizontal component. The vertical component is scarcely reflected at all in the results.
- A low permeability region near the borehole, e.g. due to a "borehole skin" significantly distorts the representative permeability of the formation, when calculated by Moye´s formula. In such cases the permeability of the formation may be underestimated by several orders of magnitude.
- Vertical anisotropy and "borehole skin" have not been sufficiently investigated in the field, which means that their real importance is still unknown. The results of this investigation should draw attention to their relative importance.

On the basis of the present study the following recommendations are given:

- To study methods for testing anisotropic permeability.
- To study the conditions under which "borehole skin" occurs.
- To study methods of testing in which the results are unaffected by the "borehole skin".
- To study methods of field investigations providing information on the type of the medium present, and on the connectivity between the fractures.
- Prior to field tests, to investigate the considered methods by means of a numerical model, such as the one presented here. Such investigations enable the study of the test behaviour and its sensitivity to various parameters, and better planning of the field test considered. With a numerical model one can also obtain numerical solutions valuable for the determination of the investigated field parameters.

NOMENCLATURE

Symbol	Description	Dimension	SI unit
B	length of packer	L	m
c	compressibility	$M^{-1}LT^{2}$	1/Pa
C	constant in Bank's formula	-	-
C_M	constant in Moye's formula	-	-
C_D	constant in Dagan's formula	-	-
D	thickness of aquifer	L	m
D1	distance from water table to the lower packer	L	m
g	acceleration of gravity	LT^{-2}	m/s^2
H	characteristic length of flow domain	L	m
k	permeability	L^2	m^2
L	distance between packers	L	m
P	pressure	$ML^{-1}T^{-2}$	Pa
q	specific discharge	LT^{-1}	m/s
r	radial (horizontal) coordinate	L	m
r_w	borehole radius	L	m
R	radius of low permeability region	L	m
t	time	T	s
z	Cartesian coordinate in the vertical direction	L	m

μ	dynamic viscosity	$ML^{-1}T^{-1}$	Pas
ρ	density	ML^{-3}	kg/m^3
ϕ	porosity	-	-
Φ	potential $\Phi = p + \rho gz$	$ML^{-1}T^{-2}$	Pa
ξ	coordinate function		

<u>subscripts</u>

f	fracture
i	initial value
h	horizontal
v	vertical
d	dimensionless parameter
o	reference value

<u>superscripts</u>

f	fluid
r	rock

1. INTRODUCTION

1.1 General

The conventional method of determining hard rock permeability is the double packer test. This method is extensively used by SGU within the Swedish KBS - project. During such a test, water is injected at constant pressure through the section between the packers. The permeability is calculated using the recorded pressure and the rate of flow at a quasi-steady state. If the test is performed below a certain depth, say below 100 m. and the quantities of the injected water are small, then the position of the phreatic surface remains practically unaffected and may therefore be treated as a fixed boundary.

The flow through pervious formations such as porous media is described mathematically by partial differential equations, using the continuum approach. In these equations, the properties of the formation are represented by continuous functions, defined at each mathematical point. With the continuum approach, one attributes to each mathematical point, the average value of the property in a small surrounding volume. A parameter, e.g. porosity at a point is a smooth and continuous function, only if this volume is larger than a certain size (physical point, representative elementary volume, etc.). Yet in order to be considered "a point", the physical point must be small in comparison with the flow domain.

The continuum approach may be applied to some types of fractured rocks. The question of the size of the physical point relative to the flow domain becomes critical when treating fractured rocks by the continuum approach. It is obvious that the types of fractured rocks amenable to the continuum approach are those with well developed fracture systems. Then the blocks play the role of the solid grains and the fractures play the role of the intergranular voids.

The permeability of the fractured formation depends on the width, spacing and orientation of the individual fractures. In hard rock formations one may expect large variations in the values of these parameters, implying a high degree of inhomogeneity and anisotropy. The permeability logs of the boreholes investigated by SGU show a large variation in the permeability along the boreholes.

In addition to the natural inhomogeneities a region of low permeability may occur near the borehole as a "borehole skin". The "borehole skin" may among others be caused by: drilling with untreated water, which may cause deposition of bacteria, and drilling with water incompatible with the formation or with the formation water, which could lead to changes in the mineral composition of the filling material of the fractures or to the formation of precipitates.

Another reason for a low permeability near the borehole, may be the stress redistribution as a direct consequence of the drilling of the hole. Stress redistribution may change the initial openings of the fractures, changing the fracture permeability. Increase or reduction in the fracture width depends on the initial state of tension or compression of the rock mass. Because of the proportionality of the permeability to the square of the fracture width, small changes in the openings of the fractures may lead to considerable changes in the rock permeability.

When investigating a prospective site for a radioactive repository one looks for rocks with low fracture density and poor connection between the fractures. Hard rock formations may include regions of dense fracturing, for which the assumption of continua holds, as well as regions intersected by a few fractures, with a poor connection between them, for which the continuum approach certainly fails. Stokes (1980) has formulated the conditions under which a fractured rock formation may be treated as an ordinary porous medium. He has also proposed an interesting field test to check if the stated requirements are fulfilled for a particular medium.

The solution of the partial differential equations for a flow problem expresses a relationship between the flow parameters e.g. rate of flow, pressure, etc. and the parameters of the formation such as permeability, porosity, etc. The solution for the properties of the formation as unknown parameters, i.e. the inverse problem, is in general not unique. A unique interpretation of a packer test can be made only for a homogeneous and isotropic formation.

A mathematical solution is possible in most cases, on the basis of oversimplifying assumptions. In the case of the packer test problem, one uses the equations of flow based on the continuum approach. Moreover the existing methods for the determination of the permeability assume that the formation being tested is both homogeneous and isotropic.

The method for the interpretation of packer tests presented by Dagan (1976) appears to be the only one with a sound theoretical basis. However, the formula most commonly used in practice, for instance by SGU in the framework of the Swedish KBS - project, is Moye´s (1967) formula. Both methods assume that the formation being tested is homogeneous and isotropic, and that there is no flow from the formation into the borehole.

Moye´s formula presupposes a specific flow pattern which may be significantly different from the actual one. It therefore lacks theoretical support, and its applicability has not yet been checked. Despite this uncertainty, Moye´s formula is used extensively, mainly because of its simplicity. It was initially used for the exploration of the foundations of dams, tunnels etc., where the accuracy of determining permeability is less crucial than that required for the prospective sites for radioactive waste repositories. Since the travel times of contaminated water particles from the repository to the biosphere is directly related to the permeability, the order of magnitude of this parameter is critical in the selection of the site for a radioactive repository.

In some rocks the tested region between the packers may be intersected by a single fracture only, with poor connection with other fractures. In such a case, the flow takes place in the plane of the fracture i.e. in a two-dimensional space.

When investigating a fractured rock formation it is impossible to obtain a detailed physical description of the medium. As already pointed out, unless the formation is homogeneous and isotropic there does not exist a unique solution to the inverse problem of the packer test. Therefore, in interpreting and calculating the permeability by using the results of a packer test, we are limited to the use of formulae for homogeneous and isotropic formations.

It of great interest to investigate how inhomogeneity, anisotropy and flow from the formation into an unsealed borehole is reflected in the results of a packer test. As the existing solutions do not consider these effects, we have solved the problem by a numerical method. Because Moye´s formula has been used by SGU, we have compared the results obtained by the numerical method with those obtained by Moye´s formula.

1.2 Cases investigated

The following cases have been investigated:

- A homogeneous and isotropic formation. The results of a first series of simulations with a sealed borehole are compared with the results of Dagan´s solution in order to validate the numerical model used for the simulations. In a second series of simulations the influence of flow from the formation into an unsealed borehole has been investigated.
- An inhomogeneous formation. The types of inhomogeneities considered are: (i) a low permeability region near the borehole and (ii) horizontal layers adjacent to the test section.
- An anisotropic formation with the principal directions of anisotropy aligned with the coordinate axes.
- Discrete formations: a fracture network and a single fracture.

1.3 Method of investigation

The present investigation is based on a set of numerical simulations of packer tests performed in synthetic formations, implying that the properties of the considered flow domain are known a priori. The results of the simulated test are used for the calculation of the permeability using various approximate methods, e.g. Moye´s formula and the obtained value is compared with the known permeability.

2. MATHEMATICAL FORMULATION OF THE FLOW PROBLEM

2.1 Basic concepts

The flow through the fractured rock formations in consideration is assumed to obey Darcy´s law. The test section is assumed to be located at such a depth that the boundaries have no influence on the flow in the surroundings of the tested region.

2.2 Basic equations of the flow model

The flow pattern during a packer test is axissymmetric, and the following equation is considered

$$\phi c \frac{\partial \Phi}{\partial t} - \frac{1}{r}\frac{\partial}{\partial r}\left(r \frac{k_r}{\mu}\frac{\partial \Phi}{\partial r}\right) - \frac{\partial}{\partial z}\left(\frac{k_z}{\mu}\frac{\partial \Phi}{\partial z}\right) = 0 \tag{2.1}$$

where ϕ is porosity, c is the total compressibility of water and rock ($c = c^f + c^r$), μ is the dynamic viscosity of the water, k_r and k_z are the permeabilities in the r- and z-direction, respectively, and Φ is the potential, here defined as

$$\Phi = P + \rho g z \tag{2.2}$$

where P is pressure, ρ is the density of the water and g is the acceleration of gravity.

Equation (2.1) is solved with the appropriate boundary and initial conditions (2.8) to (2.12), using the Galerkin finite element method.

2.3 Dimensionless form of equations

In the present analysis the dimensionless form of equation (2.1) for a homogenous and isotropic formation will be considered, and the following dimensionless parameters are defined

$$r_d = \frac{r}{H} \tag{2.3}$$

$$z_d = \frac{z}{H} \tag{2.4}$$

$$t_d = \frac{tk}{\phi c \mu H^2} \tag{2.5}$$

$$\Phi_d = \frac{\Phi_i - \Phi}{\Delta\Phi} \tag{2.6}$$

where H is a characteristic reference length, Φ_i is the initial potential, and $\Delta\Phi$ some potential difference chosen as a reference value.

Using the above definitions, equation (2.1) is written in dimensionless form in the following way

$$\frac{\partial \Phi_d}{\partial t_d} - \frac{1}{r_d}\frac{\partial}{\partial r_d}\left(r_d \frac{\partial \Phi_d}{\partial r_d}\right) - \frac{\partial^2 \Phi_d}{\partial z_d^2} = 0 \tag{2.7}$$

The advantage of using the dimensionless parameters, defined by equations (2.2) to (2.5), is that the results obtained for one set of parameter values may be applicable also to other parameter sets.

2.4 Boundary and initial conditions

The aquifer is assumed initially to be at hydrostatic conditions or at constant potential

$$t = 0 : \quad \Phi = \Phi_i \tag{2.8}$$

In the region between the packers water is injected at constant pressure creating a potential difference $\Delta\Phi$ (Fig. 2.1).

$$r = r_w , \quad -\frac{L}{2} < z < \frac{L}{2} \quad : \quad \Phi = \Phi_i + \Delta\Phi \tag{2.9}$$

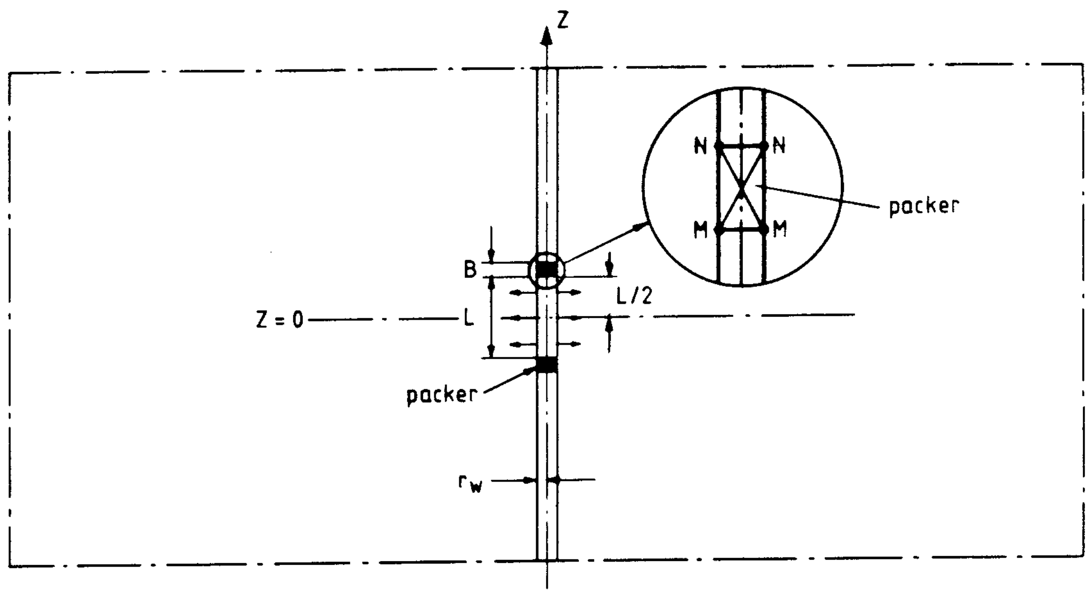

Figure 2.1 Sketch for nomenclature.

Under ideal conditions where the borehole is sealed flow takes place only in the region between the packers.

$$r = r_w \;,\; -(B + \frac{L}{2}) > z > B + \frac{L}{2} \quad : \quad \frac{\partial \Phi}{\partial r} = 0 \tag{2.10}$$

If the borehole is unsealed, then water can flow from the formation into the borehole. Because of the small flow rates from the formation into the borehole, it may be assumed that the water in the borehole is stagnant, i.e. at a constant potential.

$$r = r_w \;,\; -(B + \frac{L}{2}) > z > B + \frac{L}{2} \quad : \quad \Phi = \Phi_i \tag{2.11}$$

where B is the length of the packer.

At infinity the potential remains unaffected and equal in value to the initial potential.

$$r \to \infty \quad : \Phi = \Phi_i \tag{2.12}$$

In the numerical treatment, the flow domain must be given finite dimensions, which should be larger than the radius of influence during the test in order to simulate an infinite flow domain.

Typical flow patterns with unsealed and sealed boreholes are presented in figures 2.2 and 2.3, respectively.

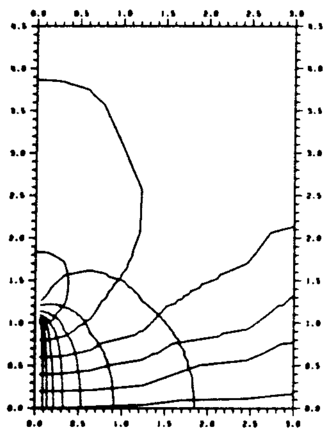

Figure 2.2 Typical flow pattern during a permeability test with an unsealed borehole.

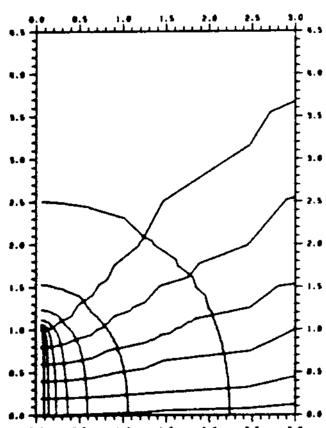

Figure 2.3 Typical flow pattern during a permeability test with a sealed borehole.

2.5 Existing methods

No solutions are known for equation (2.1) under the conditions given by (2.8) to (2.12). Here we will review only Moye´s formula, Bank´s formula and Dagan´s solution. The limitations of these solutions have been discussed in chapter 1.

2.5.1 Moye´s formula

Moye (1967) assumes that the flow is radial in the region near the borehole and spherical in the rest of the flow domain. The transition between radial and spherical flow is assumed to take place at a distance of $r = 0.5\,L$ from the borehole, where L is the distance between the packers.

Combining the steady-state equations for radial and spherical flow, Moye obtains

$$k = (1 + \ln(\frac{L}{2r_w}))\ \mu Q \ /\ 2\pi L \Delta P \tag{2.13}$$

where ΔP is the injection overpressure and Q is the rate of flow.

2.5.2 Bank´s formula

Bank (1972) suggested the following dimensionless form of equation (2.13)

$$Lk\Delta P \ /\ \mu Q = C \tag{2.14}$$

and proposed $C = 1$, instead of $C = (1 + \ln(L/2r_w))/2\pi$ in Moye´s formula. However, the value of C equal to one, as suggested by Bank, has no foundation.

2.5.3 Dagan´s method

Dagan (1977) presented an approximate solution by using the method of distributed sources along the axis of the borehole. The solution, in an integral form is approximated by a finite sum

$$(q_i \mu / k)\ A_{ij} = \Delta P \qquad (i,j = 1,\ldots N) \tag{2.15}$$

where N is the number of intervals into which the length L is divided, k is permeability, q_i is the rate of flow corresponding to the interval i and ΔP is overpressure.

The A_{ij} matrix is given by

$$A_{ij} = (1/4\pi)\ln \prod_{m=-M}^{m=+M} \frac{|a_{ijm}|+a_{ijm} + (r_w^2/2|a_{ijm}|)}{|a_{ijm} - \Delta L|+a_{ijm} - \Delta L+(r_w^2/2|a_{ijm} - \Delta L|)} \times$$

$$\frac{|b_{ijm}|+b_{ijm} + (r_w^2/2|b_{ijm}|)}{|b_{ijm} - \Delta L|+b_{ijm} - \Delta L+(r_w^2/2|b_{ijm} - \Delta L|)} \times$$

$$\frac{|c_{ijm} - \Delta L|+c_{ijm} - \Delta L+(r_w^2/2|c_{ijm} - \Delta L|)}{|c_{ijm}|+c_{ijm} + (r_w^2/2|c_{ijm}|)} \times$$

$$\frac{|d_{ijm} - \Delta L|+d_{ijm} - \Delta L+(r_w^2/2|d_{ijm} - \Delta L|)}{|d_{ijm}|+d_{ijm} + (r_w^2/2|d_{ijm}|)} \qquad (2.16)$$

where M is the number of images and

$$\begin{aligned} a_{ijm} &= (j-i+0.5)\Delta L - 4mD \\ b_{ijm} &= (j+i+0.5)\Delta L - 2D1 + 2(2m + 1)D \\ c_{ijm} &= b_{ijm} - 2D \\ d_{ijm} &= a_{ijm} + 2D \end{aligned} \qquad (2.17)$$

D is the thickness of the aquifer, D1 is the distance from the water table to the lower packer and $\Delta L = L/N$.

For D >1.2 D1 equation (2.16) can be approximated by

$$A_{ij} = (1/4\pi)\ln \frac{|a_{ijo}|+a_{ijo}+(r_w^2/2|a_{ijo}|)}{|a_{ijo}-\Delta L|+a_{ijo}-\Delta L+(r_w^2/2|a_{ijo}-\Delta L|)} \times$$

$$\frac{|c_{ijo}-\Delta L|+c_{ijo}-\Delta L+(r_w^2/2|c_{ijo}-\Delta L|)}{|c_{ijo}|+c_{ijo}+(r_w^2/2|c_{ijo}|)} \qquad (2.18)$$

Dagan´s solution is used for comparison with Moye´s formula as well as for the validation of our numerical method.

2.6 Comparison between Dagan´s method and Moye´s formula.

Dagan calculated the rate of flow by using equations (2.15), (2.17) and (2.18) and presented the results in a dimensionless form (figure 2.4)

$$Q\mu/2\pi\ kL\Delta P = f(L/r_w) \qquad (2.19)$$

for a wide range of L/r_w values.

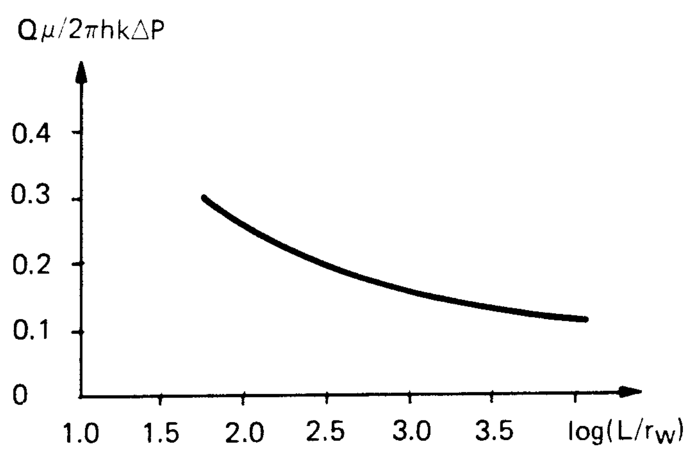

Figure 2.4 Dimensionless rate of flow as a function of L/r_w (after Dagan, 1978).

A comparison of equations (2.19) and (2.14) leads to the conclusion that for Dagan´s solution

$$C = 1/2\pi\ f(L/r_w) \qquad (2.20)$$

The coefficients C in Dagan´s solution and in Moye´s formula are compared for L/r_w values ranging between 35.7 and 179.0 ($\log(L/r_w)$ = 1.55 to 2.25). For a radius of borehole of 0.028 metres, this range corresponds to L values between 1 and 5 metres

We calculated the rates of flow corresponding to this range of values by dividing the length L between the packers into 20 intervals. For L/r_w = 35.7 and L/r_w = 179.0, the dimensionless rates of flow of 0.315 and 0.206, respectively, are obtained. The corresponding C values are 0.505 and 0.77, respectively.

In the same range of L/r_w, the values of C in Moye´s formula are 0.618 and 0.874, respectively. In the first case Moye´s formula overestimates the permeability value by a factor of 1.22, while in the second case by a factor of 1.13. Bank´s C = 1 is too different from the "true" C value and should be excluded.

The value of L/r_w in the SGU double packer tests is 71.4. For this value, the error in Moye´s formula as compared with Dagan´s solution is

$$(C_M - C_D)/C_D = (0.730-0.622)/0.622 = 0.17$$

This means that with the same assumptions as in Dagan´s solution, Moye´s formula overestimates the permeability by 17 %. One may conclude that Moye´s formula can be considered a fairly good approximation for most practical purposes.

2.7 A numerical method.

Because Dagan´s solution and Moye´s formula are limited to homogeneous isotropic formations and sealed boreholes, a more general solution is necessary for the purposes of the present investigation.

A solution to equation (2.1) with the boundary and initial conditions expressed by equations (2.8) to (2.12) is obtained by the Galerkin finite element method.

Equation (2.1) can be written as

$$(\phi c)_r \frac{\partial \Phi}{\partial t} = \frac{\partial}{\partial r}(k_r f_r \frac{\partial \Phi}{\partial r}) + \frac{\partial}{\partial z}(k_z f_r \frac{\partial \Phi}{\partial z}) \qquad (2.21)$$

where

where

$$f_r = \frac{r}{\mu} \quad , \quad (\phi c)_r = r\phi c \tag{2.22}$$

According to Galerkin's method the approximate solution is obtained in the form of a finite sequence

$$\Phi(x_i,t) = \Phi_n(t)\ \xi_n(x_i), \qquad (n=1,2,...N) \tag{2.23}$$

where ξ is a set of N linearly independent coordinate functions and $\Phi_n(t)$ are time-dependent coefficients.

Let the operator $L(\Phi)$ corresponding to (2.21) be defined as follows

$$L(\Phi) = \frac{\partial}{\partial x_i}(k_{ij}\ f_r \frac{\partial \Phi}{\partial x_j}) - (\phi c)_r \frac{\partial \Phi}{\partial t} \tag{2.24}$$

with i=1 for the r-direction, i=2 for the z-direction, and $k_{11}=k_r$, $k_{22}=k_z$ the principal directions of anisotropy.

Galerkin's method requires that $L(\Phi)$ be orthogonal to each of the N coordinate functions, i.e

$$< L(\Phi),\xi_n > = 0 \tag{2.25}$$

The time derivative $\partial\Phi/\partial t$ is calculated as the weighted mean over the entire flow domain (Neuman 1973), i.e.

$$\frac{\partial \Phi}{\partial t} = \int_\Omega \phi c \xi_n \frac{\partial \Phi}{\partial t}\, d\Omega \ / \ (\int_\Omega \phi c \xi_n\, d\Omega), \quad (n=1,2,..\ N) \tag{2.26}$$

Combination of eqs. (2.23) to (2.26) yields

$$\Phi_m \int_\Omega \frac{\partial}{\partial x_i}(k_{ij}\ f_r \frac{\partial \xi_m}{\partial x_j})\, d\Omega -$$

$$- \frac{\partial \Phi_m}{\partial t}\ \delta_{m(n)} \int_\Omega (\phi c)_r \xi_n d\Omega = 0, \quad (m,n = 1,2,...N) \tag{2.27}$$

where (n) indicates that the summation is only over m.

In this study the elements are triangles and the basis functions are linear functions of the coordinates.

A similar equation to (2.27) holds for each individual element with a basis function expressed in local coordinates instead of the global coordinates.

Transforming the first integral of eq. (2.27) by Green's theorem, writing equations similar to (2.27) for each element (e) and assembling, one obtains

$$\sum_{(e)} (k_{ij} \overset{(e)}{f_r} \Phi_m \partial \xi_m / \partial x_i)(\partial \overset{(e)}{\xi_n} / \partial x_i) d\Omega + \sum_{(e)} (\partial \Phi_m / \partial t) \delta_{m(n)} \overset{(e)}{(\phi c)_r} \xi_n d\Omega +$$

$$+ \sum_e \int_\Gamma q_n \xi_n d\Gamma = 0 , \quad (m,n = 1,2,\ldots N), \ (i,j = 1,2) \qquad (2.28)$$

where q is the rate of flow through the side of the element. One assumes that at any time q is constant along each side of the element, k_{ij} and ϕ are considered constant in each element, while f and c vary linearly according to the relations

$$f_r = \overset{(e)}{f_{r\ell}} \xi_\ell , \quad (\phi c)_r = \overset{(e)}{(\phi c)_{r\ell}} \xi_\ell \qquad (2.29)$$

where ℓ represents the corner of the triangle.

The time derivative in eq. (2.27) is expressed as a backward finite difference which leads to a fully implicit scheme. With these assumptions, after some mathematical manipulations, eq. (2.27) can be written in the form

$$\sum_{(e)} (A_{nm}^{k+1} + F_{nm}^{k} / \Delta t_k)_m^{k+1} = q_n + F_{nm}^{k} \Phi_n^{k} / \Delta t_k \qquad (2.30)$$

where

$$A_{nm} = \sum_e f_{r\ell} k_{ij} \int_\Omega \overset{(e)}{\xi} (\partial \overset{(e)}{\xi_n} / \partial x_i)(\partial \overset{(e)}{\xi_m} / \partial x_j) d\Omega \qquad (2.31)$$

$$F = \delta_{m(n)} \Sigma \phi c \xi_n \qquad (2.32)$$

and q is the rate of flow at the nodal point. Equation (2.32) represents a linear set of algebraic equations which is solved under the initial and the boundary conditions expressed by equations (2.8) to (2.12).

3. NUMERICAL SOLUTIONS

The permeability of a hard rock formation is calculated by formulae based on the assumptions of homogeneity and isotropy in spite of the fact that actual formations are inhomogeneous and anisotropic. In addition, the existing solutions do not account for the flow from the formation into the unsealed region of the borehole, outside the packers.

The purpose of the present simulations is to check the error in the calculated permeability of some models of inhomogeneous and anisotropic formations when using any of the above formulae. The simulations presented have been carried out using a computer program based on the numerical method of solution. In this method the flow domain is discretized into triangular elements.

The calculations have been carried out for a sealed as well as an unsealed borehole. In both cases point M in figure (2.1) of the flow domain is a singular point with a theoretically infinite velocity. If the borehole is unsealed, then also point N is singular. This calls for some caution in the discretization of the flow domain in the immediate neighbourhood of these points. The sensitivity of the solutions with respect to the degree of refinement of the mesh has been checked in order to determine the required refinement of the element mesh.

3.1 Input parameters

Distance between the packers (L)	2 m
Packer length (B)	0.3 m
Borehole radius (r_w)	0.028 m
Water density (ρ)	1000 kg/m^3
Dynamic viscosity of water (μ)	0.001 Pas
Total compressibility (c)	10^{-10} Pa^{-1}
Overpressure (P)	4×10^{5} Pa

The numerical examples have been carried out for various permeabilities of the flow domain. The results of the calculations, presented in tables (3.1) to (3.12), give the following information:

- Value of true permeability (input)

- Overpressure (input)

- Rate of flow into the formation (output).
- Rate of flow out of the formation, into the unsealed part of the borehole (output).
- Calculated peremability by Moye's formula (equation 2.13)
- The C value in equation (2.14) calculated by using the calculated rate of flow into the formation.
- Value of C coefficient in Moye's formula (equation 2.13). $C = (1 + (\ln(L/2r_w))/2\pi$
- Ratio of C coefficient in Moye's formula to the true value of coefficient C. This ratio equals the ratio of Moye's permeability to the true permeability of the formation.

3.2 Homogeneous isotropic formation

The numerical method is compared with Dagan's analytical solution for a homogeneous and isotropic formation and sealed borehole. Several simulations have been performed with different permeabilities and different injection pressures. The results are presented in table 3.1.

The C value in equation (2.14) obtained by Dagan's solution for a borehole radius of 0.028 metres and a length between the packers of 2 metres ($L/r_w = 71.4$) is 0.622 (paragraph 2.6). The dimensionless rate of flow calculated with the numerical solution is C = 0.590 (table 3.1).

When compared with Dagan's solution, the relative error in the C value is

$$(C_D - C)/C_D = (0.622-0.590)/0.622 = 0.0515$$

or about 5.2 %. One may conclude from the above results that the agreement between the numerical and the analytical solutions is quite good.

Moye's formula overestimates the permeability by a factor of 1.23 (table 3.1).

In a second series of simulations, the borehole is considered to be unsealed. The flow pattern with an unsealed borehole differs significantly from the flow pattern of a domain bounded by an impervious borehole (figures 3.1 and 3.2). With an unsealed borehole, about half of the injected flow rate escapes the formation into the unsealed region of the borehole (table 3.2). On the other hand, there is only a small increase in the rate of injection into the formation, in comparison with a sealed borehole.

One may conclude that changes in the boundary conditions along the borehole outside the packers do not cause a corresponding change in the injected rate of flow, and that one may therefore calculate the permeability of an unsealed borehole by formulae suitable for a sealed borehole.

For an unsealed borehole Moye´s formula overestimates the permeability by a factor of 1.38, as versus 1.23 with a sealed borehole (table 3.2). The above calculations have been performed on the assumption that the water level in the borehole does not vary as a result of the flow return. Actually, the water level in the borehole does rise, causing a decrease in the flow return.

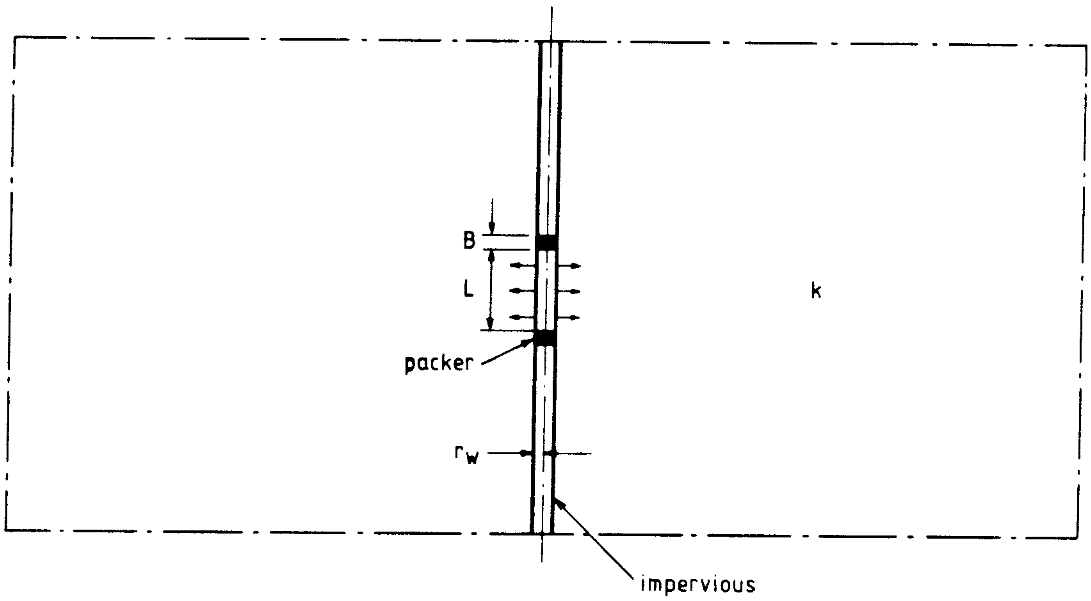

Figure 3.1 Schematic representation of a packer test in a homogeneous and isotropic formation. The borehole is sealed.

Table 3.1 Results of a numerical simulation of packer tests in a homogeneous and isotropic formation. The borehole is sealed.

true k m^2	over pressure Pa	flow rate into the formation m^3/s	flow rate out of the formation m^3/s	Moye's formula k m^2	true C (input)	Moye's C (C_M)	$\frac{C_M}{C}$
10^{-14}	$4 \cdot 10^5$	$1.35 \cdot 10^{-5}$	-	$1.23 \cdot 10^{-14}$	0.590	0.730	1.23
10^{-14}	$2 \cdot 10^5$	$6.75 \cdot 10^{-6}$	-	$1.23 \cdot 10^{-14}$	0.590	0.730	1.23
10^{-13}	$4 \cdot 10^5$	$1.35 \cdot 10^{-5}$	-	$1.23 \cdot 10^{-13}$	0.590	0.730	1.23
10^{-12}	$4 \cdot 10^5$	$1.35 \cdot 10^{-3}$	-	$1.23 \cdot 10^{-12}$	0.590	0.730	1.23

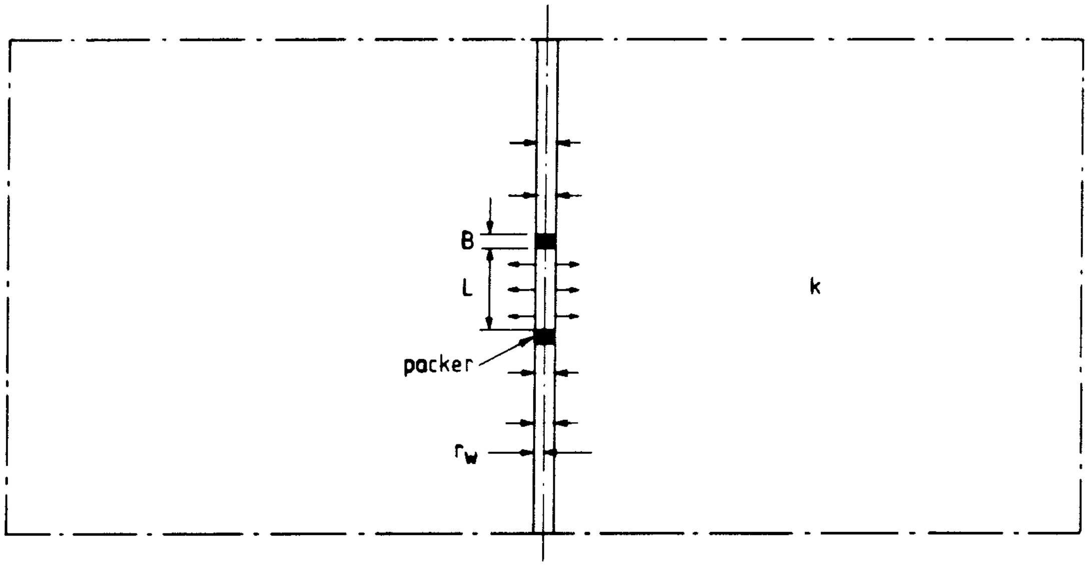

Figure 3.2 Schematic representation of a packer test in a homogeneous and isotropic formation. The borehole is unsealed.

Table 3.2 Results of a numerical simulation of packer tests in a homogeneous and isotropic formation. The borehole is unsealed.

true k	over pressure	flow rate into the formation	flow rate out of the formation	Moye's formula k	true C (input)	Moye's C (C_M)	$\frac{C_M}{C}$
m^2	Pa	m^3/s	m^3/s	m^2			
10^{-14}	$4 \cdot 10^5$	$1.50 \cdot 10^{-5}$	$7.45 \cdot 10^{-6}$	$1.37 \cdot 10^{-14}$	0.53	0.730	1.38
10^{-13}	$4 \cdot 10^5$	$1.50 \cdot 10^{-4}$	$8.55 \cdot 10^{-5}$	$1.37 \cdot 10^{-13}$	0.53	0.730	1.38
10^{-12}	$4 \cdot 10^5$	$1.50 \cdot 10^{-3}$	$1.20 \cdot 10^{-3}$	$1.37 \cdot 10^{-12}$	0.53	0.730	1.38

3.3 Inhomogeneous isotropic formation

3.3.1 Low permeability near the borehole

The purpose of the following simulations is to check the influence of a local decrease in the rock permeability near the borehole. This decrease is considered to be a side effect resulting from mechanical or biological clogging, stress redistribution as a result of the drilling, etc.

The conditions under which a "borehole skin" occurs have not yet been sufficiently studied. One of the purposes of the present investigation is to draw attention on the effect of a "borehole skin" on the calculated permeability.

When the permeability of an inhomogeneous formation is calculated by formulae for homogeneous formations, e.g. Moye´s formula one obtains an equivalent permeability. In the present case the equivalent permeability is that of a series of two permeabilties and as is well known, the small permeability has a strong influence on the equivalent permeability. In such a case it appears that Moye´s formula underestimates the true permeability of the formation. This is demonstrated by the results presented in tables 3.3 and 3.4.

The representative permeability of the rock is considered 10^{-12} m^2 in all simulations but one, in which it is assumed to be 10^{-14} m^2. In the region nearest to the borehole different permeabilities are considered in the range of 10^{-15} m^2 to 10^{-13} m^2. The outer boundary region of low permeability are taken, in the different simulations, in the range between 0.11 to 0.63 metres. The net thickness, obtained by substracting the radius of the well, is 0.082 to 0.602 metres.

Moye´s formula leads to the following results: in case of high contrast in skin permeability and formation permeability of 10^{-15} m^2 and 10^{-12} m^2 one obtains an equivalent permeability of the same order of magnitude as the lower permeability, even for the small thickness of 0.082.

In cases of a skin permeability of 10^{-14} m^2 and rock permeability of 10^{-12} m^2, one obtains values between 0.36×10^{-13} m^2 and 0.21×10^{-13} m^2, depending on the extent of the low permeability region.

In the case of a low permeability region of 10^{-13} m^2 and rock permeability of 10^{-12} m^2, one obtains values between 0.31×10^{-12} m^2 and 0.20×10^{-14} m^2.

The above conclusions apply also for a sealed borehole, which means that the results do not depend on the length of the packers.

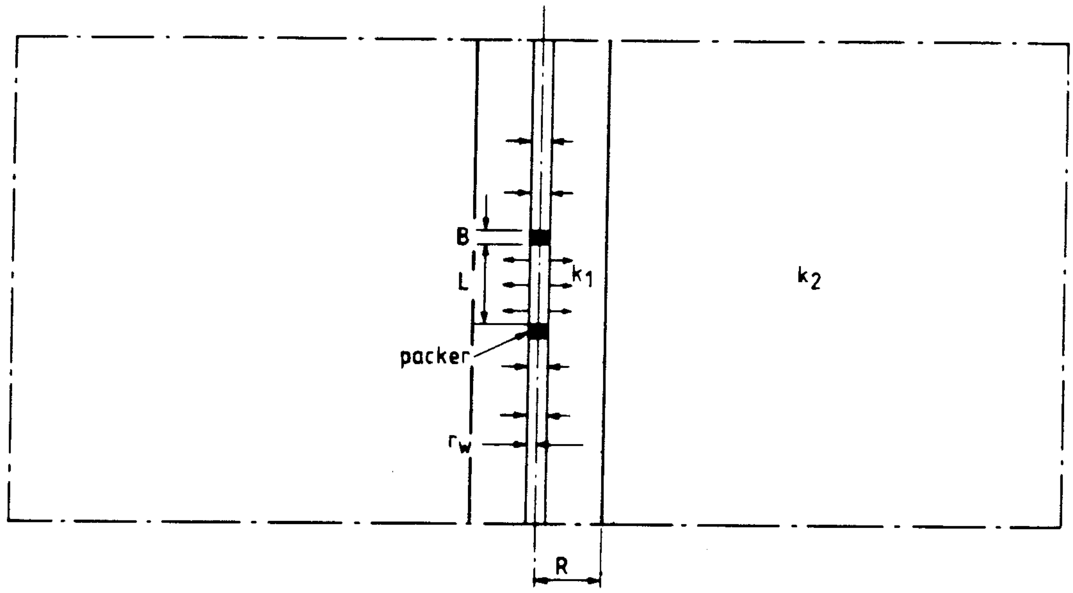

Figure 3.3 Schematic representation of a packer test with permeability of the region near the borehole lower than in the remaining part of the rock formation. The borehole is unsealed.

Table 3.3 Results of numerical simulations of packer tests with permeability in the region near the borehole lower than in the remaining part of the rock formation. The borehole is unsealed.

R	k_1	k_2	over pressure	flow rate into the formation	flow rate out of the formation	Moye's formula k
m	m^2	m^2	Pa	m^3/s	m^3/s	m^2
0.11	10^{-15}	10^{-12}	$4\cdot10^{5}$	$3.98\cdot10^{-6}$	$1.40\cdot10^{-7}$	$0.36\cdot10^{-14}$
0.11	10^{-14}	10^{-12}	$4\cdot10^{5}$	$3.92\cdot10^{-5}$	$6.50\cdot10^{-6}$	$0.36\cdot10^{-13}$
0.11	10^{-13}	10^{-12}	$4\cdot10^{5}$	$3.35\cdot10^{-4}$	$3.02\cdot10^{-4}$	$0.31\cdot10^{-12}$
0.18	10^{-15}	10^{-12}	$4\cdot10^{5}$	$2.96\cdot10^{-6}$	$5.60\cdot10^{-8}$	$0.27\cdot10^{-14}$
0.18	10^{-14}	10^{-12}	$4\cdot10^{5}$	$2.92\cdot10^{-5}$	$2.60\cdot10^{-6}$	$0.27\cdot10^{-13}$
0.18	10^{-13}	10^{-12}	$4\cdot10^{5}$	$2.65\cdot10^{-4}$	$2.0\ \cdot10^{-4}$	$0.24\cdot10^{-12}$
0.33	10^{-15}	10^{-12}	$4\cdot10^{5}$	$2.28\cdot10^{-6}$	$4.40\cdot10^{-8}$	$0.21\cdot10^{-14}$
0.33	10^{-14}	10^{-12}	$4\cdot10^{5}$	$2.27\cdot10^{-5}$	$2.60\cdot10^{-6}$	$0.21\cdot10^{-13}$
0.33	10^{-13}	10^{-12}	$4\cdot10^{5}$	$2.14\cdot10^{-4}$	$1.27\cdot10^{-4}$	$0.20\cdot10^{-12}$
0.63	10^{-15}	10^{-12}	$4\cdot10^{5}$	$1.88\cdot10^{-6}$	$7.52\cdot10^{-8}$	$0.17\cdot10^{-14}$
0.63	10^{-15}	10^{-14}	$4\cdot10^{5}$	$1.82\cdot10^{-6}$	$2.69\cdot10^{-7}$	$0.17\cdot10^{-14}$

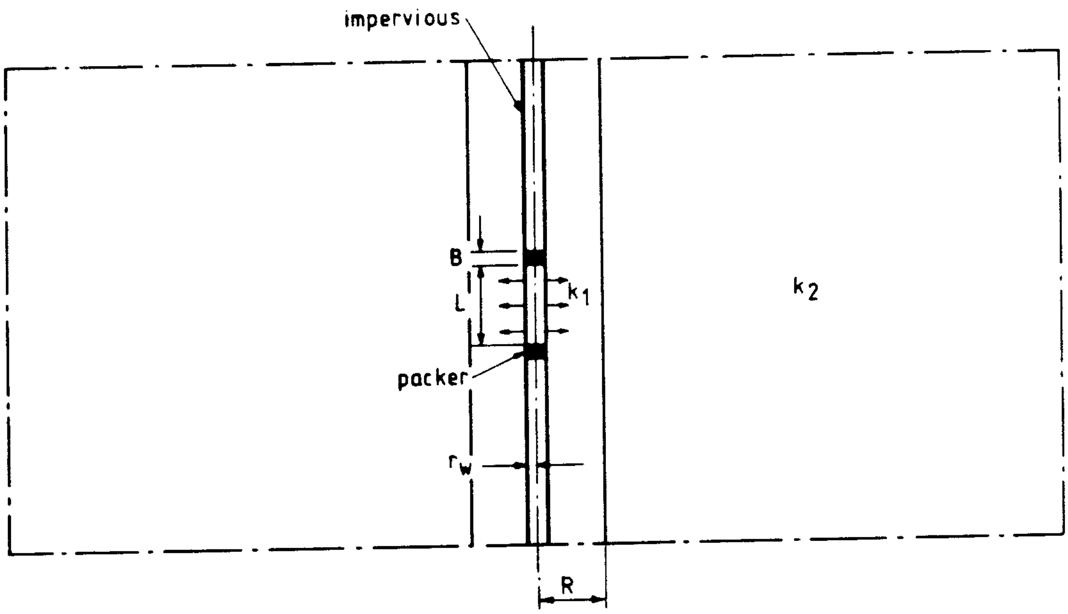

Figure 3.4 Schematic representation of a packer test with permeability in the region near the borehole lower than in the remaining part of the rock formation. The borehole is sealed.

Table 3.4 Results of numerical simulations of packer tests with permeability in the region near the borehole lower than in the remaining part of the rock formation. The borehole is sealed.

R	k_1	k_2	over pressure	flow rate into the formation	flow rate out of the formation	Moye's formula k
m	m^2	m^2	Pa	m^3/s	m^3/s	m^2
0.11	10^{-15}	10^{-12}	$4 \cdot 10^5$	$3.99 \cdot 10^{-6}$	-	$0.36 \cdot 10^{-14}$
0.11	10^{-14}	10^{-12}	$4 \cdot 10^5$	$3.92 \cdot 10^{-5}$	-	$0.36 \cdot 10^{-13}$
0.11	10^{-13}	10^{-12}	$4 \cdot 10^5$	$3.35 \cdot 10^{-4}$	-	$0.31 \cdot 10^{-12}$

3.3.2 Vertical inhomogeneity

Scanning of borehole permeability logs (Carlsson et al., 1980) shows large inhomogeneities in the vertical direction. The calculated permeability is attributed to the region between the packers alone. It may, however, have been influenced by a different permeability in the adjacent regions.

In this section we check the influence of inhomogeneities adjacent to the section of injection on the calculated permeability. The region between the packers is assumed homogeneous (figure 3.5), while the adjacent regions are assumed to be of different permeability. The input data and the results of the simulations with a sealed and an usealed borehole are presented in tables 3.5 and 3.6, respectively.

Moye´s formula, underestimates the permeability of the region between the packers, or overestimates, depending on the permeability of the adjacent region. However, the factor of underestimation or overestimation is relatively moderate even for large contrasts in permeability.

Lower permeability regions adjacent to the section of injection lead to an underestimation of the actual permeability by a factor of about 0.92.

Layers of higher permeability adjacent to the section of injection lead to an overestimation of the actual permeability by a factor of about 1.8.

As for homogeneous formations, flow from the formation into the borehole has no significant effect on the injection rates and on the respective calculated permeabilities.

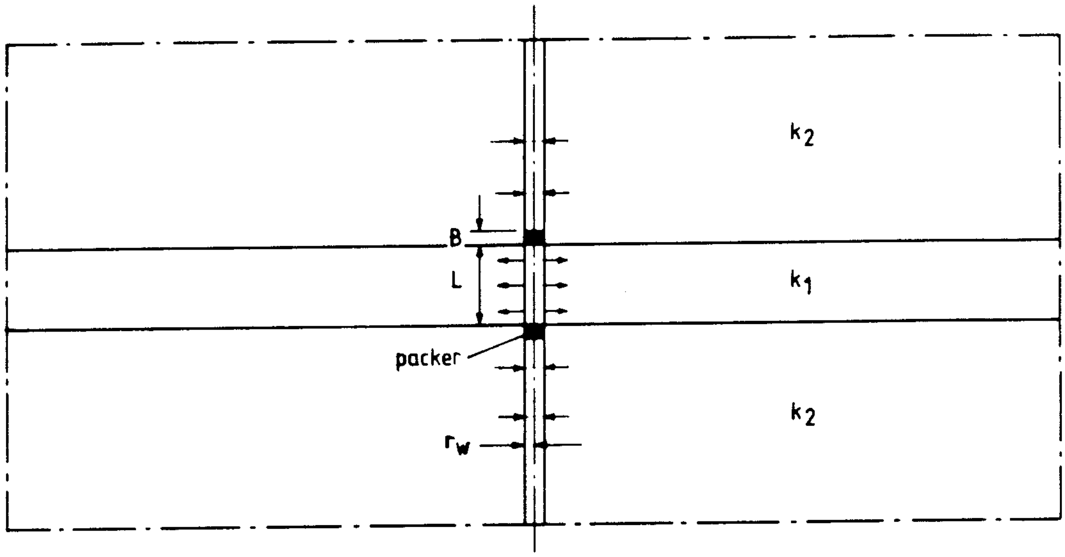

Figure 3.5 Schematic representation of packer tests in formations with a vertical inhomogeneity. The borehole is unsealed.

Table 3.5 Results of numerical simulations of packer tests in formations with a verical inhomogeneity. The borehole is unsealed.

k_1	k_2	over pressure	flow rate into the formation	flow rate out of the formation	Moye's formula k	true (input) C_{k1}	Moye's C	$\frac{C_M}{C_{k1}}$
m^2	m^2	Pa	m^3/s	m^3/s	m^2		(C_M)	
10^{-14}	10^{-15}	$4 \cdot 10^5$	$1.01 \cdot 10^{-5}$	$2.09 \cdot 10^{-6}$	$0.919 \cdot 10^{-14}$	0.790	0.73	0.92
10^{-14}	10^{-13}	$4 \cdot 10^5$	$1.89 \cdot 10^{-5}$	$1.21 \cdot 10^{-5}$	$1.720 \cdot 10^{-14}$	0.420	0.73	1.74
10^{-14}	10^{-12}	$4 \cdot 10^5$	$1.98 \cdot 10^{-5}$	$1.66 \cdot 10^{-5}$	$1.800 \cdot 10^{-14}$	0.400	0.73	1.83

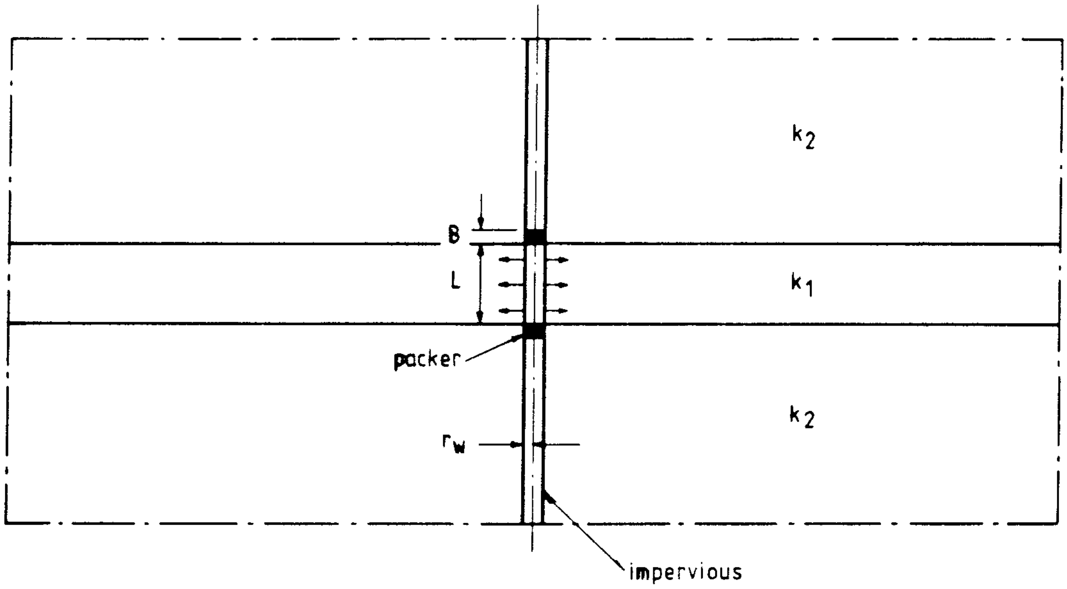

Figure 3.6 Schematic representation of packer tests in formations with a vertical inhomogeneity. The borehole is sealed.

Table 3.6 Results of numerical simulations of packer tests in formations with a vertical inhomogeneity. The borehole is sealed.

k_1	k_2	over pressure	flow rate into the formation	flow rate out of the formation	Moye's formula k	true (input) C_{k_1}	Moye's C	$\frac{C_M}{C_{k1}}$
m^2	m^2	Pa	m^3/s	m^3/s	m^2		(C_M)	
10^{-14}	10^{-15}	$4 \cdot 10^5$	$9.81 \cdot 10^{-6}$	-	$0.89 \cdot 10^{-14}$	0.82	0.73	0.89
10^{-14}	10^{-16}	$4 \cdot 10^5$	$8.26 \cdot 10^{-6}$	-	$0.75 \cdot 10^{-14}$	0.97	0.73	0.75
10^{-14}	10^{-12}	$4 \cdot 10^5$	$1.95 \cdot 10^{-5}$	-	$1.78 \cdot 10^{-14}$	0.410	0.73	1.78
10^{-14}	10^{-13}	$4 \cdot 10^5$	$1.86 \cdot 10^{-5}$	-	$1.69 \cdot 10^{-14}$	0.430	0.73	1.70

3.4 Anisotropic formations

The effect of anisotropy is checked for a formation with principal directions of anisotropy along the horizontal and the vertical axes. Anisotropy ratios of 1/10 and 1/100, of the horizontal component to the vertical or vice versa, are considered.

The settings for an unsealed and sealed borehole are schematically displayed in figures 3.7 and 3.8, respectively. The results of the calculations, presented in tables 3.7 and 3.8 respectively, can be summarized as follows:

For a sealed borehole Moye´s formula gives more or less the value of the horizontal permeability. In cases of higher permeability in the vertical direction, with k_v/k_h between 10 and 100, the horizontal permeability is overestimated by a factor of 2.08 to 4.53.

For lower permeabilities in the vertical direction, with k_v/k_h in the range of 1/10 to 1/100, Moye´s formula gives approximately the horizontal permeability.

For an unsealed borehole in a formation with a lower permeability in the vertical direction than in the horizontal, the behaviour is similar to that of a sealed borehole, i.e. Moye´s formula gives approximately the value of the horizontal permeability.

For higher permeability in the vertical direction than in the horizontal, with a ratio k_v/k_h = 10 the horizontal permeability overestimated by a factor of 1.85, while for a ratio k_v/k_h = 100 the geometrical mean is amplified by a factor of about 3.02.

Comparing the above to the performance of Moye´s formula in isotropic formations, one may conclude that only in cases of very high ratios of vertical to horizontal permeabilities is there a mild influence on the results, while in general one obtains more or less the value of the horizontal permeability.

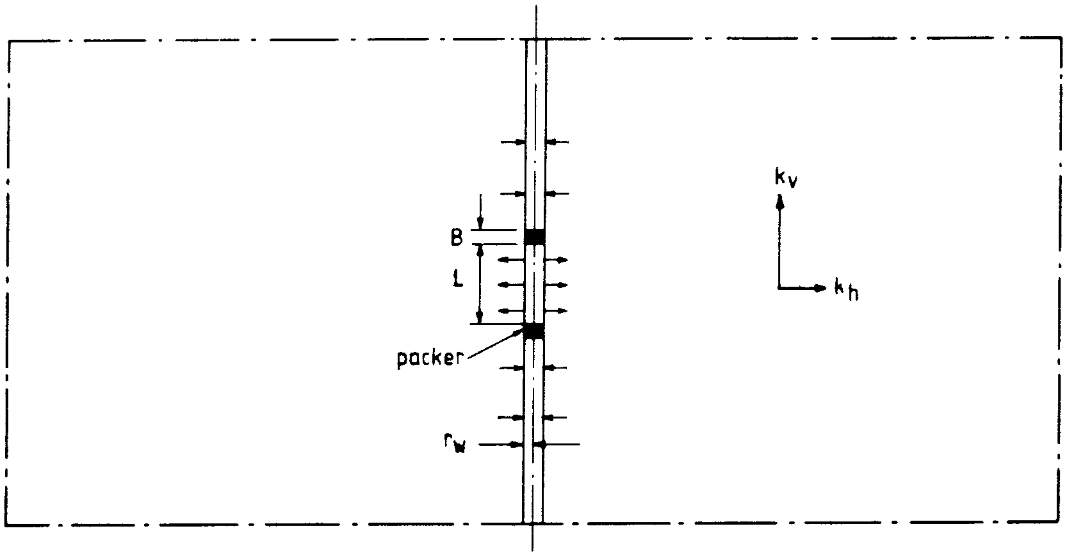

Figure 3.7 Schematic representation of a packer test in an anisotropic formations. The borehole is unsealed.

Table 3.7 Results of numerical simulations of packer tests in an anisotropic formations. The borehole is unsealed.

k_h	k_v	over pressure	flow rate into the formation	flow rate out of the formation	Moye's formula k
m^2	m^2	Pa	m^3/s	m^3/s	m^2
10^{-14}	10^{-13}	$4 \cdot 10^5$	$2.29 \cdot 10^{-5}$	$1.53 \cdot 10^{-5}$	$2.08 \cdot 10^{-14}$
10^{-14}	10^{-12}	$4 \cdot 10^5$	$4.98 \cdot 10^{-5}$	$4.21 \cdot 10^{-5}$	$4.53 \cdot 10^{-14}$
10^{-13}	10^{-14}	$4 \cdot 10^5$	$1.21 \cdot 10^{-4}$	$4.89 \cdot 10^{-5}$	$1.11\ 10^{-13}$
10^{-12}	10^{-14}	$4 \cdot 10^5$	$8.96 \cdot 10^{-4}$	$6.21 \cdot 10^{-4}$	$0.82\ 10^{-12}$

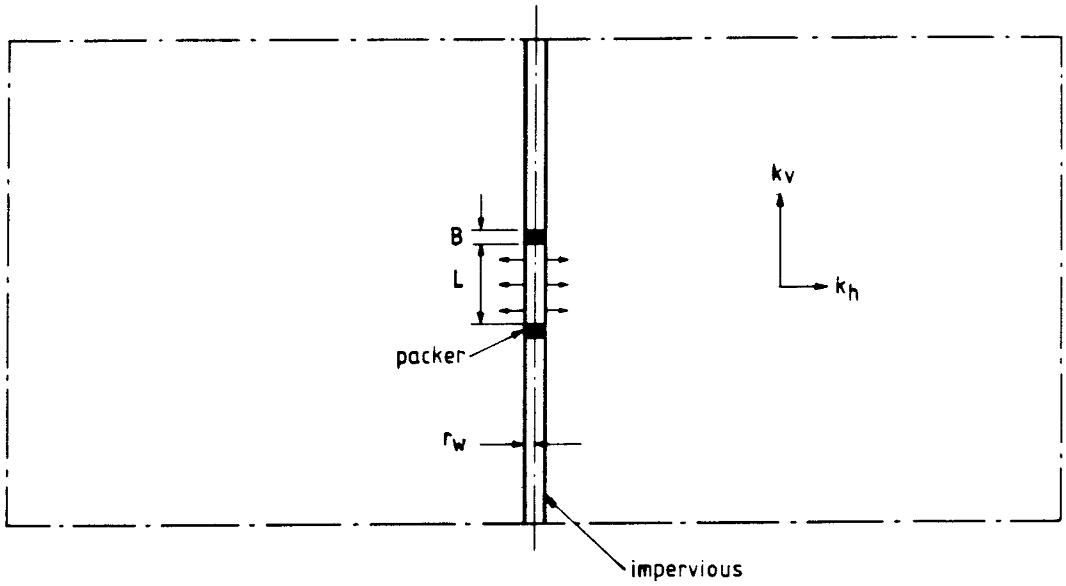

Figure 3.8 Schematic representation of a packer test in anisotropic formation. The borehole is sealed.

Table 3.8 Results of numerical simulations of packer tests in anisotropic formation. The borehole is sealed.

k_h	k_v	over pressure	flow rate into the formation	flow rate out of the formation	Moye's formula k
m^2	m^2	Pa	m^3/s	m^3/s	m^2
10^{-14}	10^{-13}	$4 \cdot 10^5$	$2.03 \cdot 10^{-5}$	-	$1.85 \cdot 10^{-14}$
10^{-14}	10^{-12}	$4 \cdot 10^5$	$3.32 \cdot 10^{-5}$	-	$3.02 \cdot 10^{-14}$
10^{-13}	10^{-14}	$4 \cdot 10^5$	$1.09 \cdot 10^{-4}$	-	$0.99 \cdot 10^{-13}$
10^{-12}	10^{-14}	$4 \cdot 10^5$	$8.76 \cdot 10^{-4}$	-	$0.80 \cdot 10^{-12}$

3.5 Discrete media

This section deals with the simulation of packer tests in discrete media. We consider an interconnected fracture network, which can be treated, in principle, by the continuum approach, and an isolated fracture. The isolated fracture can be regarded also as belonging to a system of unconnected fractures having the same properties.

3.5.1 Fracture network

The various settings used in the calculations are displayed schematically in figures 3.9 to 3.11. The investigated medium is assumed to be an ordered system of fractures and impervious blocks. The blocks have the form of hollow cylinders with a height of 2 metres and a difference between the inner and outer radia of 2 metres. The fracture width is 0.0002 metres. The section between the packers is assumed to be intercepted by one fracture only. The permeability of the continumm equivalent, presented in tables 3.9 to 3.12, is taken as an average over the investigated length of 2 m. between the packers.

First we consider a fracture network with isotropic permeability. Packer tests have been simulated in formations with an unsealed as well as with a sealed borehole. The results of the calculations are presented in tables 3.9 and 3.10.

In a second series of simulations, we consider an anisotropic network with vertical fracture permeability 10 times higher than the horizontal. The borehole is assumed to be unsealed. The input data and results of the calculations are presented in figure 3.11.

The permeabilities calculated by Moye´s formula gives slightly higher overestimated values than the homogeneous equivalent. As in the homogeneous case, higher vertical permeability values (ratios of vertical to horizontal by 10 to 1) are not reflected in the permeabilities calculated by Moye´s formula.

3.5.1 A single fracture

We consider a single homogeneous fracture, as well as an inhomogeneous one, with low permeability near the borehole. The fracture width is taken as 0.0002 metres. The representative intrinsic permeability of the homogeneous fracture is 10^{-10} m^2 (as the fracture may be partially filled, its permeability is not necessarily correlated to the fracture width). The permeabilities of the continuum equivalent (an average over the length of 2 m.) is 10^{-14} m^2.

The flow through a fracture is two-dimensional and thus differs significantly from the axisymmetrical flow on which Moye´s formula is based. Calculations using Moye´s formula, therefore seem to be of questionable value. On the other hand, the structure of the formation we deal with (single fracture or interconected network) is unknown. Therefore, in practice we will always use formulae for axisymmetric flow. It is interesting to find out what is the error in the calculation of permeability caused by using the inappropriate Moye´s formula.

The rate of flow through a horizontal homogeneous fracture can be calculated using Van Everdingen and Hurst (1949) solution (see Appendix). The results of the calculations for a test of ten minutes duration, presented in table 3.12, show that Moye´s formula underestimates the true permeability of the formation by a factor of only about 0.4. This conclusion should be restricted to the results obtained with the considered data set.

A second series of simulations is conducted with a low permability region near the borehole. From the results presented in table 3.13 and obtained with the numerical model, one may draw similar conclusions as for a continuum (section 3.3.1), i.e. Moyes' formula gives permeabilities closer to the skin region, of low permeability.

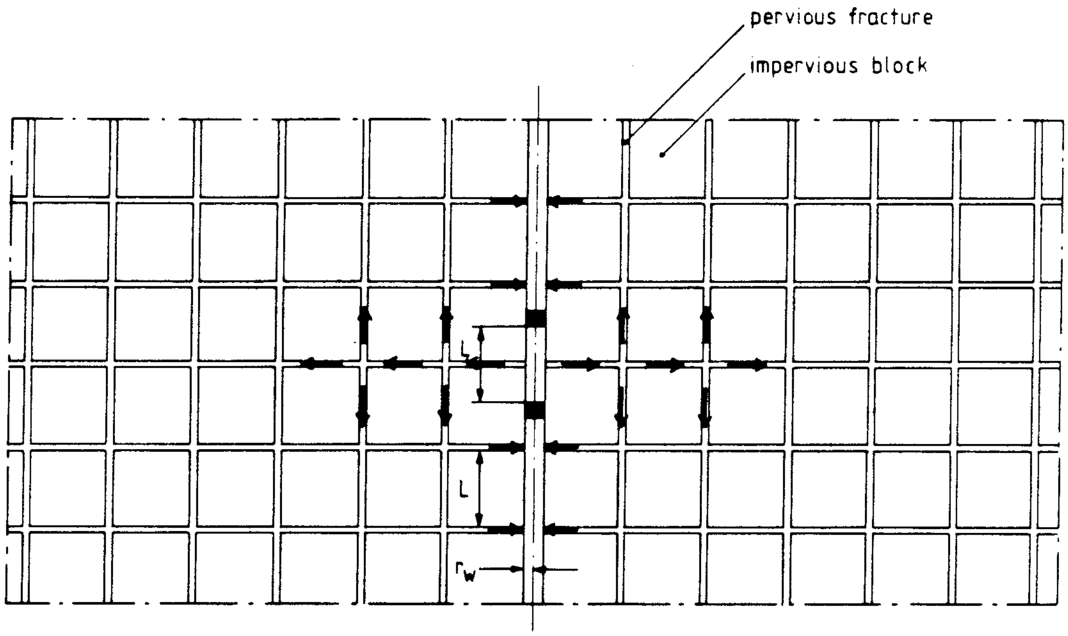

Figure 3.9 Schematic representation of packer tests in a discrete medium. The borehole is unsealed.

Table 3.9 Results of numerical simulations of packer tests in a discrete medium. The borehole is unsealed.

true k	over pressure	flow rate into the formation	flow rate out of the formation	Moye's formula k	true (input) C	Moye's C (C_M)	$\frac{C_M}{C}$
m^2	Pa	m^3/s	m^3/s	m^2			
10^{-14}	$4 \cdot 10^5$	$1.947 \cdot 10^{-5}$	$9.739 \cdot 10^{-6}$	$1.78 \cdot 10^{-14}$	0.41	0.730	1.78

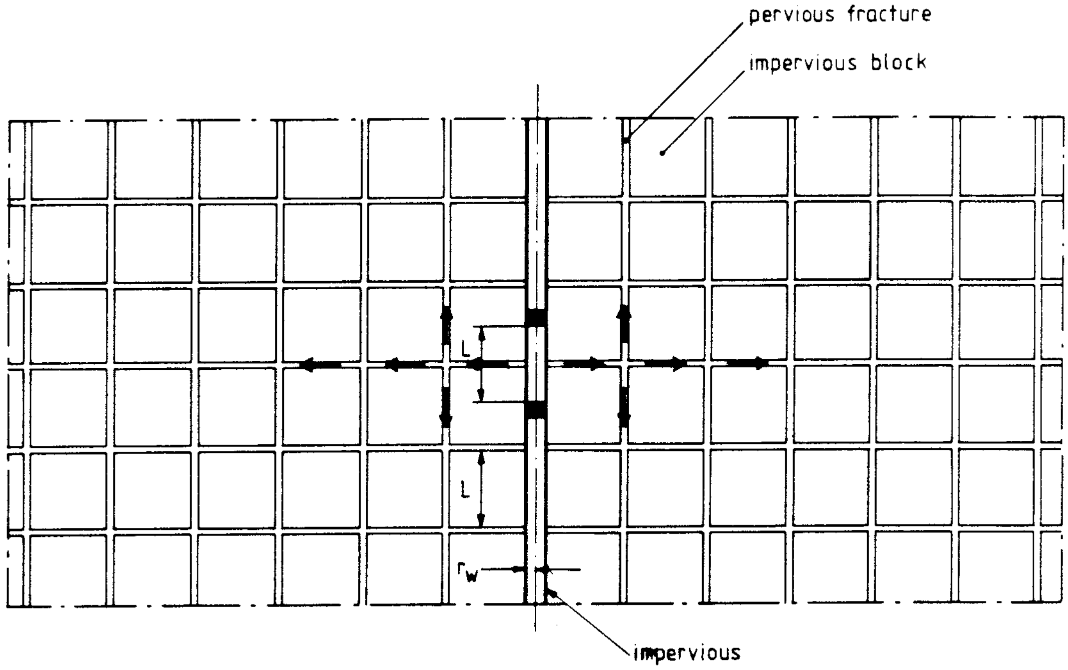

Figure 3.10 Schematic representation of packer test in a discrete medium. The borehole is sealed.

Table 3.10 Results of numerical simulations of packer tests in a discrete medium. The borehole is sealed.

true k	over pressure	flow rate into the formation	flow rate out of the formation	Moye's formula k	true (input) C	Moye's C	$\frac{C_M}{C}$
m^2	Pa	m^3/s	m^3/s	m^2		(C_M)	
10^{-14}	$4 \cdot 10^5$	$1.886 \cdot 10^{-5}$	-	$1.08 \cdot 10^{-14}$	0.42	0.730	1.74

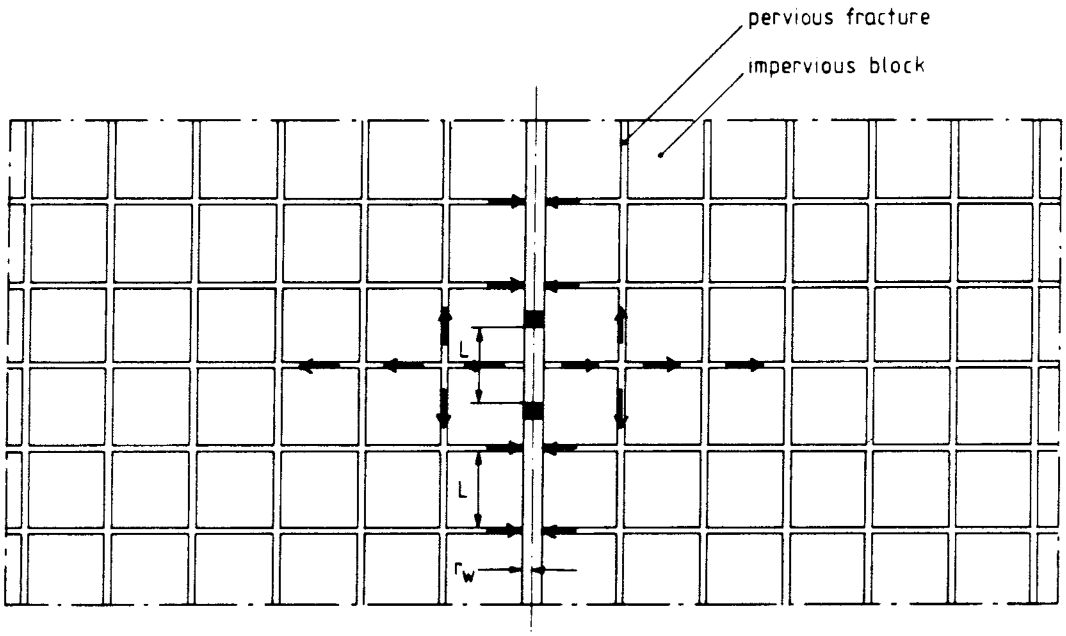

Figure 3.11 Schematic representation of packer test in a discrete medium. The borehole is unsealed. The permeability of the vertical fractures is 10 times higher than that of the horizontal ones.

Table 3.11 Results of numerical simulations of packer tests in a discrete medium. The borehole is unsealed. The permeability in the vertical fractures is 10 times higher than that of the horizontal ones.

k_h	k_v	over pressure	flow rate into the formation	flow rate out of the formation	Moye's formula k
m^2	m^2	Pa	m^3/s	m^3/s	m^2
10^{-14}	10^{-13}	$4 \cdot 10^5$	$2.33 \cdot 10^{-5}$	$1.62 \cdot 10^{-5}$	$2.12 \cdot 10^{-14}$

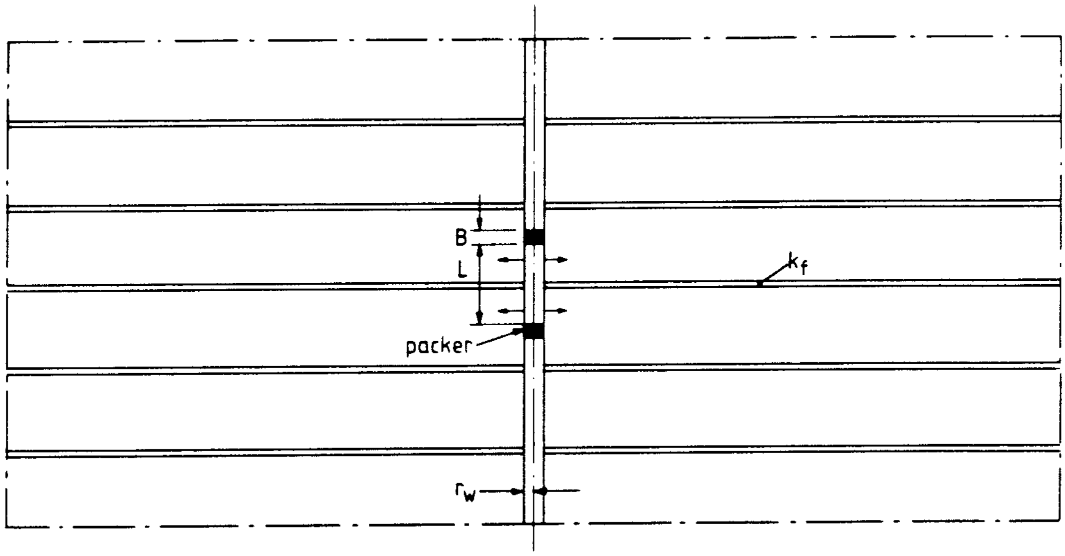

Figure 3.12 Schematic representation of a packer test in a discrete medium with horizontal fractures only.

Table 3.12 Results of numerical simulations of packer tests in a a discrete medium with horizontal fractures only.

true k	over pressure	flow rate into the formation	flow rate out of the formation	Moye's formula k	observations
m^2	Pa	m^3/s	m^3/s	m^2	
10^{-14}	$4 \cdot 10^5$	$4.55 \cdot 10^{-6}$	-	$0.414 \cdot 10^{-14}$	rate of flow after 10 min.

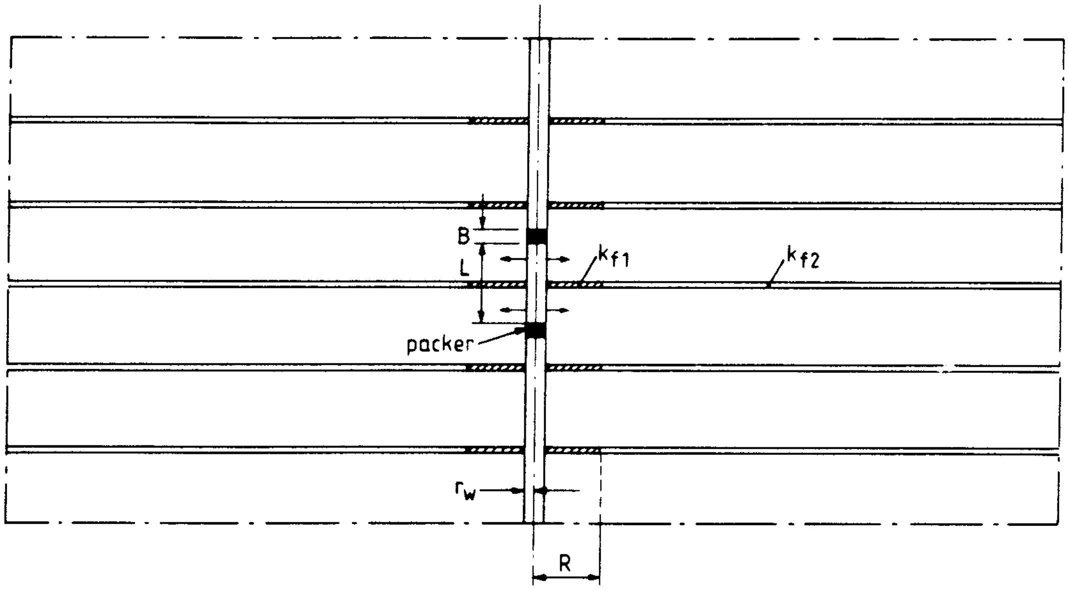

Figure 3.13 Schematic representation of a packer test in a discrete medium with horizontal fractures only. The permeability close to the borehole is lower than elsewhere.

Table 3.13 Results of numerical simulations of packer tests in a discrete medium with horizontal fractures only. The permeability close to the borehole is lower than elsewhere.

R	k_1	k_2	over pressure	flow rate into the formation	flow rate out of the formation	Moye's formula k
m	m^2	m^2	Pa	m^3/s	m^3/s	m^2
0.11	10^{-15}	10^{-12}	$4\cdot10^5$	$4.65\cdot10^{-6}$	-	$0.423\cdot10^{-14}$
0.11	10^{-14}	10^{-12}	$4\cdot10^5$	$4.31\cdot10^{-5}$	-	$0.392\cdot10^{-13}$
0.11	10^{-13}	10^{-12}	$4\cdot10^5$	$2.47\cdot10^{-4}$	-	$0.225\cdot10^{-12}$
0.18	10^{-15}	10^{-12}	$4\cdot10^5$	$3.66\cdot10^{-6}$	-	$0.333\cdot10^{-14}$
0.18	10^{-14}	10^{-12}	$4\cdot10^5$	$3.45\cdot10^{-5}$	-	$0.314\cdot10^{-13}$
0.18	10^{-13}	10^{-12}	$4\cdot10^5$	$2.19\cdot10^{-4}$	-	$0.199\cdot10^{-12}$
0.33	10^{-15}	10^{-12}	$4\cdot10^5$	$2.22\cdot10^{-6}$	-	$0.202\cdot10^{-14}$
0.33	10^{-14}	10^{-12}	$4\cdot10^5$	$2.15\cdot10^{-5}$	-	$0.196\cdot10^{-13}$
0.33	10^{-13}	10^{-12}	$4\cdot10^5$	$1.62\cdot10^{-4}$	-	$0.147\cdot10^{-12}$

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APPENDIX

Analysis of the transient flow period

During a packer test in a large aquifer, the flow is unsteady. However, after some period of time, a quasi-steady flow regime is reached and steady state formulae can be used for the calculation of the rock permeability. The elapse of time after which quasi-steady flow is reached depends on the flow pattern, spherical, radial, etc., on the radius of the cavity from which the fluid is injected, and on the properties of the fluid and of the formation such as permeability, porosity, fluid and formation compressibilities and the fluid viscosity.

a. Spherical flow

Spherical flow in a homogeneous and isotropic formation is described by the following equation

$$\frac{\phi c\mu}{k}\frac{\partial\Phi}{\partial t} = \frac{\partial^2\Phi}{\partial t^2} + \frac{2}{r}\frac{\partial\Phi}{\partial r} \qquad (A.1)$$

Equation (A.1) can be written in dimensionless form by defining the following dimensionless parameters

$$r_d = \frac{r}{r_w}, \quad t_d = \frac{tk}{\phi c\mu r_w^2}, \quad \Phi_d = \frac{\Phi_i - \Phi(r_d,t_d)}{\Phi_i - \Phi(1,t_d)} \qquad (A.2)$$

where Φ_i denotes the initial potential. Substitution of equation (A.2) into (A.1) yields

$$\frac{\partial\Phi_d}{\partial t_d} = \frac{\partial^2\Phi_d}{\partial r_d^2} + \frac{2}{r_d}\frac{\partial\Phi_d}{\partial r_d} \qquad (A.3)$$

Chatas (1966) presented a solution of equation (A.3) for an infinite aquifer, with initial constant potential (Φ_i), and constant potential maintained at the cavity boundary (r_w). The resulting rate of injection is

$$q = \frac{4\pi r_w k\Delta P q_d}{\mu} \qquad (A.4)$$

where q_d is the dimensionless rate of flow defined by

$$q_d = 1 + (\pi t_d)^{-\frac{1}{2}} \tag{A.5}$$

b. Radial flow

Radial flow in a homogeneous and isotropic formation is described by the equation

$$\frac{\phi c \mu}{k}\frac{\partial \Phi}{\partial t} = \frac{\partial^2 \Phi}{\partial r^2} + \frac{1}{r}\frac{\partial \Phi}{\partial r} \tag{A.6}$$

By defining the same dimensionless parameters as for the spherical cases equation (A.2), one may write equation (A.6) in the dimensionless form

$$\frac{\partial \Phi_d}{\partial t_d} = \frac{\partial^2 \Phi_d}{\partial r_d^2} + \frac{1}{r_d}\frac{\partial \Phi_d}{\partial r_d} \tag{A.7}$$

and the dimensionless discharge becomes

$$q_d = q\,\frac{\mu}{2\pi h k \Delta P} \tag{A.8}$$

where h represents the thickness of the aquifer.

Van Everdingen and Hurst (1949) present a solution of equation (A.7) for an infinite aquifer, with constant initial potential (Φ_i), and constant potential and the borehole boundary (r_w). They calculated the cumulative volume of fluid injected into the formation, and found

$$V = 2\pi\phi c r_w^2 \Delta P V_d \tag{A.9}$$

where V_d is the dimensionless cumulative volume defined by

$$V_d(t_d) = \frac{4}{\pi^2}\int_0^\infty \frac{(1 - e^{-u^2 t_d})}{u^3(J_o^2(u) - Y_o^2(u))}\,du \tag{A.10}$$

where J_o and Y_o are Bessel functions of the first and of the second kind, respectively, and of order zero. The integral in equation (A.10) can be evaluated only numerically.

The rate of flow can be calculated using equation (A.9) and the definition

$$Q = \frac{\Delta V}{\Delta t} \tag{A.11}$$

The dimensionless rates of flow for spherical and radial flow are represented graphically in Figure A.1. It shows that a quasi-steady state is reached faster for spherical flow than for radial flow.

The formations tested by SGU are characterized by a permeability of the order of magnitude of $10^{-14} m^2$. The radius of the borehole is usually 0.028 m. If we consider porosity to be 0.003, fluid viscosity 0.001 Pas, and a total compressibility of 10^{-10} Pa^{-1}, then we obtain from equation (A.2)

$$t_d = 42517.0 \ t \tag{A.12}$$

For a test of one minute duration only, the corresponding dimensionless time is $2.55 x 10^6$ and for ten minutes $2.55 x 10^7$. As one may see from Figure A.1, even after one minute the flow is quasi-stationary.

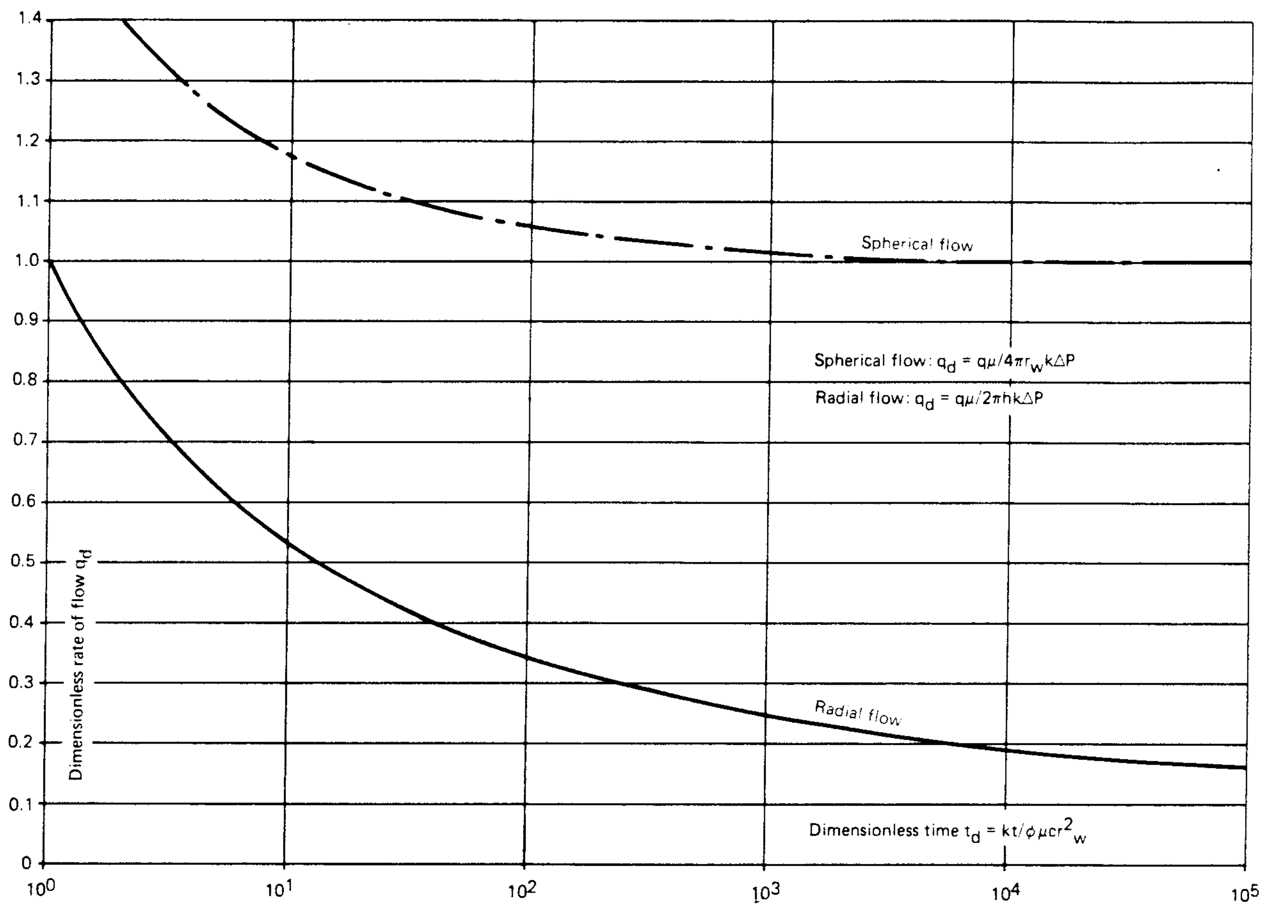

Figure A.1 Dimensionless rates of flow for spherical and radial flow.

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