

## **Use of electric analogy for the determination of the soil permeability from field tests**

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### **Abstract**

This paper is concerned with the evaluation of the shape factor by means of the electric analogy. This factor is used for the determination of the soil permeability from field tests. After a description of the experimental device, we present the methodology followed for the determination of the shape factor. Then, we study the influence, on this factor, of some parameters such as the position of the infiltration cavity in the soil layer and the presence of an obstacle or of heterogeneity near the cavity.

### **1 Introduction**

Design and calculation of civil engineering substructures and environmental facilities depend strongly on the soil permeability. Its determination is generally carried out using field tests, which consist in the measurement of both variation of the hydraulic potential and water flow in a borehole (Figure 1). The interpretation of this test is carried out according to the Hvorslev equation:

$$k = \frac{Q}{m D H} \quad (1)$$

Where  $k$  is the soil permeability,  $Q$  denotes the flow rate,  $H$  is the hydraulic potential and  $m$  is the shape factor. The latter characterises the interaction between the cavity and the soil.

The expression of the shape factor for a cylindrical cavity is due to Hvorslev (1951):

$$m = 2\pi(L/D) / \ln(L/D + \sqrt{(L/D)^2 + 1}) \quad (2)$$

Where  $L$  and  $D$  indicates respectively the length and the diameter of the cavity.

Equation 2 results from the resolution of the Laplace equation in a saturated, isotropic and infinite domain. Others experimental and numerical methods were developed and various values for the shape factor were proposed for homogeneous soils (Chapuis 1989, Shahrou & Lafhaj 1996). However in practice, engineers are confronted with more complex conditions such as the presence of heterogeneities in the soil massif.

The electric analogy was largely used to study the problem of water flow in soils (Mandel 1939, Schneebeli 1966). It was also used to study the shape factor for a spherical cavity in homogeneous soils (Smiles & Young 1956, Wilkinson 1980). In this paper, we propose to use this method to study the shape factor for complex configurations such as those encountered when tests are performed in the proximity of the water table or an impermeable substratum or when tests are performed in heterogeneous soils.

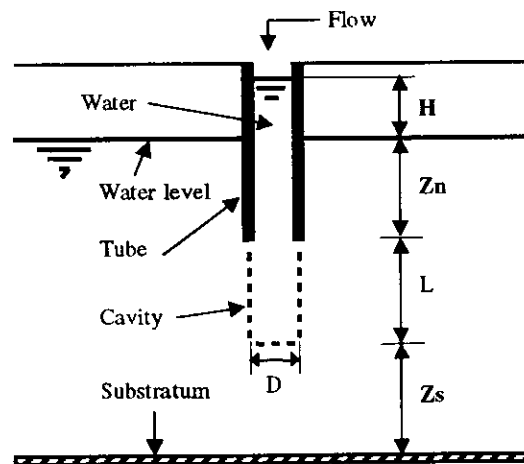


Figure 1: Measurement of the soil permeability form field tests

## 2 Experimental device and procedure

### 2.1 Introduction

When an electric driver of resistivity  $\rho$  is subjected to an electric tension  $U$ , the generalised Ohm's law gives the vector density of current  $i$ :

$$\mathbf{i} = -\frac{1}{\rho} \text{grad}(U) \quad (3)$$

Since the distribution of the density of current is governed by:

$$\text{div}(\mathbf{i}) = 0 \quad (4)$$

We can deduce that the fundamental equation:

$$\Delta U = 0 \quad (5)$$

This equation is similar to that which governs the flow of water in saturated soils. Between these two phenomena, there is an analogy between:

- (i) the permeability  $k$  of the soil and the electric conductivity of the material  $1/\rho$ ,
- (ii) the rate of infiltration  $v$  of the water in the soil and the density of the current  $i$ ,
- (iii) the electric tension  $U$  and the hydraulic load  $H$ .

### 2.2 Experimental device

The experimental device used in this work is illustrated in figure 2. It is composed of a plastic tank (dimensions are length 120 cm, width 80 cm and depth 60 cm) filled with water, which stands for the soil. To reproduce the infiltration cavity, we used a zinc cylinder of 5mm in diameter ( $D$ ). This cylinder is weld with an insulated tube in order to reproduce the casing of drilling (impermeable surface). The electric current arrives by the means of a conducting wire passing through the tube, this wire is welded with the zinc cavity.

An aluminium plate is placed on the surface of the tank, it permits to reproduce a condition of constant potential, which corresponds to the water table.

The zinc is used like an anode, because it oxidises by producing water-soluble ions, without phenomenon of protection by passivation (covering by a protective coating). Moreover, zinc is known to present a very small anodic polarisation (variation of the potential with the electronic flow) and constitutes a very stable electrode. Thus, in spite of its ionisation, this electrode has always the same electrochemical potential. With regard to the choice of aluminium cathode, it is less critical since this metal does not oxidise because of its negative polarity, which prohibits any oxidation. Cathodic polarisation is negligible thanks to the great surface of the cathode used in our device.

The electric potential between the zinc cylinder (the cavity) and plates in aluminium (water table) is applied by means of a generator of tension (0-20 V). Two multimeters are used to measure the tension applied between the cavity of zinc and the plate of aluminium and the current passing in the zinc cavity. The latter corresponds to the water flow crossing the cavity.

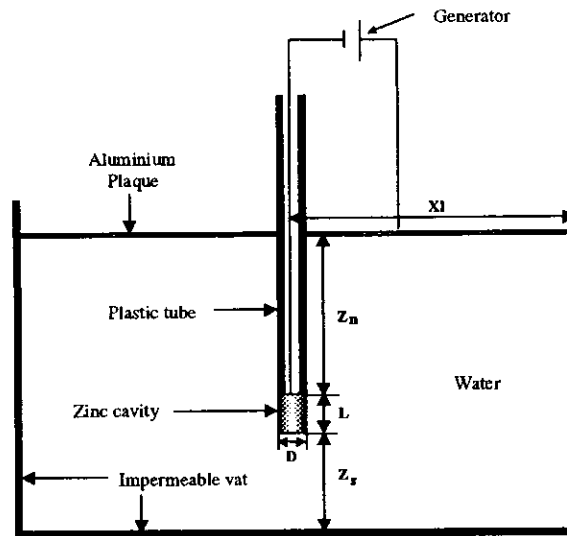


Figure 2: Device used in the study

### 2.3 Experimental procedure and interpretation

Experimental tests are carried out according to the following procedure. The tank is filled by a mineral water. The aluminium plate is gently placed on the top of the tank in order to avoid the presence of bubbles between the plate and the water, which can disturb the reproduction of the condition of water table.

When the tube (welded at its end with the cylinder of zinc) is placed at a given depth in the tank, we apply an electric potential by means of the generator. Then, we measure the electric current trough the zinc cylinder (this measurement is carried out for various values of the potential). The curve of experimental points ( $U = f(I)$ ) permits the determination of the shape factor according to the following expression:

$$m = \frac{1}{\rho} \frac{\Delta I}{D \Delta U} \quad (6)$$

Equation 6 shows that the evaluation of the shape factor requires the knowledge of the electric conductivity of water  $1/\rho$ . In order to reduce errors of measurement of

this conductivity and those related to defects of the experimental device, we determined the electric conductivity from a test performed in the centre of the tank (far a away from boundaries). For this case, we can use the relation of Hvorslev for the determination of a reference electric conductivity:

$$\left(\frac{1}{\rho}\right)_{\text{ref}} = \frac{1}{m_0} \frac{\Delta I}{D \Delta U} \quad (7)$$

$m_0$  represents the Hvorslev shape factor (equation 2).

The determination of the reference conductivity was performed for a cavity with slenderness ratio  $L/D = 5$ . Figure 3 shows the variation of the electric intensity measured according to the applied electrical potential. It can be noted that the electric potential is proportional to the current intensity; this result indicates that the water conductivity is stable during the test.

The calculation of the slope of the curve ( $U$ ,  $f(I)$ ) gives 149.5 V/A. Using the Hvorslev shape factor ( $m_0 = 13.5$  for  $L/D = 5$ ); the reference conductivity is calculated according to expression 7, we obtain:

$$\left(\frac{1}{\rho}\right)_{\text{ref}} = 984.68 \cdot 10^{-4} \text{ S/m.}$$

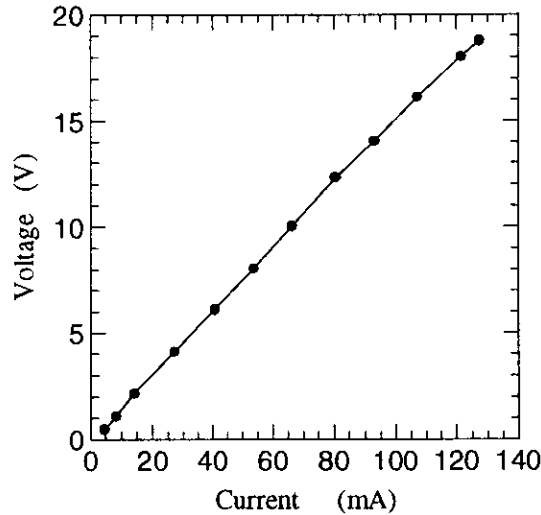


Figure 3: Determination of the electric conductivity (Cavity:  $L = 5D$ ,  $Z_n = 60D$ )

### 3 Study of the shape factor

In this section, we propose to study the shape factor when the infiltration cavity is close to the water table or to the substratum. We also study the influence, on this factor, of the presence of an obstacle or heterogeneity in the vicinity of the cavity.

### 3.1 Influence of the position of the cavity in the soil layer

In order to study the influence of the position of the cavity on the shape factor, tests were carried out for cavities situated at various depths. Figure 4 illustrates the obtained results. It can be observed that the shape factor decreases with the depth of the cavity, in particular when the cavity is in the proximity of the surface or the tank bottom. The decrease of the shape factor (until a depth of about  $40D$ ) is due to the distance of the cavity from the water table, while that in the second part (from a depth about  $90D$ ) is due to the proximity the impermeable substratum. The reduction of the shape factor, for a cavity with  $L/D = 10$ , is about 20% when the depth of the cavity increases from  $5D$  to  $110D$ . In the central part of the tank, we observe a stabilisation of the shape factor for cavities with small slenderness ratio ( $L/D = 2$  or  $L/D = 5$ ). This result confirms the hypothesis of the infinite domain for tests performed in the tank centre for the determination of the water conductivity (section 2.2).

In Figure 5 we present a comparison between experimental results and the numerical modelling realised with the boundary element program BEASY (BEASY 1994, Brebbia & Dominguez 1992). We remark a good agreement between experimental and numerical results.

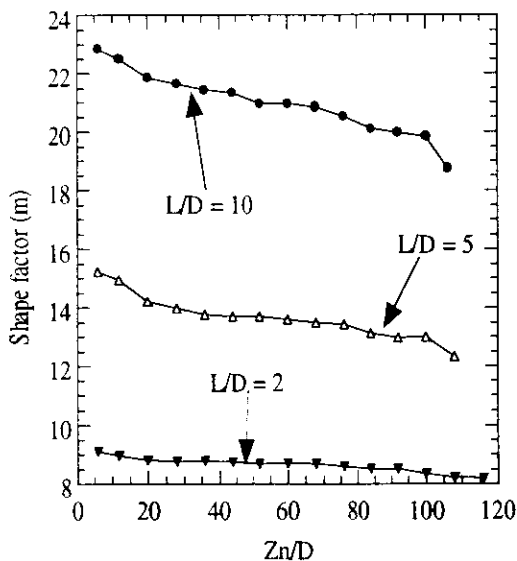


Figure 4: Influence of the cavity position on the shape factor

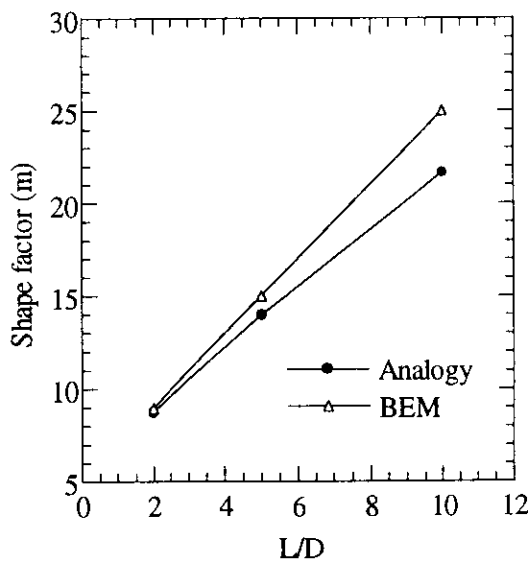


Figure 5: Comparison between experimental and numerical results

### 3.2 Influence of the presence of a sheet-pile

The experimental device was used to study the influence, on the shape factor, of the presence of a sheet-pile in the proximity of the infiltration cavity. Tests were performed on a cavity placed in the centre of the tank and then translated in the direction of a lateral side, which stands for the impermeable sheet-pile (Figure 6a). Results of this test are illustrated in figure 6b. It can be observed that the shape factor decreases when the cavity becomes closer to the sheet-pile: it decreases from 21 to 16.2 when the distance between the cavity and the sheet-pile decreases from 120D to 20D. This result indicates that attention must be paid in the interpretation of field tests performed in the proximity of impermeable bodies such as sheet-piles.

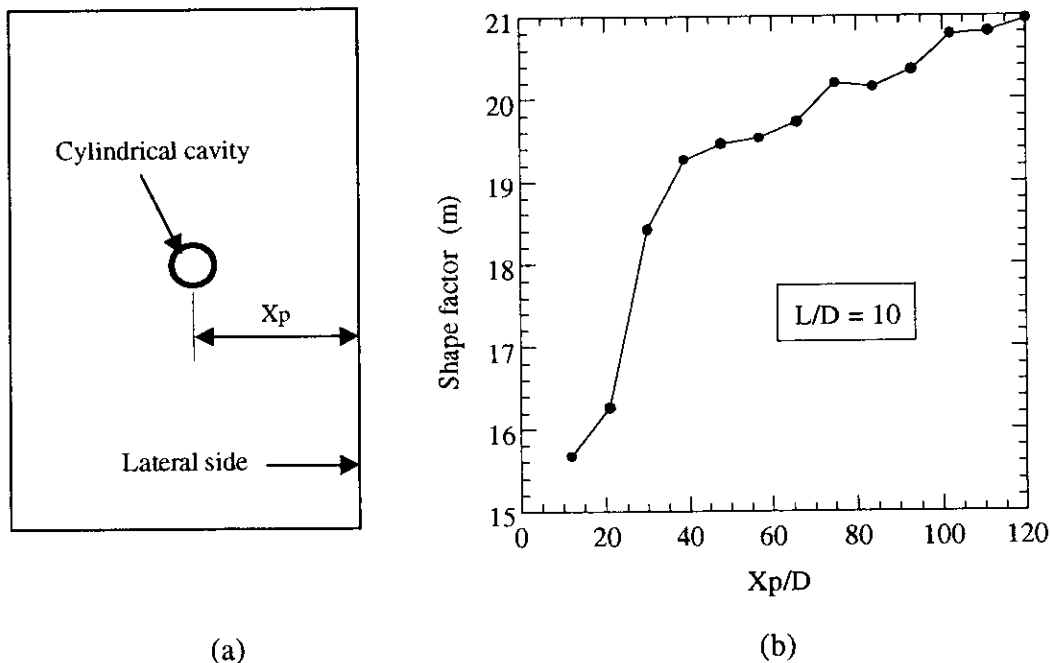


Figure 6: Influence of the proximity of sheet-pile on the shape factor  
(a) Experimental procedure  
(b) Variation of the shape factor with the distance  $X_p$

### 3.3 Influence of the proximity of a borehole

Geotechnical exploration programs require generally several boreholes for both field tests and soil sampling. In this section, we propose to study the influence of the presence of a borehole in the proximity of the infiltration cavity on the shape factor. Tests were performed with the experimental device illustrated in figure 7a.

A copper tube with 15 mm in diameter ( $3D$ ) was used to model an existing borehole. Figure 7b shows the variation of the shape factor with the distance between the infiltration cavity and the existing borehole. It can be noted that the presence of borehole has a negligible influence on the shape factor when its distance from the cavity is greater than  $10D$ . This result shows that the presence of a borehole can be neglected in practice.

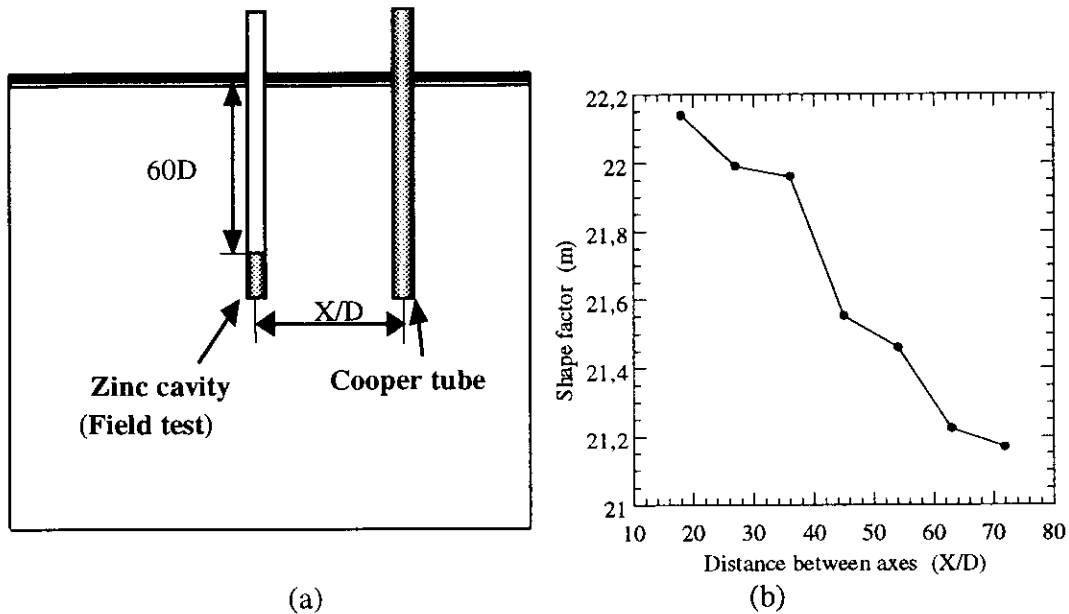


Figure 7: Influence of the presence of a borehole on the shape factor

(a): Experimental procedure

(b): Variation of the shape factor with the distance between the cavity and the borehole

### 3.4 Influence of the presence of heterogeneity

In this part, we study the influence, on the shape factor, of the presence of a permeable or impermeable heterogeneity (blocs or decompressed soils) in the vicinity of the infiltration cavity. A cylinder in nylon ( $12D$  in diameter and  $20D$  in length) was used to represent the impermeable heterogeneity, and aluminium was used to model the permeable one (figure 10a).

The study was carried out by varying the distance between the cavity and the heterogeneity. Figure 8b illustrates the shape factor for studied cases. It can be observed that the presence of a permeable heterogeneity affects slightly the shape factor, while an impermeable block affects the shape factor when is close to the infiltration cavity (distance centre-to-centre about  $9D$ ).

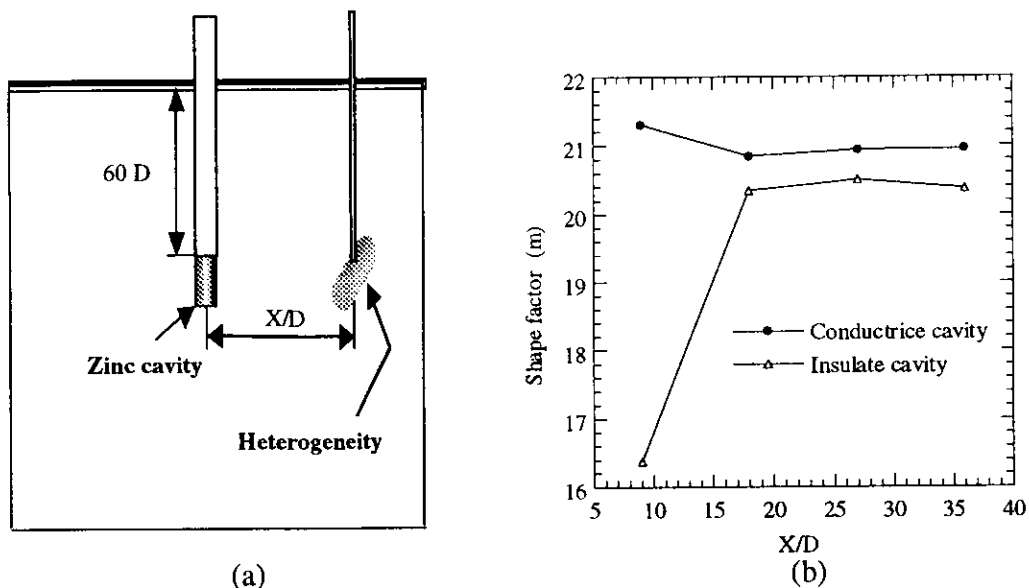


Figure 8: Influence of the presence of heterogeneity on the shape factor

(a): Experimental procedure

(b): Variation of the shape factor with the distance between the cavity and the heterogeneity

#### 4 Conclusion

This paper included a study by means of electric analogy of the shape factor, which is used in the determination of soil permeability from field tests.

Experimental tests show that the shape factor depends on the cavity position in the soil massif. It increases in the proximity of the water table and decreases when the cavity becomes closer to an impermeable substratum.

The presence of a permeable heterogeneity or a borehole close to the infiltration cavity affects slightly the shape factor. But the presence of an impermeable heterogeneity or impermeable obstacle reduces significantly the shape factor: we observed a reduction of the shape factor of about 30% for a cavity situated at  $20D$  from a sheet-pile.

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