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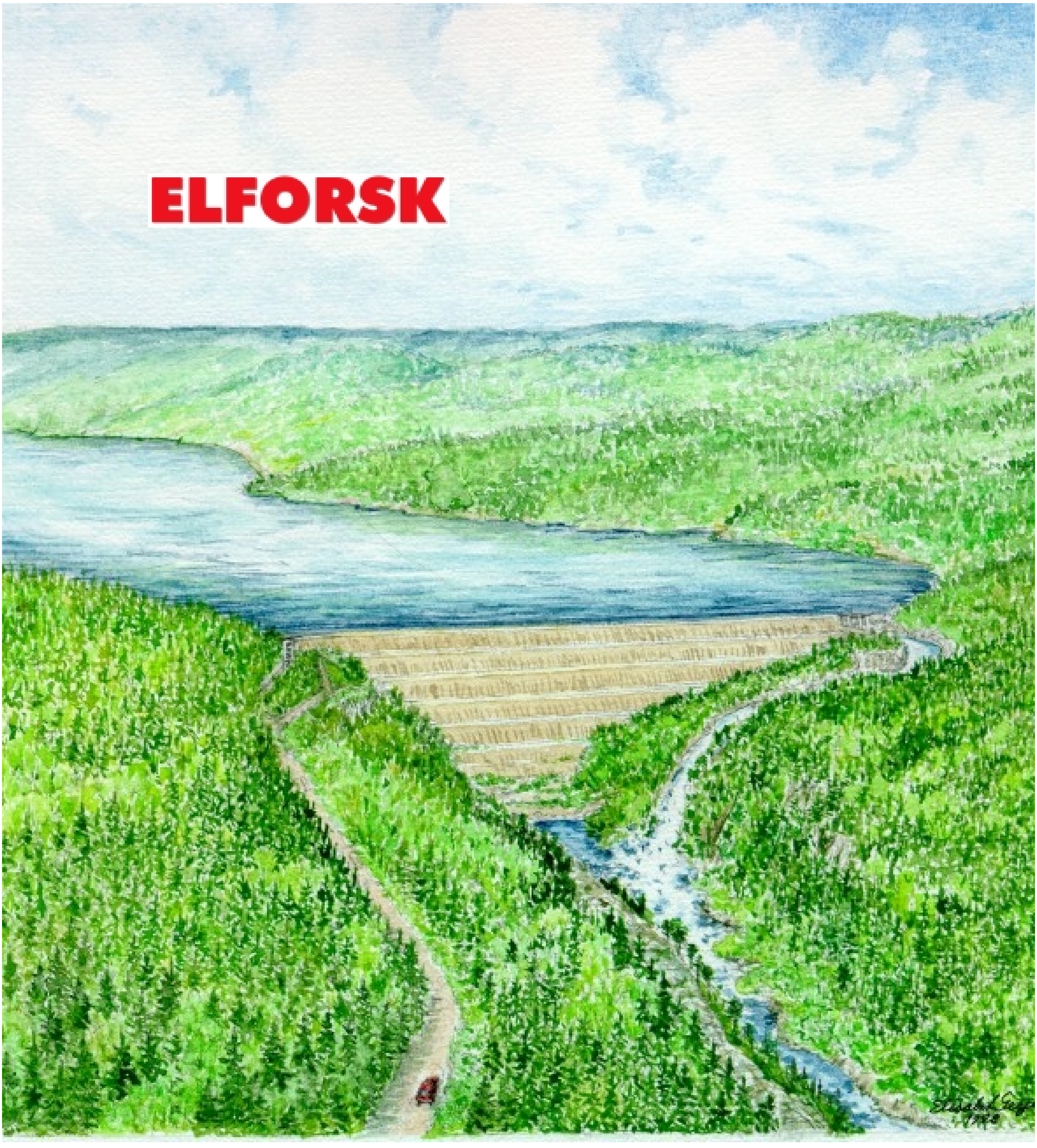

# DAMMSÄKERHET

## COMPARATIVE EVALUATION OF CFX AND PHOENICS CODES IN MODELLING FLOW IN POROUS MEDIA

Rapport 99:49

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Summary

Comparison has been made between the two commercial CFD programs, CFX and PHOENICS, for the simulation of laminar seepage in porous media. The main purpose is to evaluate which program is more suitable for seepage flow modelling.

The problem examined is a rectangular dam with homogenous material property. The conducted simulations show that the two programs can produce almost the same results for all the simulated cases, only marginal difference from the theoretical values is discerned.

It is recommended that CFX should be used for seepage flow studies for embankment dams. The program is more user-friendly and has the built-in possibility of modelling both laminar and turbulent flow through porous media.

# Innehållsförteckning



# Appendices

# 1 Background

A mutual research and development program on dam safety issues has been established between British Columbia Hydro and Power Authority (BC Hydro), Canada and the Swedish Association of River Regulation Enterprises (VASO). As a part of this program, comparative studies are made of seepage flow through an embankment dam with simple geometry. This is considered as the first step towards the actual seepage modelling for the Bennett dam in Canada.

Correct prediction of the seepage through an embankment dam can assist one to understand its hydraulic behaviour, especially the behaviour of the central core when damage has occurred to it. The stability analysis of the downstream slope depends to great extent upon the result of the seepage modelling.

At Vattenfall Utveckling AB (VUAB), seepage analyses has been made using the program PHOENICS, and the results were compared with analytical solutions. The user himself needs to program the code if pressure boundary exists where the flow velocity is unknown, as is the case with the seepage simulation through embankment dams. This limits its user-friendliness, especially for new users.

At present, more user-friendly, functional and robust CFD codes are available. The program CFX, previously called CFDS-FLOW3D, is one of them. One of its main advantages is that it has multi-block technique, which facilitates model set-up and flow modelling in areas of interest, like concentrated seepage through a damaged dam core. With this, it is expected that shorter time is needed for model set-up and better modelling accuracy can be obtained.

The purpose of the present study is to justify the shift from PHOENICS to CFX, and to test the suitability of CFX in modelling porous media problems, and to lay a basis for Bennett dam investigations.

# 2 Project Description

A limited comparison of suitability is made by VUAB between the PHOENICS and CFX programs, and it includes the following components: (1) to re-produce the PHOENICS simulations made before, with the current version (version 2.1); (2) to set up a CFX model with the same geometry as in PHOENICS; (3) to compare the results, also with the analytical result; and (4) to summarise the experiences based on the modelling and make suggestions for the Bennett dam investigations.

The possibility of modelling turbulent seepage in CFX is also discussed.

# 3 Darcy's law in PHOENICS and CFX

## 3.1 Darcy's law

There is certain difference in the way that the PHOENICS and CFX programs formulate their codes for laminar flow in porous media where Darcy's law is used.

For the case of large resistance in porous material, a large adverse gradient is built up to balance the resistance. This is usually the case for many practical problems. Inactivating the convective acceleration and diffusion effects in the governing equations, the momentum equation of the porous media model in PHOENICS reduces to Darcy's law in the following form (in Cartesian coordinate system)

$$\frac{\partial p_i}{\partial x_i} = -\rho \times g_i - \frac{\mu}{k_i} u_i, \quad i = 1,2,3 \tag{1}$$

where p = pressure (N/m$^2$), u = Darcy´s velocity (m/s), μ = viscosity of seepage fluid (Nxs/m$^2$), k = *specific permeability* (m$^2$), and $g_i$ = vector of gravitational acceleration (m/s$^2$). PHOENICS simply uses the Darcy velocity. The porosity is implicitly embodied by the specific permeability as any change in the porosity will cause change in the specific permeability.

The CFX code uses the actual mean velocity of flow in the pores instead of the Darcy velocity. In CFX, if the convective and diffusion terms in the governing equations are inactivated, the CFX porous media equations becomes

$$\frac{\partial p_i}{\partial x_i} = -\rho \times g_i - \frac{\mu \times n}{k_i} (u_n)_i \tag{2}$$

where n = effective porosity (-) and $u_n$ = actual mean flow velocity (m/s). The porosity must be explicitly specified in the program. In the present version of CFX only isotropic porosity is allowed, however the specific permeability (or hydraulic conductivity) can be specified as anisotropic.

The relationship between $u_n$ and u simply is

$$u_n = \frac{u}{n} \tag{3}$$

This difference should be kept in mind when the simulation results are interpreted. The specific permeability, k, depends solely on the properties of the solid matrix, not the seepage fluid. Quite often hydraulic conductivity, K (m/s), is used instead of k, and their relationship can be expressed as

$$\frac{\rho \times g}{K} = \frac{\mu}{k} \tag{4}$$

For water, K/k = ρ x g/μ ≈ $10^7$ and for air K/k = ρ x g/μ ≈ $7 x 10^5$

## 3.2 Range of validity

The Reynolds number, Re, for flow in porous media is usually defined as

$$\mathrm{Re} = \frac{U \times d}{v} \tag{5}$$

where U = $\sqrt{(u_1)^2 + (u_2)^2 + (u_3)^2}$ (m/s), d is some representative length that characterises the solid matrix (m), and v is the kinematic viscosity ($m^2/s$). The definition of the Reynolds number is based on the Darcy velocity in most technical literature.

There are several ways to define the length dimension d. It is customary to employ the mean grain diameter $d_{50}$ as d as it is relative easy to determine. Sometimes $d_{10}$ is mentioned in the literature as a representative parameter. $d_{10}$ is the grain size that exceeds the size (diameter) of 10% of the material by weight. Collins, 1961, suggested d = $(k/n)^{½}$. On the basis of theoretical analysis, this formulation seems to be a better choice. Ward, 1964, uses $k^{½}$ as the representative length d (Bear 1988).

In practically all cases, Darcy’s law is valid as long as the Reynolds number based on the mean grain diameter does not exceed some value between 1 and 10. Beyond this range, the contribution of the inertial forces to the pressure drop must be included.

# 4 Model set-up

The earth dam investigated has a simple cross-sectional profile - parallel vertical walls and homogenous material property (Figure 1). Its width is L (m) and its height is $H_m$ (m). The upstream and downstream water depth is H and h (m), respectively.

If seepage face exists, its height above the downstream water level is denoted as $h_0$ (m). For constant H value, $h_0$ decreases with the increasing downstream water depth. If the downstream level is high enough relative its upstream level, the seepage face becomes negligible.

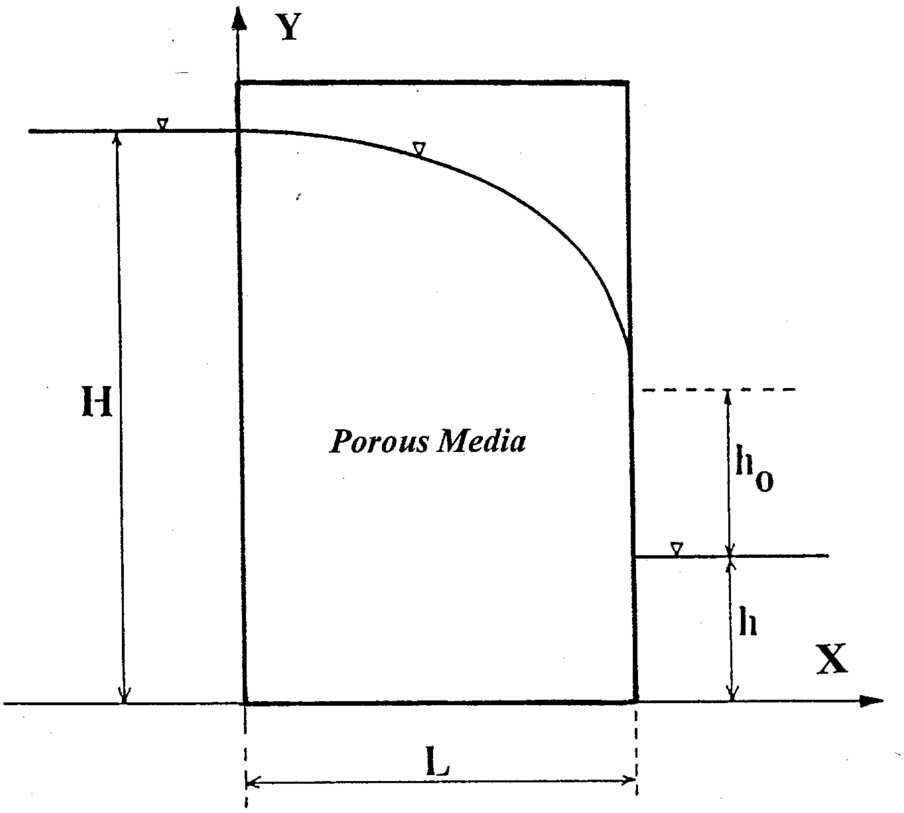


**Figure 1** **Model set-up: definition of dam profile**

For this simple case as defined in Figure 1, analytical solution (Hele-Shaw model) is available (Rehbinder 1993). This solution gives only the profile of the phreatic surface, not the seeping discharge. The *Dupuit-Forchheimer* discharge formula can be used to calculate the discharge although the *Dupuit* assumption is not valid here.

The following values are used in CFX and PHOENICS models.

| | |
|---|---|
| Dam width | L = 1.0m |
| Upstream water depth | H = 1.0m |
| Dam height | $H_m$ = 1.0m in CFX |
| | $H_m$ = 1.1m in PHOENICS |
| Volume (area) porosity | N = 0.4 |
| Hydraulic conductivity | K = 0.1m/s |
| | |
| Water temperature $T_w$ | 20ºC |
| Water density $P_w$ | 998.2 kg/$m^3$ |
| Water viscosity $\mu_w$ | 1.00E-3 nxs/$m^2$ |
| | |
| Air temperature $T_a$ | 20ºC |
| Air density $P_a$ | 1.189 kg/$m^3$ |
| Air viscosity $\mu_a$ | 1.81E-5 nxs/$m^2$ |

Three cases are examined, and this corresponds to the downstream water depth at

h = 0.00 m (Case A),
h = 0.30 m (Case B),
h = 0.50 m (Case C).

The upstream water level is constant, H = 1.0 m.

The problem is treated as two-dimensional. The grid used for the porous region is the same in the CFX and PHOENICS models, and is composed of 100 cells in each direction.

# 5 Results and comparison

Results from the CFX and PHOENICS simulations are shown in appendices 1-3. Appendix 1, 2 and 3 illustrates the results for Case A, B and C, respectively. The phreatic surface, seeping velocity and discharge are those parameters that we are interested in.

## 5.1 Phreatic surface

The results show that the phreatic surface from CFX and PHOENICS is almost identical for all the examined cases.

Together with the theoretical result, the seepage point location on the downstream face, defined as $h + h_0$, is summarised in Table 1. Very good agreement is found, except for Case B where the difference is 3 cm between CFX and PHOENICS. The values in parentheses refers to the result from previous PHOENICS simulations made at Vattenfall Utveckling AB, which give somewhat higher value of $h_0$ than the present result. This might be due to the difference in different PHOENICS versions.

**Table 1 Comparison of seepage point location ($h + h_0$) between the CFX, PHEONICS and theoretical results**

| Case Studied | Seepage point location $h+h_0$ (m) | | |
|---|---|---|---|
| | CFX | PHOENICS | Theory |
| **Case A** | 0.375 | 0.365 (0.38) | 0.37 |
| **Case B** | 0.444 | 0.421 | 0.44 |
| **Case C** | 0.542 | 0.532 (0.55) | 0.54 |

## 5.2 Seeping velocity

The agreement is very good between the results as far as the flow velocity field is concerned. Minor difference exists close to the downstream face, this is partially because the downstream boundary used in the two programs is different. The air velocity is not relevant in this study, and it has a negligible effect on the water flow.

Two points, M (0.5, 0.5) and N (0.9, 0.35), are selected in the porous region in order to compare the results of seepage flow velocity. This is illustrated in the following table (Table 2), where the Darcy velocity from the PHOENICS simulations are converted into actual flow velocity.

As mentioned before, CFX uses the real flow velocity and PHOENICS the Darcy velocity, their conversion is given by equation (3). Table 2 shows clearly that only marginal difference in the velocity is found.

**Table 2 Comparison of actual flow velocity between CFX and PHOENICS**

| Case | Program | Point M (0.5, 0.5) | | Point N (0.9, 0.35) | |
|---|---|---|---|---|---|
| | | $U_x$(cm/s) | $U_y$(cm/s) | $U_x$(cm/s) | $U_y$(cm/s) |
| **A** | CFX | 14.00 | -5.50 | 18.00 | -16.70 |
| | PHOENICS | 14.40 | -5.67 | 17.33 | -16.70 |
| **B** | CFX | 13.50 | -3.91 | 21.60 | -11.30 |
| | PHOENICS | 13.45 | -4.43 | 22.03 | -12.25 |
| **C** | CFX | 11.10 | -2.61 | 16.00 | -1.99 |
| | PHOENICS | 11.23 | -2.53 | 15.90 | -1.78 |

It is interesting to note the location of occurrence of the maximum flow velocity along the downstream face of the dam. When there is no water downstream (Case A), the maximum velocity occurs close to the bottom. With water present downstream the dam (Case B and C), the maximum velocity occurs close to the water surface. At these areas, the pressure gradient is the largest, which gives rise to largest seepage forces.

## 5.3 Seeping discharge

For the situation defined in Figure 1, The *Dupuit assumption* is not valid as the hydrostatic pressure distribution is violated. However, the *Dupuit-Forchheimer* discharge formula applies and it reads

$$Q = K \frac{H^2 - h^2}{2 \times L} \qquad (6)$$

where Q = discharge of seepage per unit width ($m^3$/sxm). For comparison, the results from the simulations are given in the following table (Table 3).

**Table 3 Comparison of seeping discharge**

| Case Examined | Seeping discharge (kg/s/m) | | |
|---|---|---|---|
| | CFX | PHOENICS | Equation (6) |
| **A (h=0.00m)** | 49.10 | 50.42 | 49.90 |
| **B (h=0.30 m)** | 45.77 | 45.88 | 45.42 |
| **C (h=0.50m)** | 37.60 | 37.81 | 37.43 |

Obviously, the results from both CFX and PHOENICS calculations are in good agreement with the exact solution.

# 6 Concluding remarks

It can be said that CFX and PHOENICS give nearly identical result in terms of phreatic surface, velocity field and seeping discharge, and agreement with the theory is good.

The difference between the present and previous results from PHOENICS is probably due to the difference in its versions. In all the cases, PHOENICS gives somewhat lower phreatic surface that CFX.

The following remarks are made for future investigations of seepage through porous media.

1. CFX is very user-friendly in terms of grid generation, model set-up and post-proces sing of results.

2. CFX has the built-in possibility of modelling seepage with higher flow velocity than allowed by Darcy's law. PHOENICS does not have this function, and the user needs to program him self (see Appendix 4).

# 7 References


[1] AEA Technology (1995), *CFX 4.1 Flow Solver user Guide*, UK.

[2] Bear, J. (1988). *Dynamics of fluids in porous media.* Dover Publications, Inc, N.Y.

[3] Bear, J. and Verruijt, A. (1987). Modeling Groundwater Flow and Pollution. D.Reidel Publishing Company, Dordrecht.

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[6] Rehbinder, G., Gustafsson, G. och Thunvik, R. (1995). Grundvattenströmningens teori.

[7] Kompendium, Kungl. tekniska högskolan (KTH) och Chalmers tekniska högskolan (CTH).

# Appendices

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| | PHOENICS result: Velocity distribution along downstream face | |
| **Appendix : 3** | **Results for Case C (downstream water level h = 0.50 m)** | **4** |
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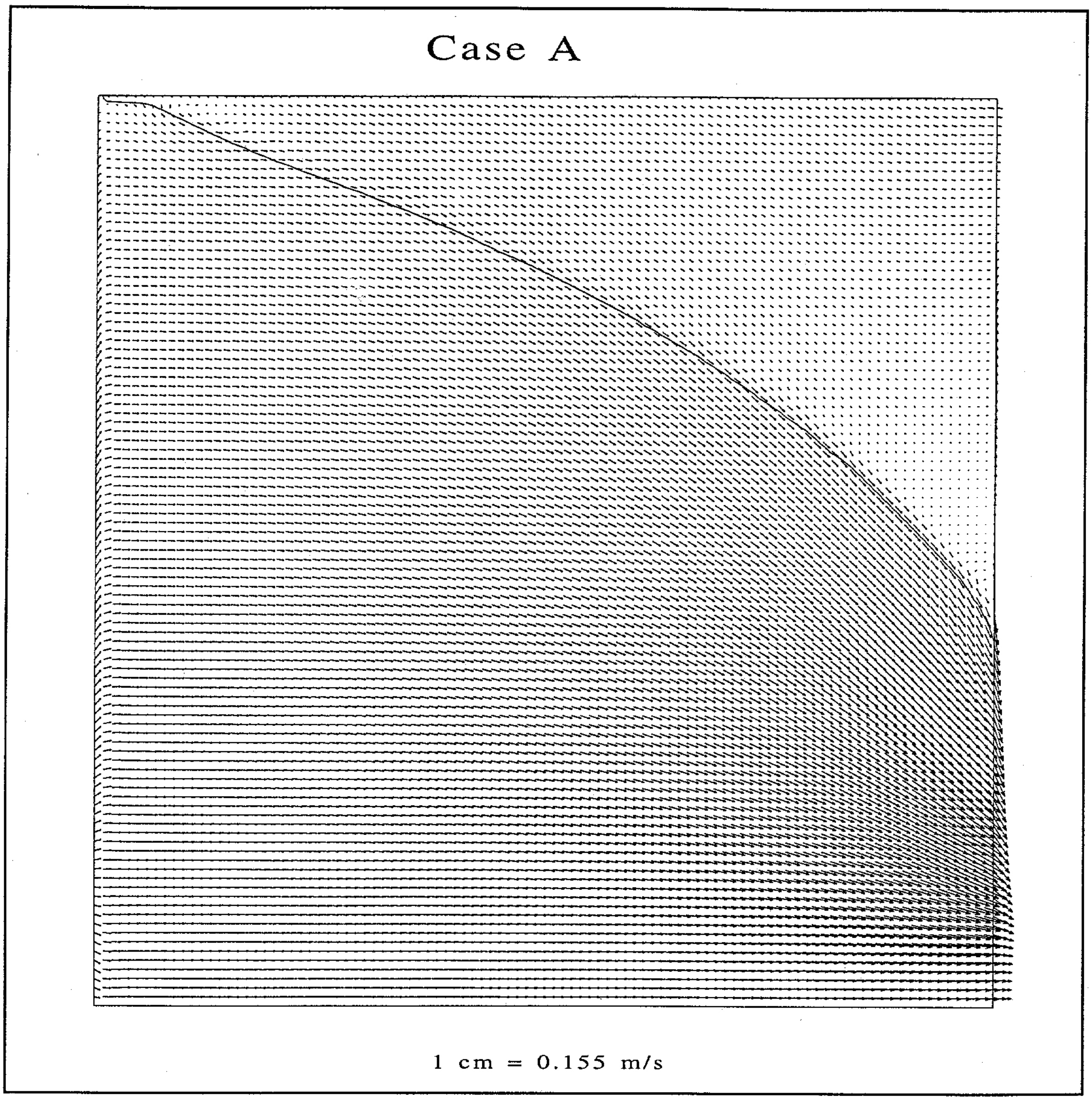
# A Appendix 1

Result from CFX

Case A: h = 0.0 m, $h_0$ = 0.375 m

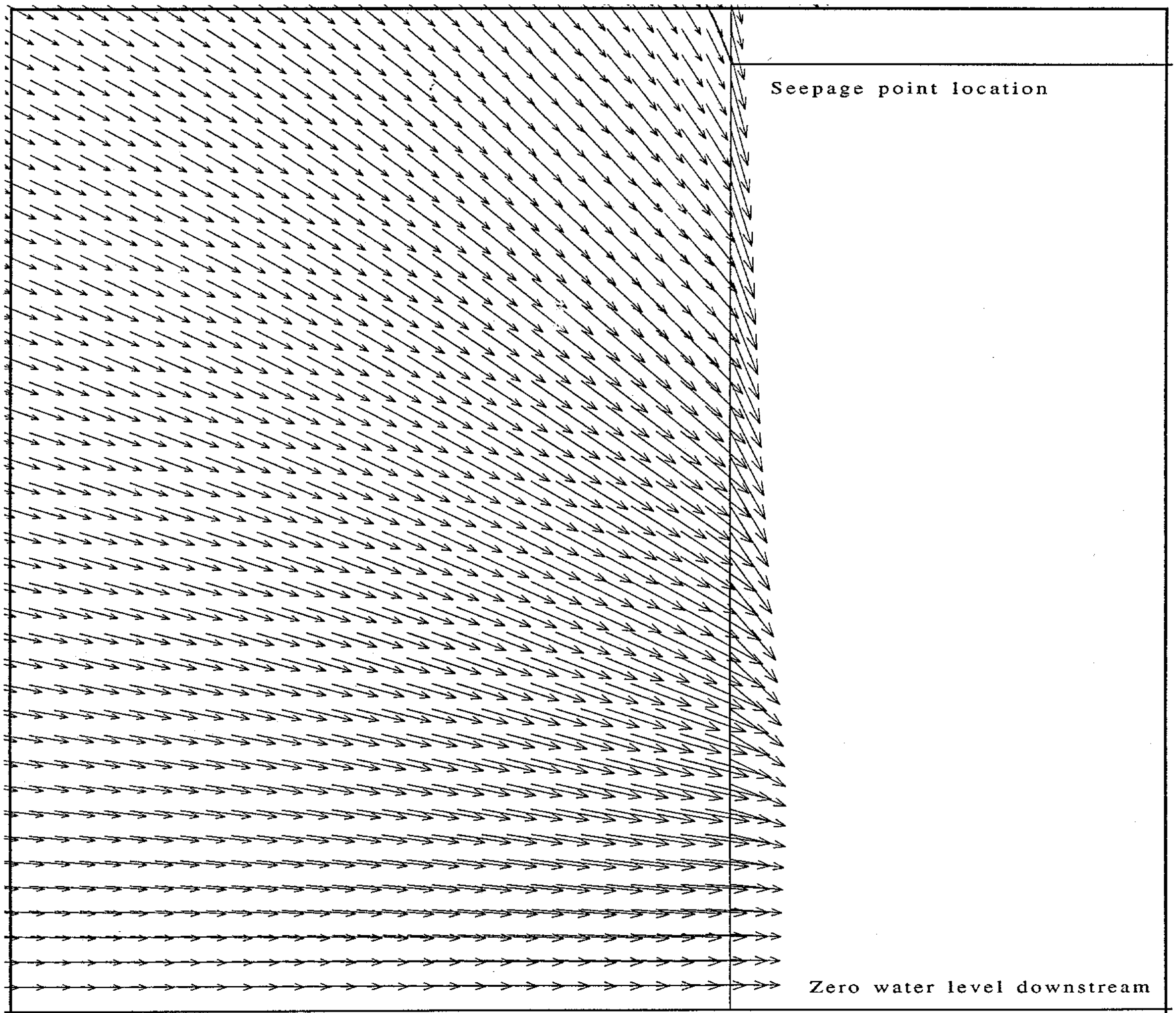
Phreatic surface & velocity vector (1 cm = 0.155 m/s)



Result from CFX

Case A: h = 0.0 m, $h_0$ = 0.375 m

Velocity distribtuin on the downstream face

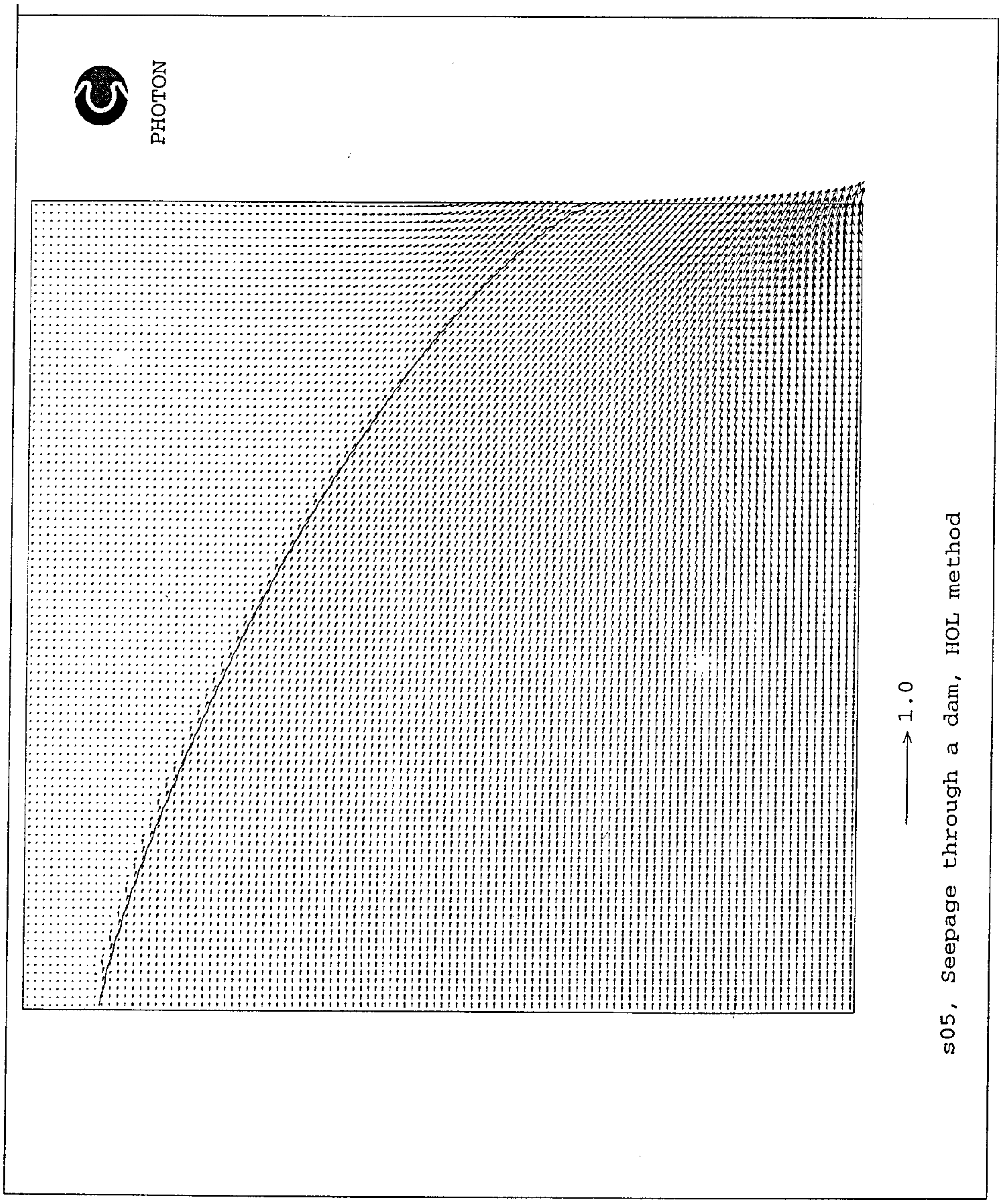



Velocity distribution along seepage face

Result from PHOENICS

Case A: h = 0.0 m , $h_0$ = 0.361 m

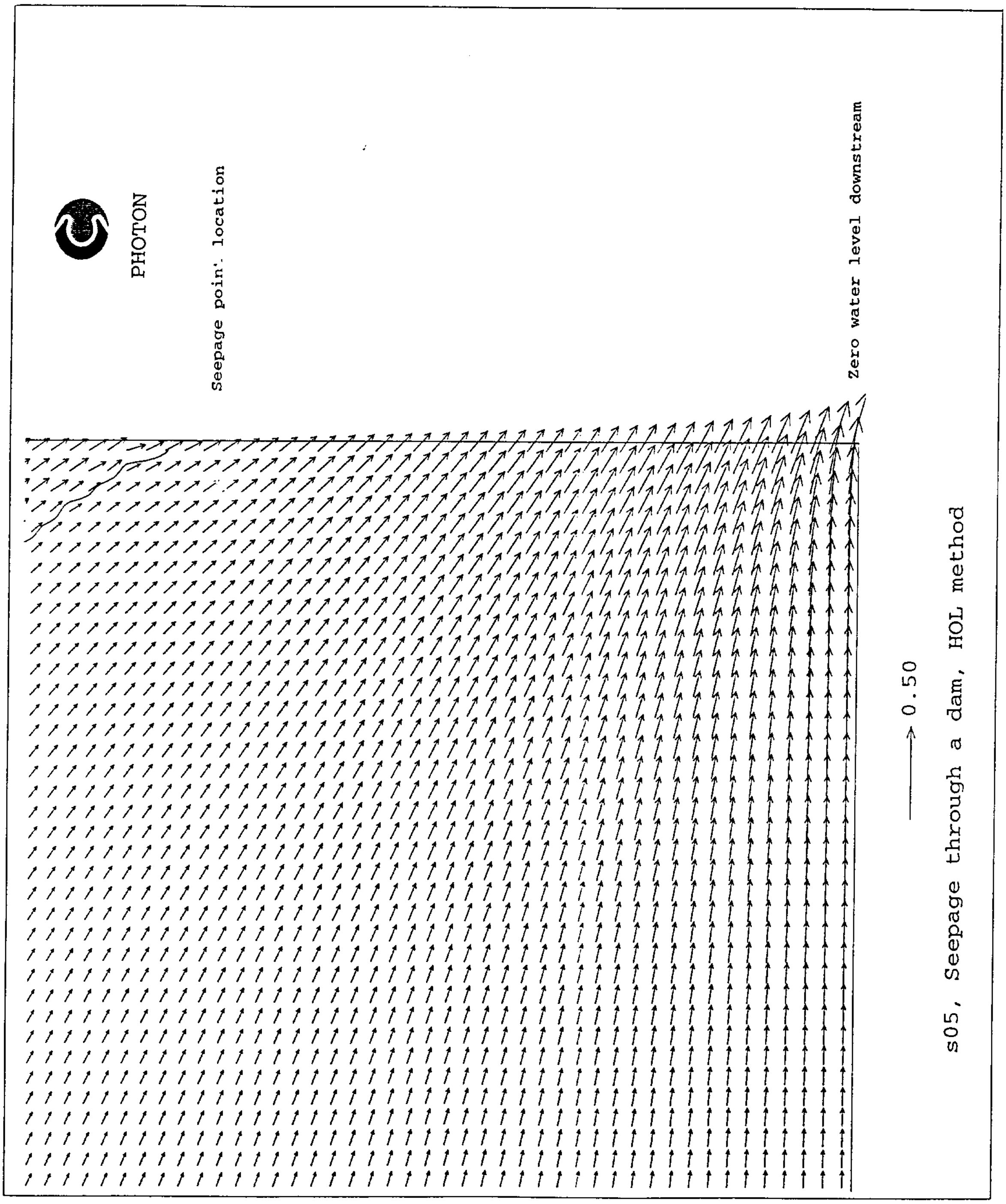
Phreatic surface & velocity vector



Result from PHOENICS

Case A: h = 0.0 m , $h_0$ = 0.361 m

Velocity distribution on the downstream face

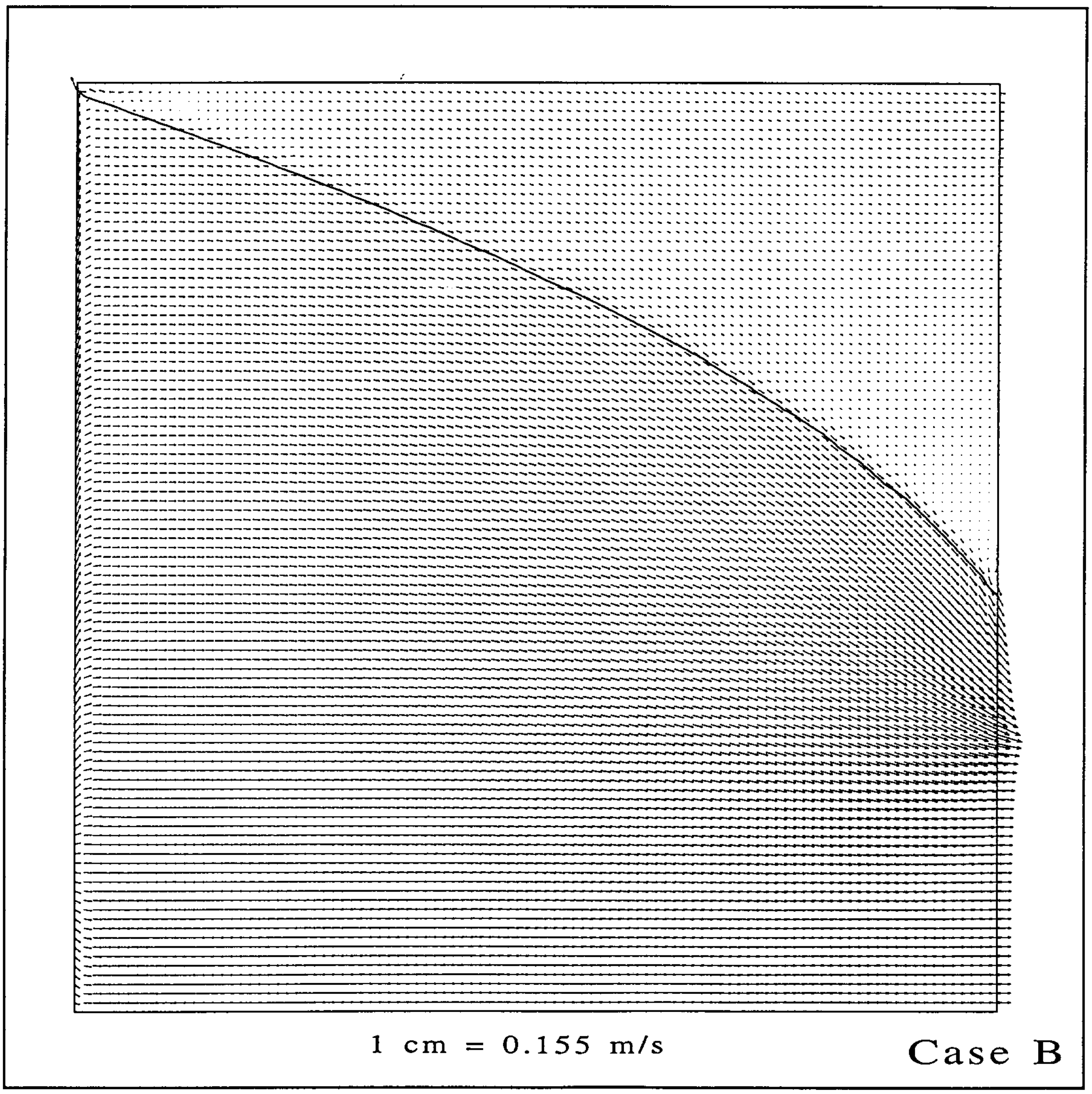


# B Appendix 2

Result from CFX

Case B: h = 0.30 m, $h_0$ = 0.444 m

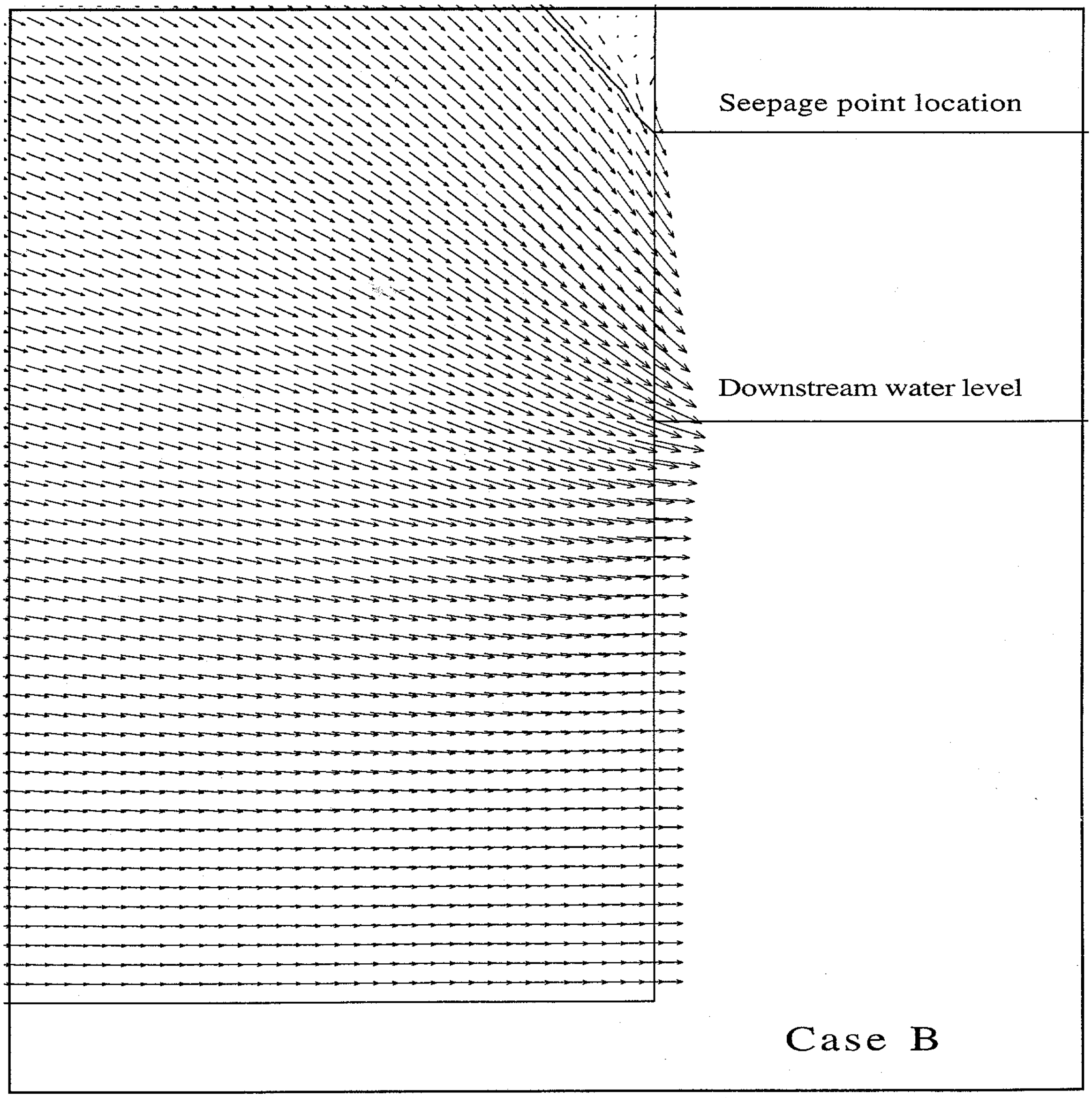
Phreatic surface & velocity vector (1 cm = 0.155 m/s)



Result from CFX

Case B: h = 0.30 m, $h_0$ = 0.444 m

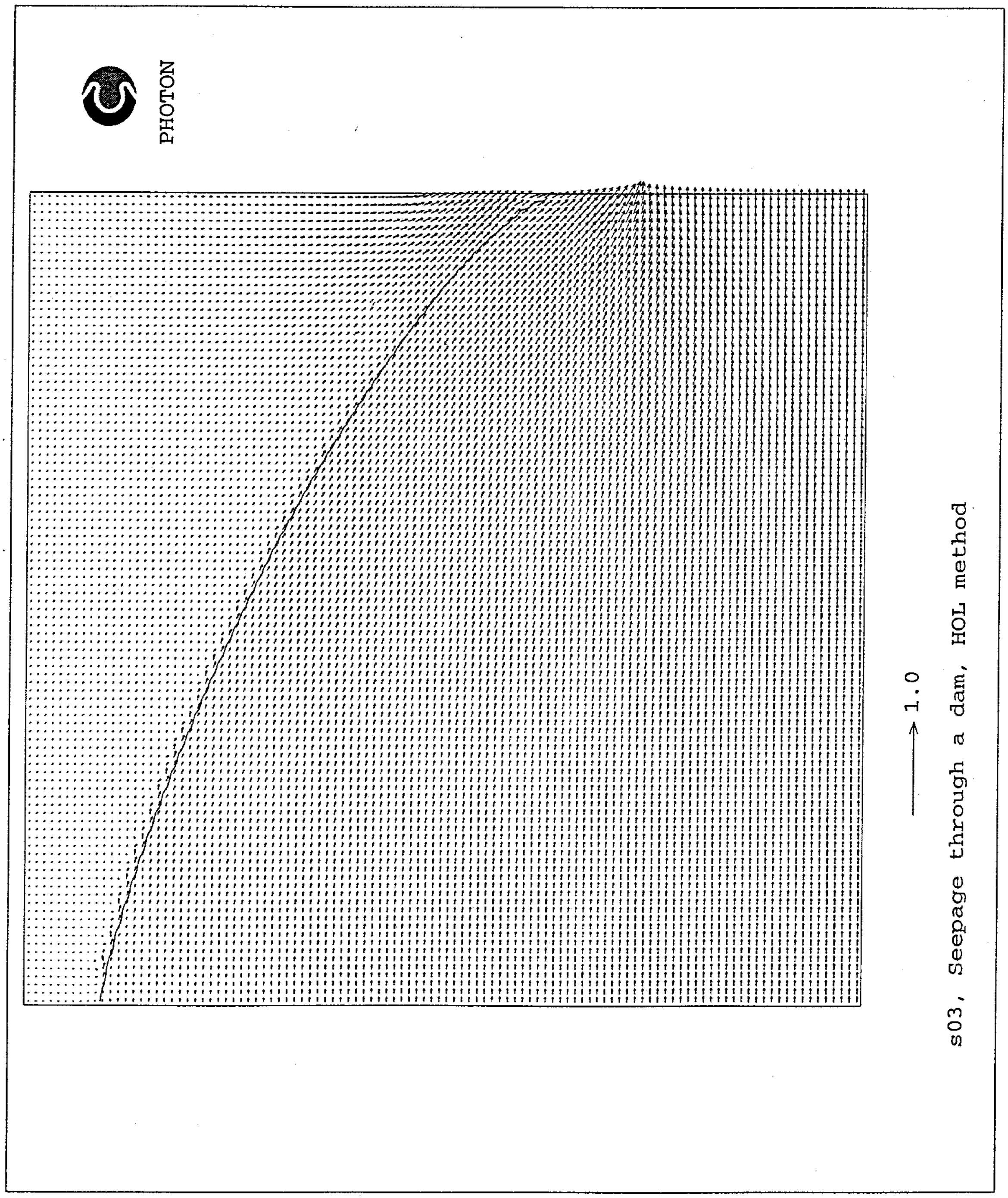
Velocity distribution on the downstream face



Result from PHOENICS

Case B: h = 0.30 m , $h_0$ = 0.412 m

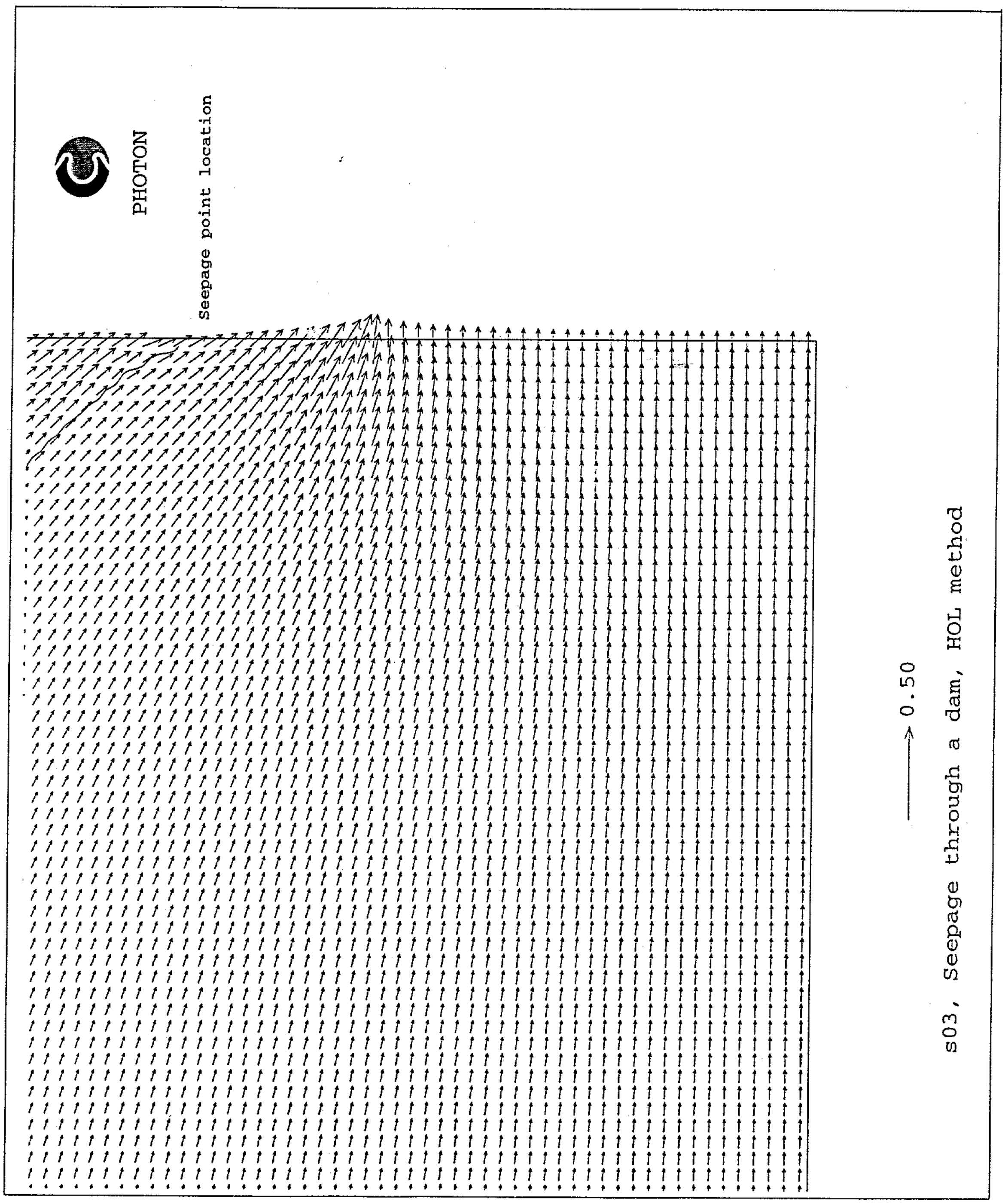
Phreatic surface & velocity vector



Result from PHOENICS

Case B: h = 0.30 m , $h_0$ = 0.412 m

Velocity distribution on the downstream face

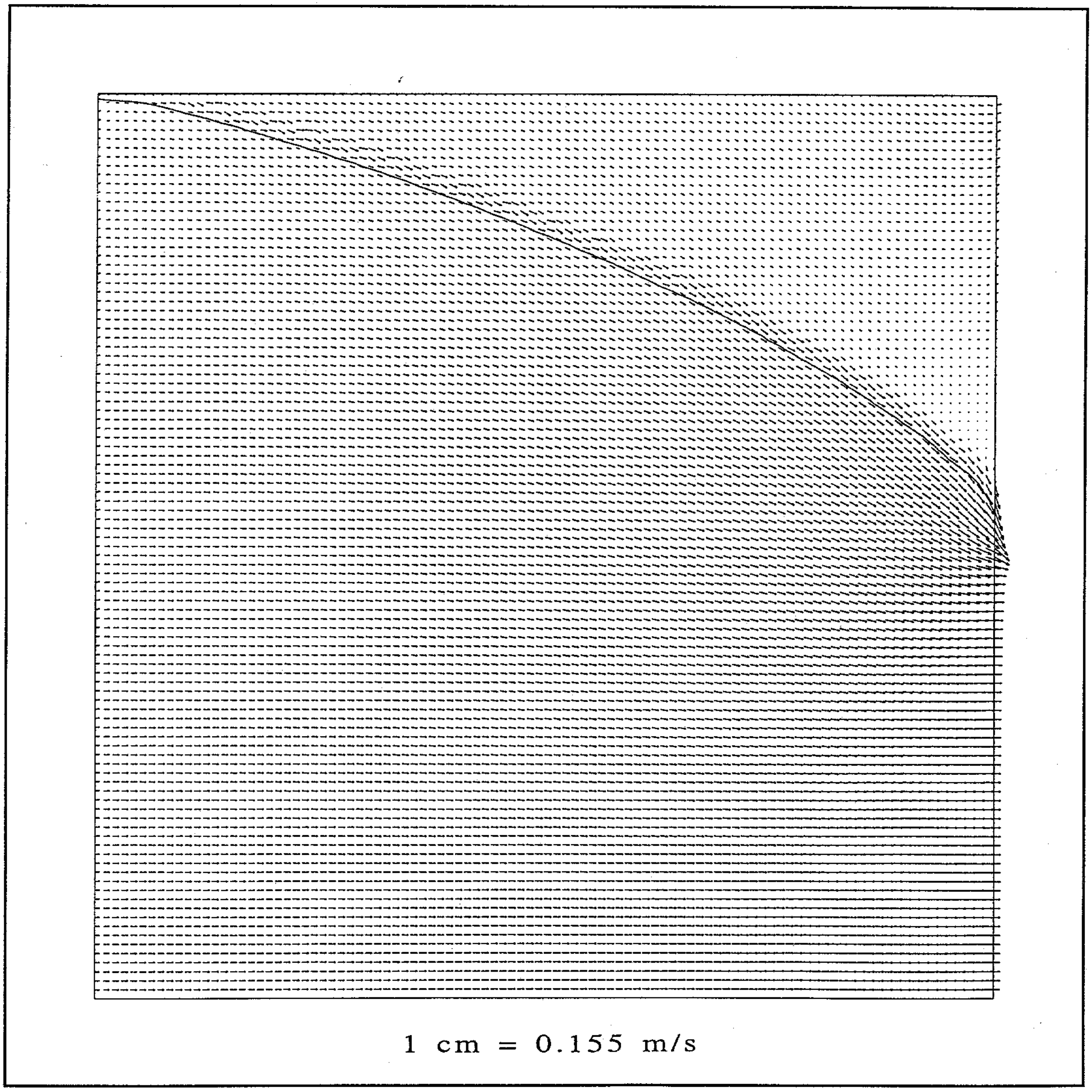


# C Appendix 3

Result from CFX

Case B: h = 0.50 m, $h_0$ = 0.542 m

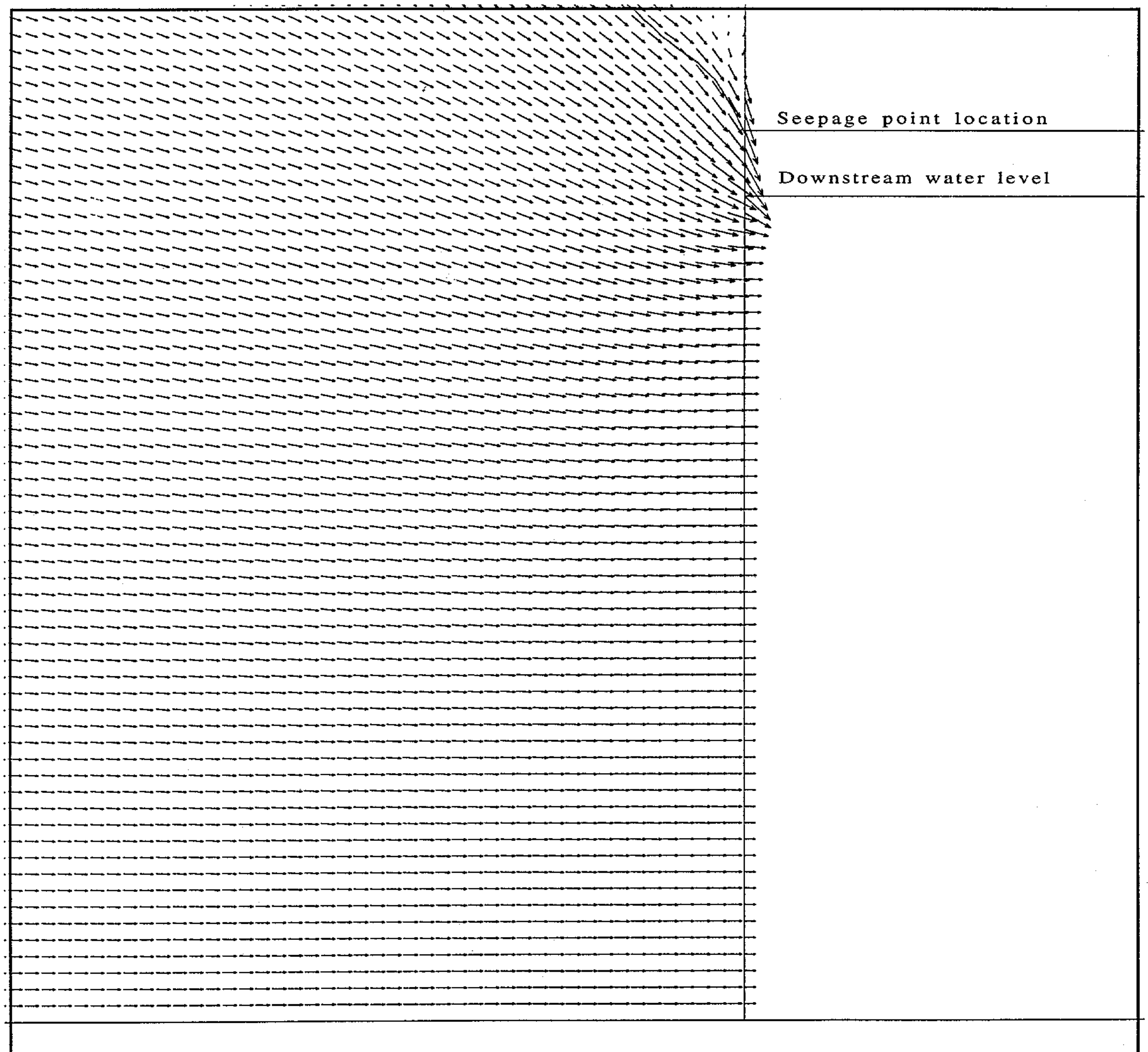
Phreatic surface & velocity vector (1 cm = 0.155 m/s)



Result from CFX

Case B: h = 0.50 m, $h_0$ = 0.542 m

Velocity distribution on the downstream face

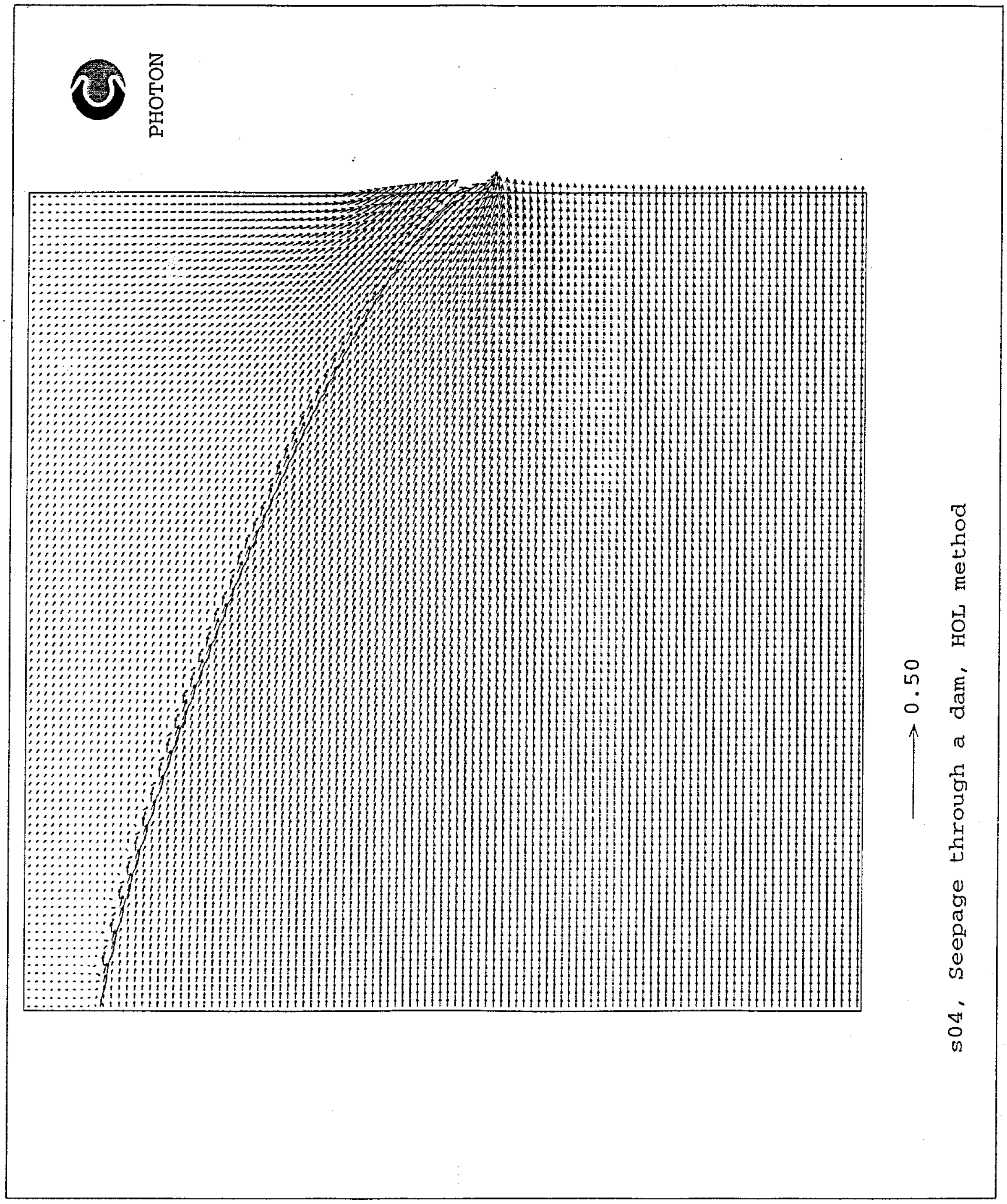



Velocity distribution along downstream face

Result from PHOENICS

Case B: h = 0.50 m , $h_0$ = 0.54 m

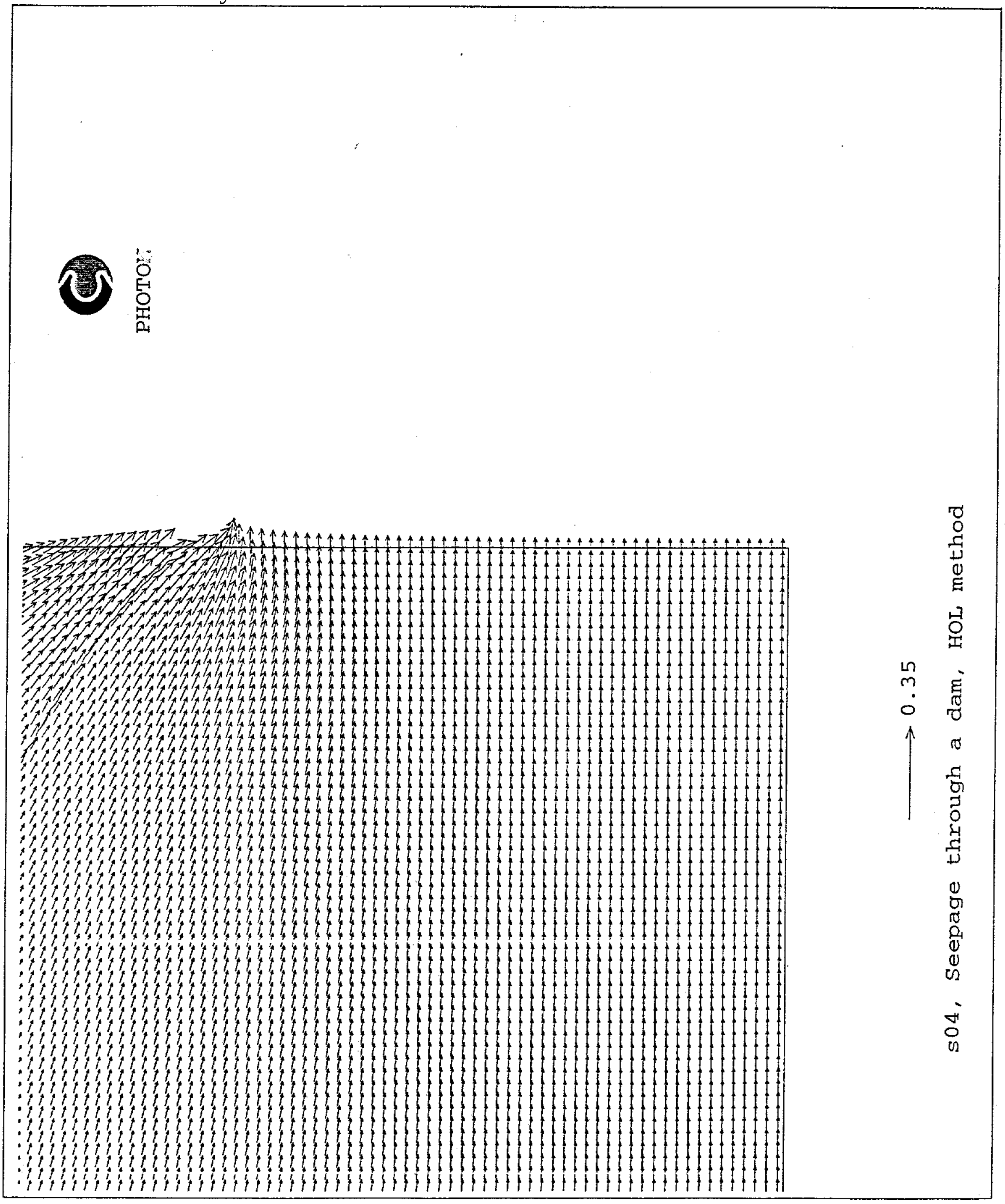
Phreatic surface & velocity vector



Result from PHOENICS

Case B: h = 0.50 m , $h_0$ = 0.54 m

Velocity distribution on the downstream face



# D Appendix 4

## D.1 Comments on the possibility of modelling turbulent flow in CFX

In CFX, if the convective and diffusion effects are neglected, the pressure drop in porous media can generally be written as

$$\frac{\partial p}{\partial x} = -\rho \times g \; - \left\{ (R_c) \; + (R_f) \times \left| (u_n) \right| \right\} \times (u_n) \,, \;\; i = 1,2,3 \qquad (5)$$

$(R_c)_i$ is Darcy resistance constant (kg/m$^3$ s) and $(R_f)_i$ is called, by CFX, resistance speed factor (kg/m$^4$). $\mathbf{R_c} = (R_c^{ij})$, and $\mathbf{R}_f = (R_f^{ij})$, both are symmetric positive definite tensors, which accounts for possible resistance anisotropies in the porous media. There are different approaches of determining these tensors (Bear 1988).

In Darcy laminar flows with the pressure drop proportional to the flow velocity, viscous forces are dominant, and the second term on the r.h.s. of equation (5) can be dropped. The range, Re < 1-10, is characterized by the Blake-Kozeny flow resistance, called Darcy flow resistance. Equation (5) thus reduces to Darcy's law with the Darcy resistance defined by

$$(R_c)_i = \frac{\rho \times g}{K_i} n = \frac{\mu}{k_i} n \qquad (6)$$

At higher Reynolds number than allowed by Darcy's law, the second term on the r.h.s. of equation (5) provides a correction for inertial losses in the porous medium. $(R_c)_i$ can also be written as

$$(R_c)_i = \frac{1}{2} \times \rho \times (C_2)_i \qquad (7)$$

where $C_2$ is inertial resistance factor (m$^{-1}$). This factor can be viewed as a loss coefficient along the flow direction, thereby allowing the inertia-caused pressure drop to be specified in terms of dynamic head.

The range, 10 < Re < 1000, corresponds to the transition regime, where the Darcy and inertial flow resistance can be equally important. To what extent they contribute to the pressure drop in porous media depends on the magnitude of Re. The flow characteristics can be described by, say, the *Ergun* equation. Note that the deviation from Darcy's law immediately beyond its range of validity is attributed to inertia forces, not to turbulence. It is observed through experiments that the onset of turbulence occurs at Re in the range 60 to 150.

When Re > 1000, the flow is obviously turbulent and the inertial resistance, called the Forchheimer flow resistance, becomes predominant, and the Darcy flow resistance can be dropped.

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