Application of the ASAP Technique in the Geophysical and Industrial Scales: a Comparison with BFC

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Abstract

Calculations for two very different scale situations, one a geophysical case represented by hydrodynamics in a lake, and the other an industrial scale facility represented by air flow in a spillway aerator, have been performed using two different approaches, i.e., employing body fitted coordinates and the Arbitrary Source Allocation Procedure which implies the use of a Cartesian grid. Comparisons between the two models considering a qualitative and quantitative point of view, show similar results obtained when analyzing the flow patterns and the distribution of a scalar variable. An overall preliminary analysis of the cases here presented, seem to indicate that calculations using the ASAP technique present more advantages when compared with the BFC approach.

INTRODUCTION

Lakes

Although the literature about models developed to represent the hydrodynamics of a water body is extensive, Cheng (1976, 1977), there still remains uncertainties due mainly to the lack of accurate data to validate the models, Hondzo, (1993). A review of published models shows that the use of 2D models has proved adequate to determine the total volumetric transport, but they fail when the flow return is considered important. As these models can neither represent the superficial transport nor the local variations of any contaminant, a 3D computation is therefore required. These phenomena are important in density stratified lakes and reservoirs. Even shallow lakes present stratification which in turn affect mixing conditions and therefore the water quality parameters, as shown by the measurements of Ishikawa and Tanaka (1992) in Kasumigaura Lake in Japan, and confirmed by Sarkkula (1991) in Pyhajarvi Lake in Finland.

Regarding turbulence modeling in water bodies, Koutitas (1980) performed numerical tests and obtained a parabolic equation for the turbulent viscosity as a function of dimensionless depth. Based on measurements by Yu (1987), Jin and Kranenburg (1993) proposed a model similar to the one of Koutitas that includes the shear velocity as a parameter. Their results in terms of velocity profiles were practically the same as the ones obtained with the standard k-e model, although they overestimated the turbulent viscosity by 30% at half the depth of the lake, where velocity gradients are nearly zero and therefore their results are not considerably affected.

Aerators

Construction of very large dams has the associated problem of very high water velocities along the spillway surface, as this increases the probability of significant damage to the spillway structure because of the cavitation phenomena. This damage is diminished and practically avoided by an increase in air concentration in the water nappe in contact with the concrete surface, provided by a structure that allows the entrance of air into the lower water layer through step or ducted structures called aerators, which are built in specific locations along the spillway walls and surface, Chanson (1990, 1991), Pinto (1989). The study of aerators is mainly through the application of empirical models which depend on the geometry of the aerator and the properties of the flow such as the Froude number, air flow and vacuum pressure in the air cavity, parameters which are feasible to measure in scaled models, Schwartz and Nutt (1963), Sanchez (1992). However, these required measurements that characterize the aerator behaviour through the empirical models tend to be insufficient and very expensive to implement, and therefore numerical simulation appears to be a very useful tool that can analyze these devices, Rutschmann and Hager (1990), Wood (1991).

MATHEMATICAL FORMULATION

The partial differential equations describing the problems examined herein, are those of continuity and momentum for both cases. For the aerator problem an additional couple of turbulence transport equations and a species equation are considered.

Chapala Lake

The three-dimensional model employed for the simulation, considers the Coriolis force, the effect of the wind on the upper layer, as well as the friction effect and the bathymetry at the bottom of the domain. At the free surface the wind effect is considered through a shear stress:

$$\tau = C_d \, \rho_a U_{10}^2 \qquad (1)$$

where $C_d \approx 0.9E-03$ is the drag coefficient, ρ_a is the air density, and U_{10} is the wind velocity at 10 m height. The friction effect is considered through a velocity quadratic expression which employs the Chézy coefficient with a value of 50. Bathymetry was specified assigning a porosity distribution at the lower layer of cells.

The effect of turbulence was considered through the simplified model of Koutitas (1980) which assumes a parabolic distribution of the turbulent viscosity, and considering the modification of Jin and Kranenburg, (1993):

$$\nu_t = \nu_{\max} \, \eta \, (1 - \eta) \qquad (2)$$

$$\nu_{\max_{\eta=\frac{1}{2}}} = 0.4 \, h \, | u_* | (\frac{1}{4}) \qquad (3)$$

where η is an non dimensional elevation (zero at the bottom and one at the free surface), *h* is the local depth, and the shear velocity was calculated from the wind generated shear stress which for this case was 8.05 mPa. With this value, the turbulent viscosity ranged from 1 to 25 cm^2/s.

Aerator

The turbulence model employed is the standard ***k***-ε model, where the kinetic energy ***k***, and its dissipation rate ε, represent the velocity and length scale of the turbulent motion, respectively. For the calculation of the air distribution, an additional concentration equation was considered, and the boundary condition applied at the water-air interface is proposed by Wood, (1991):

$$\beta = K_1 (Fr - K_2) - K_3 (\Delta P / \rho g h) \quad (4)$$

where β is the ratio of the volumetric air to water flow, Fr is the Froude number, K_1, K_2, K_3 are constants, ΔP is the pressure difference, ρ is the air density, g is the gravity and h is the water depth.

The model takes into account the friction effect at solid walls such as the air duct and the bottom of the spillway, through the wall-function approach outlined by Rodi (1980), which means that the boundary conditions are not specified right at the wall but at a point outside the viscous sublayer, where the logarithmic law of the wall prevails and the turbulence can be assumed in local equilibrium.

RESULTS

Chapala Lake

Figure 1 shows the bathymetry of the lake, the value of 1.0 corresponding to the maximum depth of 10.85 m; the grid generated for the BFC calculations which appears in fig 2a was also employed as the main object for the ASAP model whose Cartesian grid is illustrated in fig 2b. For the BFC case the number of cells in the X, Y and Z directions are 40 x 20 x 10, while for the ASAP case they are 40 x 30 x 10. For the latter case the cells are uniformly distributed in the depth direction (i.e. Z axis), while in the former, the first cell encompasses the bottom topography.

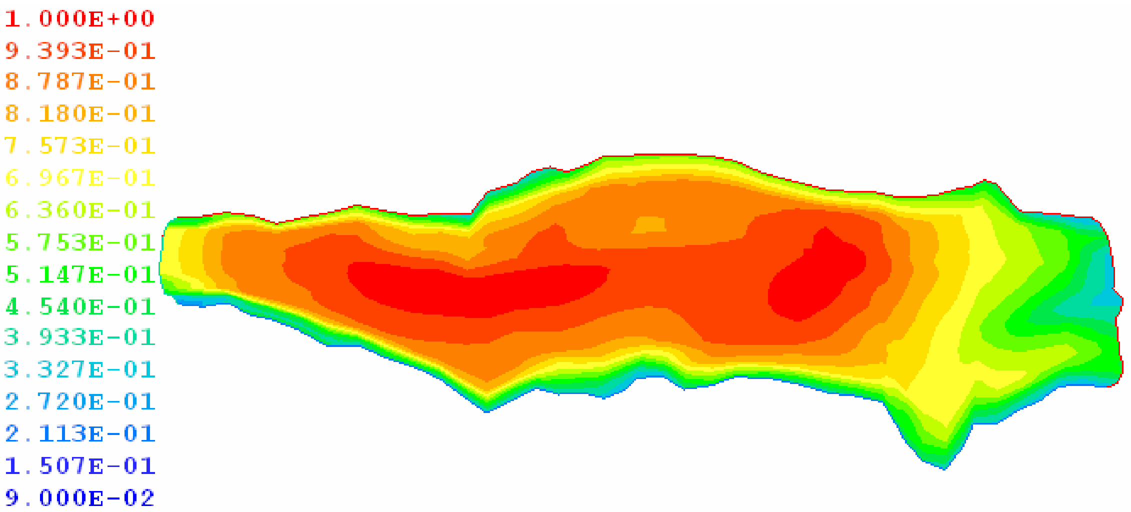
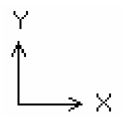
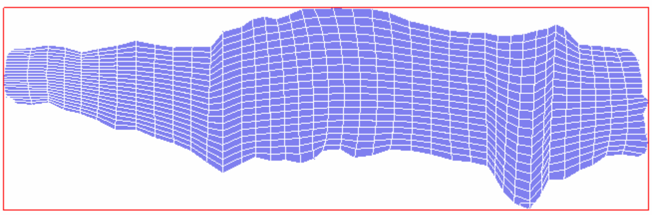


Fig 1. Bathymetry of the lake





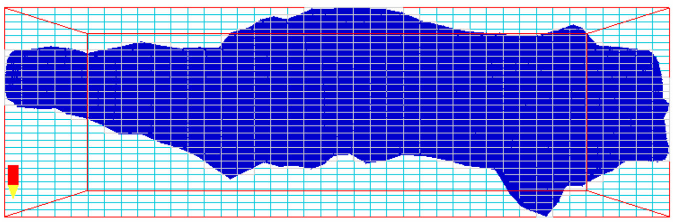


Fig 2a. BFC Grid **Fig 2b. ASAP Grid**

The flow patterns corresponding to the surface and the bottom of the lake are shown in figures 3 and 4, respectively. As for the surface velocities refers, the general flow pattern and order of magnitude is very similar. However, there appears to exist two basic differences between both approaches: the prediction according to the BFC calculations (fig 3) gives a maximum velocity of 22.5 cm/s, while the ASAP calculations (fig 4) results in a maximum value of 15.5 cm/s. The maximum values for the BFC case take place in the zone where the generated grid is very skewed (see fig 2a), and which forced to apply a heaviest relaxation in order to achieve convergence. It is interesting to mention that if the vectors corresponding to those cells are omitted when plotting (drawing) the figure, the maximum velocity becomes 15.6 cm/s, which is practically the same as for the ASAP case.

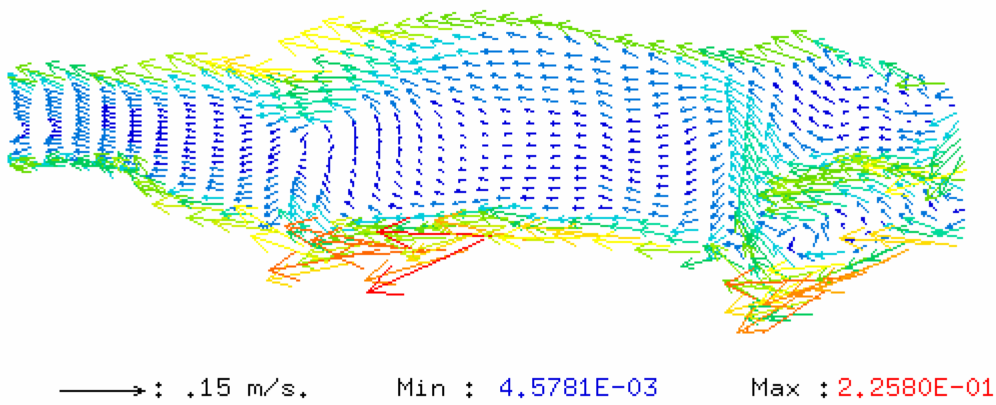


Fig 3. Surface velocity distribution, BFC

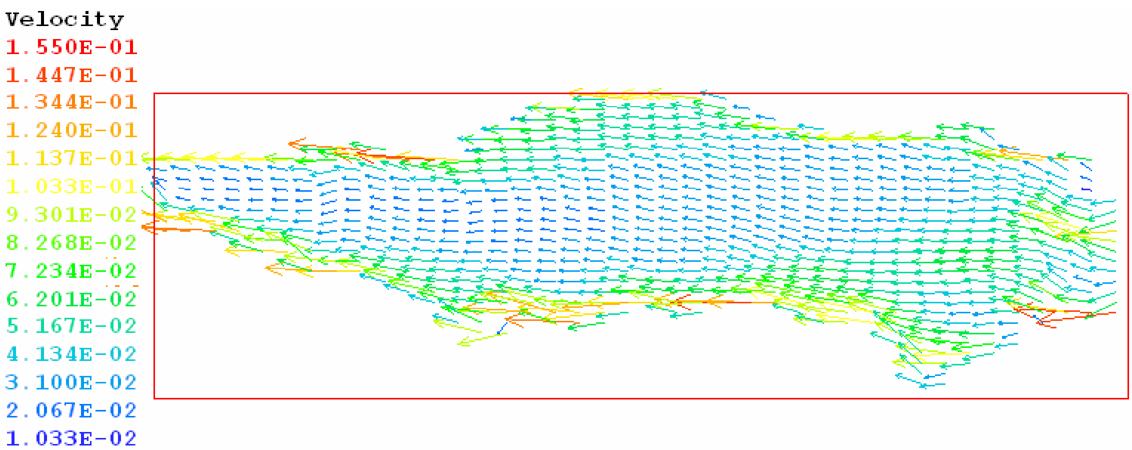


Fig 4. Surface velocity distribution, ASAP

The second difference is still more drastic considering that for the BFC case a zone with a marked upward vector deflection appears on the right side of the domain, while for the ASAP computations the flow direction is practically uniform although the change in magnitude still appears due mainly to the bathymetry of the lake. The assumption of the grid distortion being again the cause of the sudden change of direction seems plausible, as it takes place in the same region where the water suffers an acceleration on the river side inducing a local region of recirculation.

At the bottom of the lake the comparison results more favorable as the general flow pattern appears very similar for both cases. The flow return through the center of the lake is predicted by both approaches, together with the three main recirculation zones which clearly appear in figures 5 and 6. Once again the maximum velocity for the BFC case occurs in the same location as for the surface velocity distribution, and if it is omitted from the figure, the maximum velocity falls to nearly 4 cm/s which is very close to the 3.8 cm/s value obtained with the ASAP calculations.

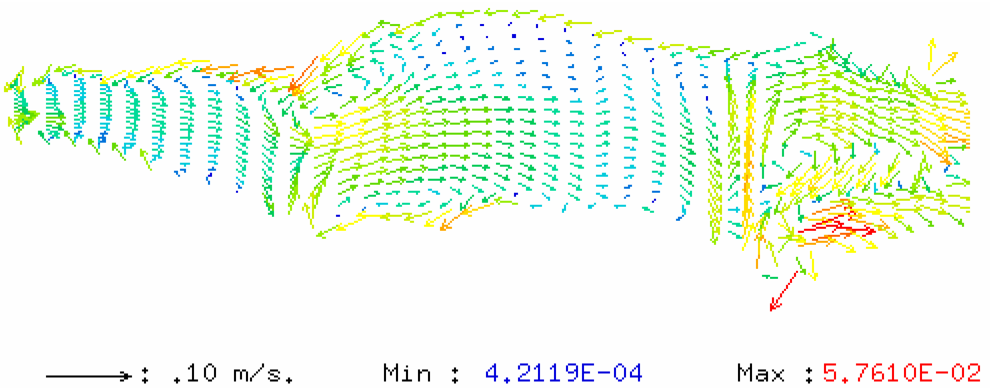


Fig 5. Bottom velocity distribution, BFC

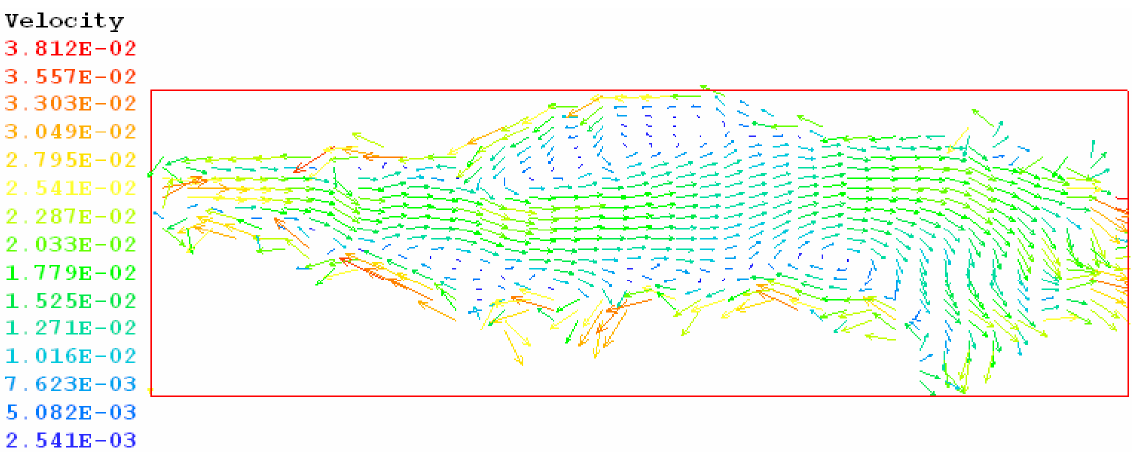


Fig 6. Bottom velocity distribution, ASAP

Spillway Aerator

The general geometric characteristics of the spillway aerator are depicted in figure 7, while the dimensions of the domain appear in the BFC grid shown in figure 8a. The corresponding Cartesian grid defined for the ASAP calculations was specified employing STL files previously generated for the geometry of the water nappe and the spillway surface; it is presented in figure 8b.

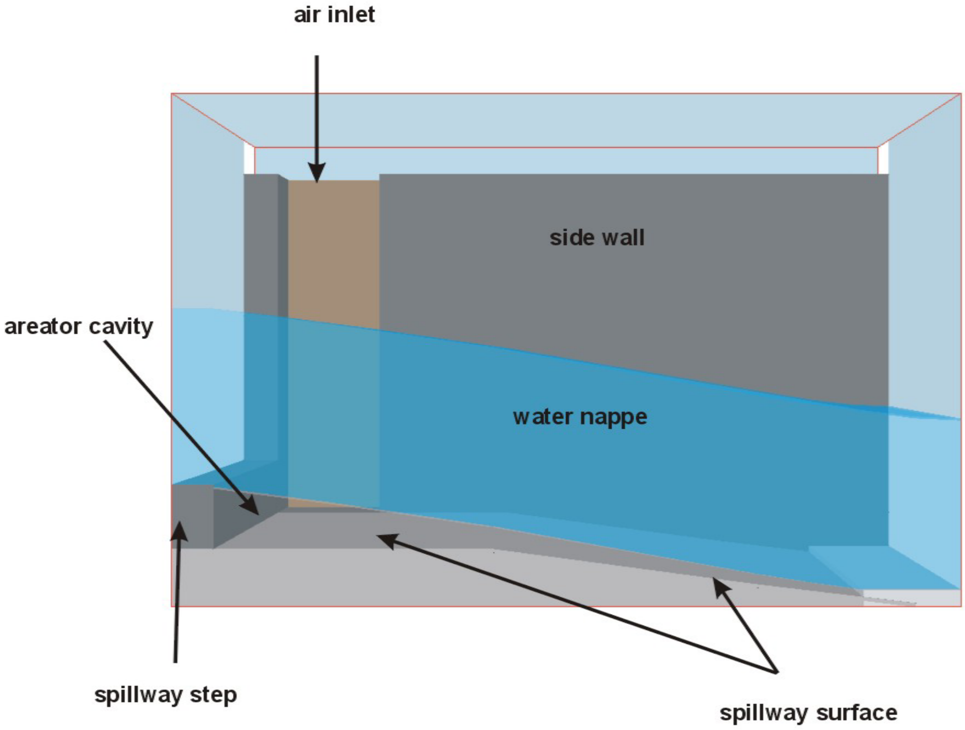
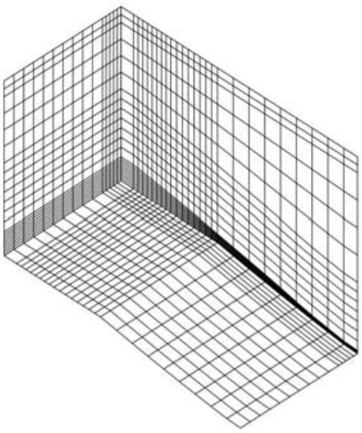


Figure 7. Spllway aerator



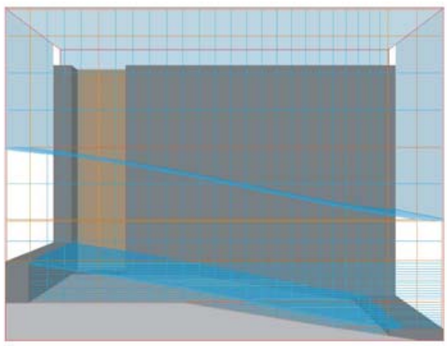


Fig 8a. BFC Grid **Fig 8b. ASAP Grid**

The main parameter for characterization of a spillway aerator is the air pressure and flow distribution inside the ventilated cavity, which is represented by the value of beta previously defined in equation (4). The air distribution depends on the vacuum pressure difference generated inside the cavity, which is also influenced by the flow pattern developed by the incoming air. The velocity vectors calculated near the spillway surface using the BFC approach are shown in figure 9, where it can be seen that a strong air jet entering into the cavity causes a well defined recirculation zone.

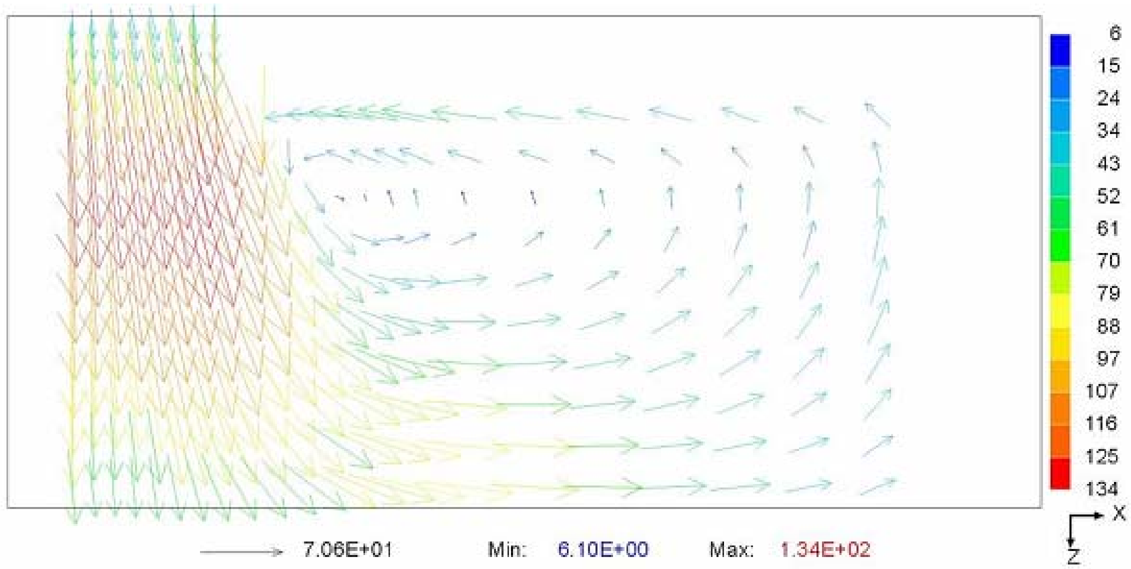


Fig. 9. Air velocity at bottom of spillway, BFC

For the ASAP case (fig 10), the general flow pattern coincides, the main differences being that the recirculation zone moves rightwards and the maximum velocity is approximately 15 percent lower than the one obtained with the BFC model.

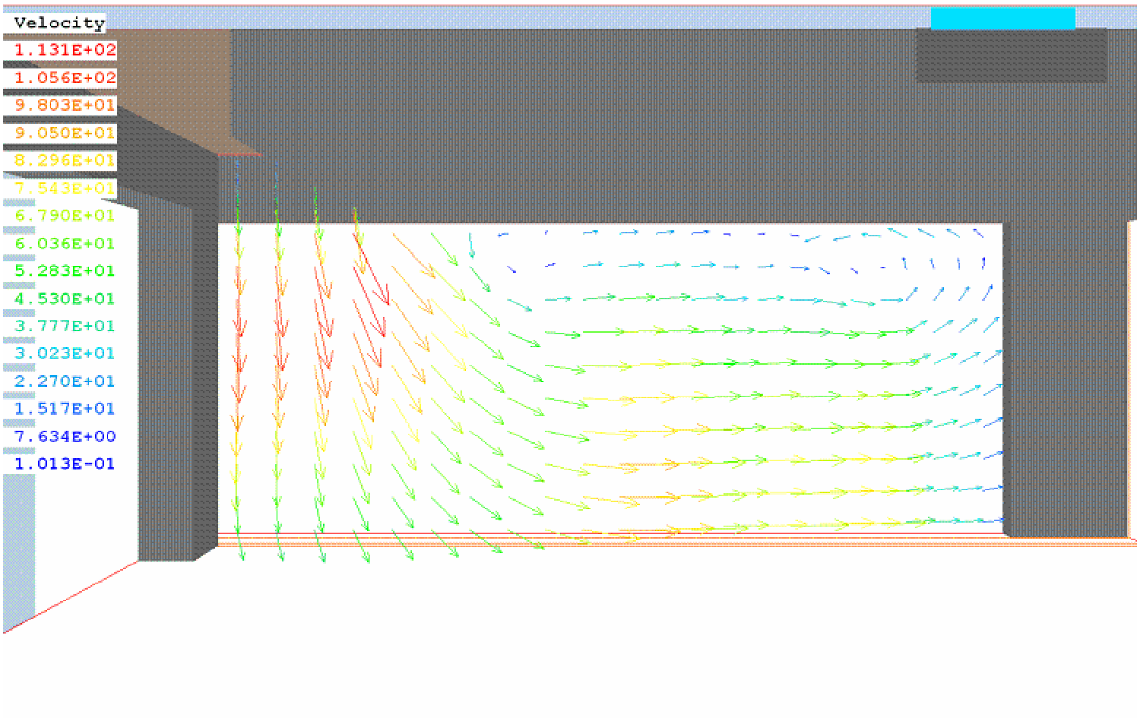


Fig. 10. **Air velocity at bottom of spillway, ASAP**

As a consequence of the flow patterns outlined above, the air ingress into the water nappe distribution represented by the β parameter in the ventilated cavity appears as in figures 11 and 12 for the BFC and ASAP case respectively.

Fig. 11. **Beta distribution in the ventilated cavity, BFC**

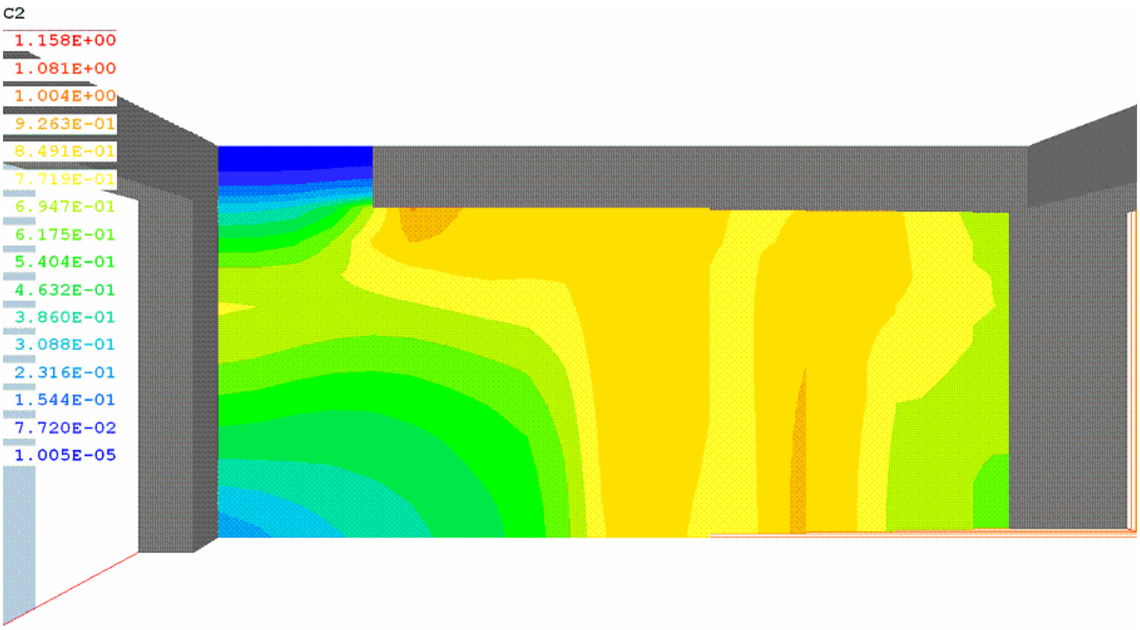


Fig. 12. Beta distribution in the ventilated cavity, ASAP

The isopleth lines follow with good approximation the same contours in both cases, differing in less than 4% the maximum value. For the BFC case is clearly marked the zone of maximum values in the location where velocities attain recirculation (fig 11), while for the ASAP case the maximum values are located basically in the same region but for a smaller zone (fig 12).

CONCLUSIONS

Calculations for two very different scale situations, one a geophysical case represented by hydrodynamics in a lake, and the other an industrial facility represented by air flow in a spillway aerator, have been performed using two different approaches, i.e., employing body fitted coordinates and the Arbitrary Source Allocation Procedure which implies the use of a Cartesian grid.

Comparisons between the two models considering a qualitative and quantitative point of view, show very much similitude in the results obtained when analyzing the flow patterns and the distribution of a scalar variable.

The computations performed with the ASAP technique require a very moderate relaxation for velocities and no relaxation at all for the pressure, while the BFC computations require as usual a stronger relaxation for velocities, and for cases like the ones here presented a heavy linear relaxation for the pressure with values oscillating between 2 and 3.

Even though a BFC computation normally requires a larger amount of space to store and manipulate the information, a direct comparison on the amount of space occupied by each case is not very simple, as the ASAP calculations require a larger amount of cells in order to attain the same grid refinement, due to those cells which are automatically blocked and kept out of the calculations for lying outside the boundaries of the domain.

An overall preliminary analysis of the cases here presented, seem to indicate the calculations using the ASAP technique present more advantages when compared with the BFC approach:

- It allows to represent the domain in a very straightforward manner by just defining the geometry with an autocad file and then simply assigning the desired grid refinement
- Convergence is much easily attained
- The results obtained do not suffer from grid generation problems, as for the BFC cases where the grid presents very skewed cells

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