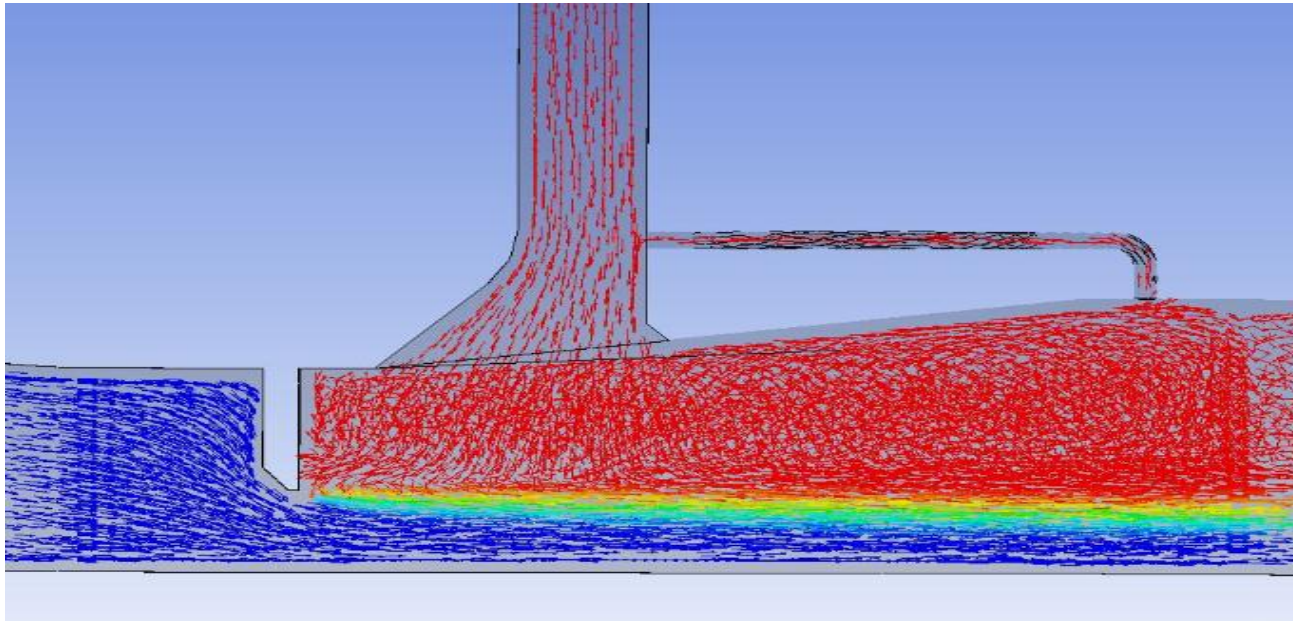
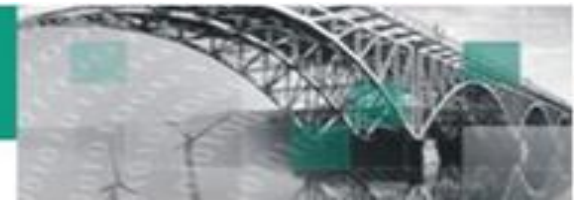




INVESTIGATION OF THE SUDDEN AIR RELEASE UP THE AIR SHAFT OF THE BERG RIVER DAM BOTTOM OUTLET STRUCTURE DURING EMERGENCY GATE CLOSURE USING NUMERICAL MODELING METHODS



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❖ CONTENT

- ❑ **Problem statement, Hypotheses and Objective**
- ❑ **Literature Review**
- ❑ **Numerical Model**
- ❑ **Simulation Results**
- ❑ **Conclusion and Recommendations**



❖ *Problem statement*

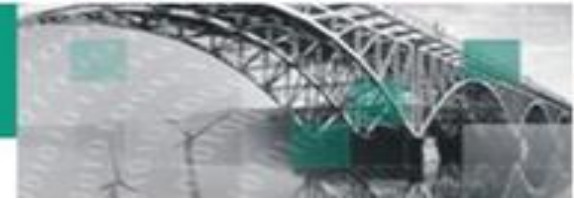
During the commissioning of the Berg River Dam Bottom (BRD) outlet, large volumes of air were released up the air shaft during emergency gate closure, an unexpected phenomenon since the structure was designed to provide aeration to the flow downstream of the gate to avoid negative pressures.

❖ *Hypotheses*

- Vortices in wet well entrained air in flow which was released downstream of the gate
- Varying discharge during gate closure caused a surge effect on the air-water mixture

Objective

- ❖ Use CFD modelling on a 3D model of the BRD for steady state simulations to determine if the air shaft is adequate to provide aeration to the flow for various emergency gate openings



❖ Literature review

Bottom outlets are recommended safety structures on dams.

✓ Purposes include:

- Flushing of sediment deposits
- Drawdown of the reservoir
- Flood and residual discharge diversion
- Environmental flood releases.

Velocity V in the bottom outlets is approximated by (Torricelli ,1643) :

$$V = (2gH_0)^{1/2}$$

where H_0 is the head on the outlet (m) and g the acceleration due to gravity (m/s^2).



✓ **Limitations** include:

- cavitation
- abrasion
- vibrations
- vortex formation at intakes
- air entrainment
- erosion

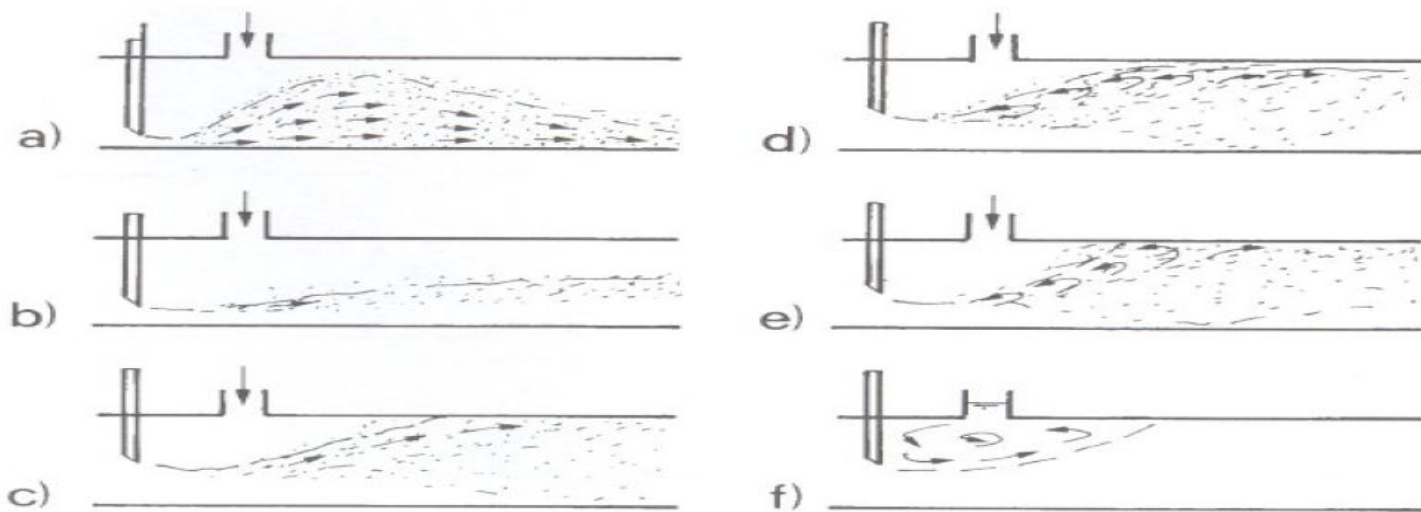


Figure 1: Classification of flow types in bottom outlets (Sharma, 1976)



✓ Gate Discharge

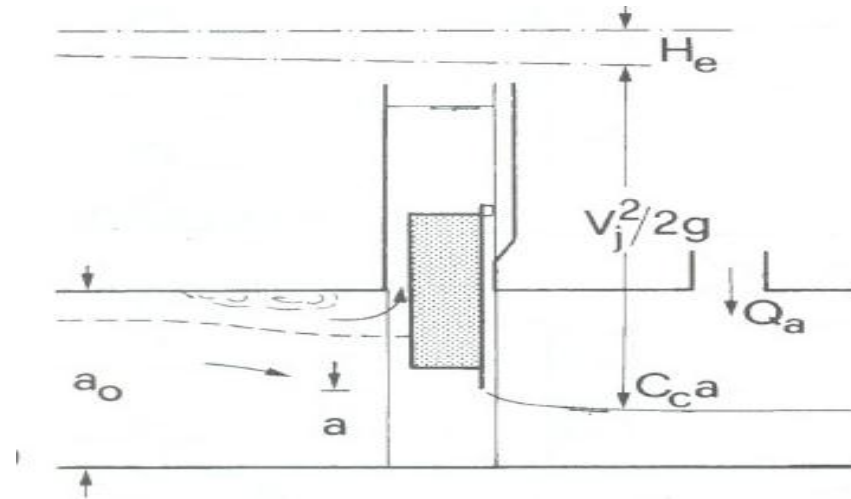


Figure 2: Definition sketch for free gate flow based on an experimental setup (Naudascher, 1991)

Gate discharge equation (Naudascher, 1991):

$$Q = C_c ab [2g(H - H_e - C_c a - h_a)]^{1/2}$$

where C_c - contraction coefficient, a - gate opening, b - gate width, $(H - H_e)$ - head on the gate with H_e the energy loss from the entrance to the gate section.



✓ **Aeration behind gates in conduits**

- Sharma (1976) recommended estimation of maximum airflow rate before ventilation shaft design.
- Inadequate air discharge could increase the vacuum behind the gates.

✓ **Air Demand ratio, β**

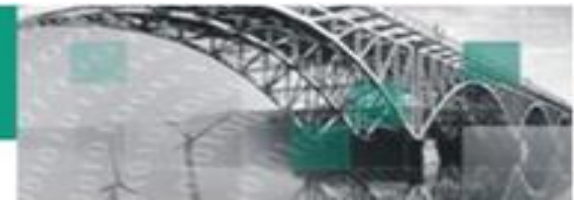
- Defined as the ratio of air flow to water flow (Kalinske and Robertson, 1943) is a function of the Froude number .

$$\beta = Q_a/Q_w$$

where Q_a is the air discharge and Q_w is the water discharge.

$$\beta = K(Fr - 1)^n$$

Where Fr = Froude number at vena contracta ($Fr = V/\sqrt{(gy)}$ where V - flow velocity at vena contracta, y - water depth at the vena contracta), K and n = empirical coefficients



- Maximum air velocity in the air shaft should be limited to 45 m/s (U.S Army Corps of Engineers, 1964)
- Using the discharge and aeration ratio equations, calculations for various openings of the emergency gate proved the air shaft's adequacy to aerate the flow downstream of the gate (air velocities were less than 45 m/s).



❖ Numerical Modelling

Table 1: Simulation scenarios

Emergency gate opening (%)	Intake gate opening (%)	Radial gate opening (%)
20	100 (middle pair of gates)	100
30	100 (middle pair of gates)	100
40	100 (middle pair of gates)	100
50	100 (middle pair of gates)	100
60	100 (middle pair of gates)	100
70	100 (middle pair of gates)	100

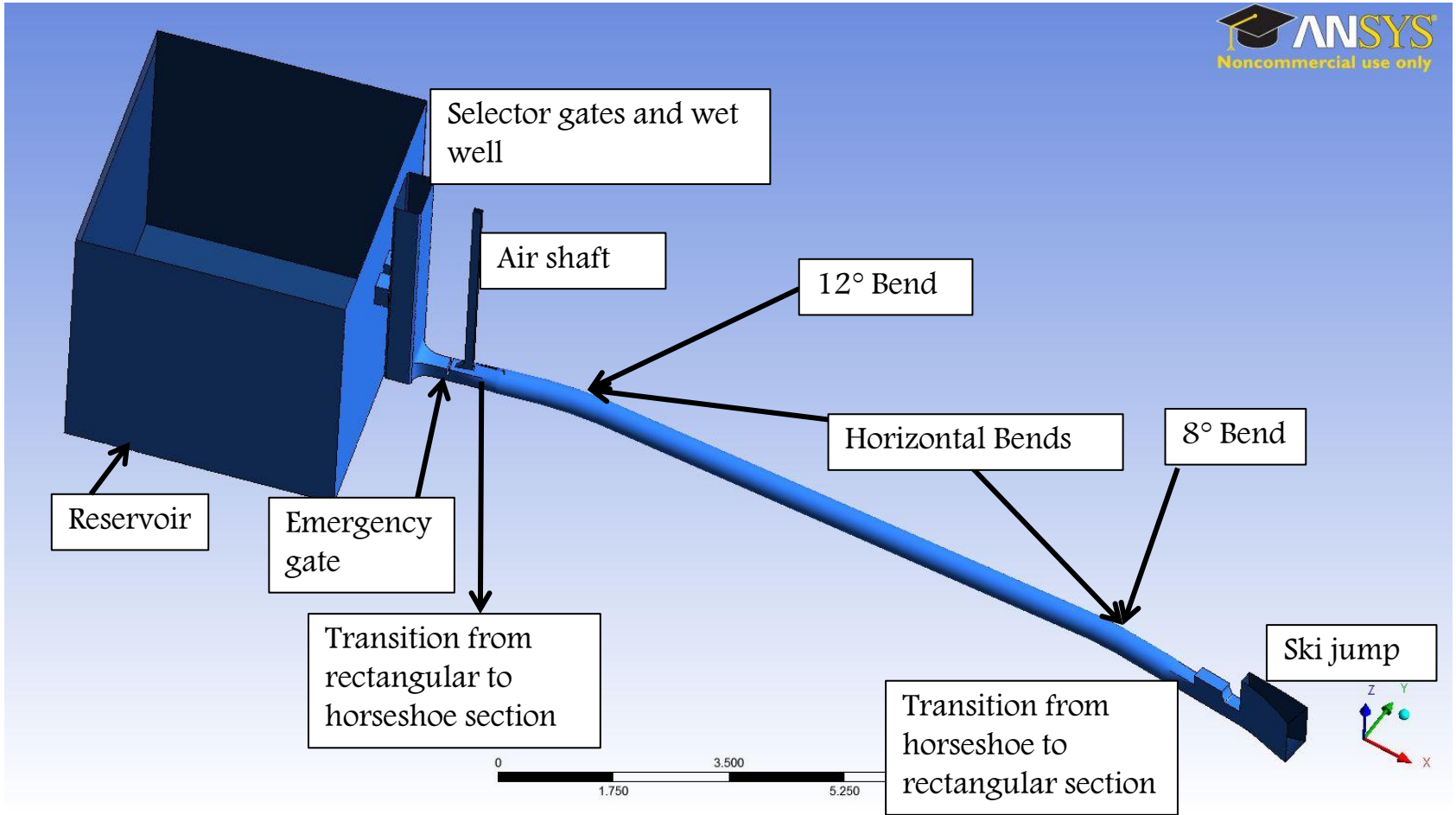


Figure 3: 3D model domain





- Model scaled to physical model size (1:14.066)
- Mesh at the gate region modified to accommodate 60° gate lip.
- Mesh sizes range from 10mm (gate and air shaft) to 60mm (reservoir).
- Over 2.5million elements generated
- Spillage allowed on side of reservoir to maintain commissioning water level.



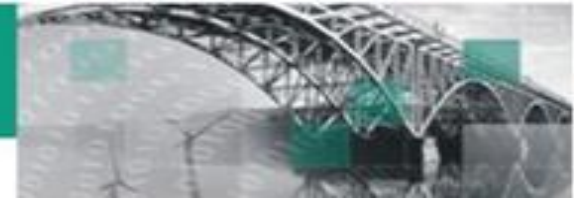
✓ Boundary Conditions

- Reservoir bottom (velocity inlet, 0.03m/s)
 - Reservoir surface
 - Wet well surface
 - Air shaft surface
 - Ski jump surface
- } Atmospheric pressure
- Operating pressure (101325 Pa)
 - Densities (1.225kg/m³- air and 998.2 kg/m³ - water)
 - Gravity enabled
 - Water air surface tension (0.0728 N/m)



✓ *ANSYS Solver*

- Steady state, fixed gate openings
- Volume of Fluid (VOF) - Air and water phases
- k-epsilon turbulence model
- Standard wall functions - No slip
- SIMPLE algorithm - First order



✓ **Limitations**

- ❖ Model complexity (Construction, Grid generation)
- ❖ Inaccurate original / as built drawings
- ❖ Calculation time and storage space
- ❖ Divergence/Model stabilisation (requires experience)
- ❖ Compromise between storage space and simulation data
- ❖ Limited post processing options in FLUENT
- ❖ Can't see what happens out of the domain



❖ *Simulation Results*

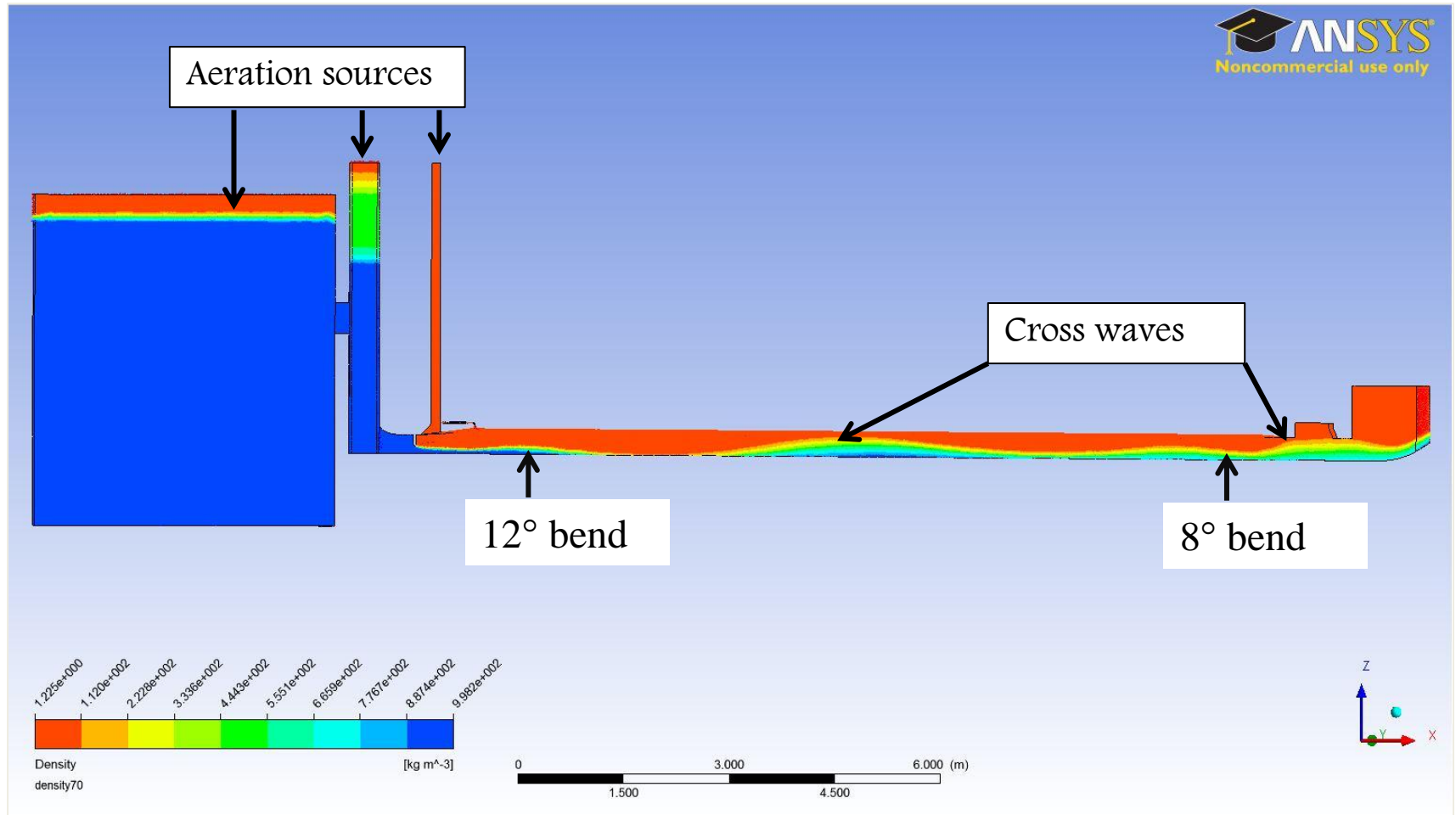


Figure 4A : Density contours for 40% emergency gate opening (CFD)



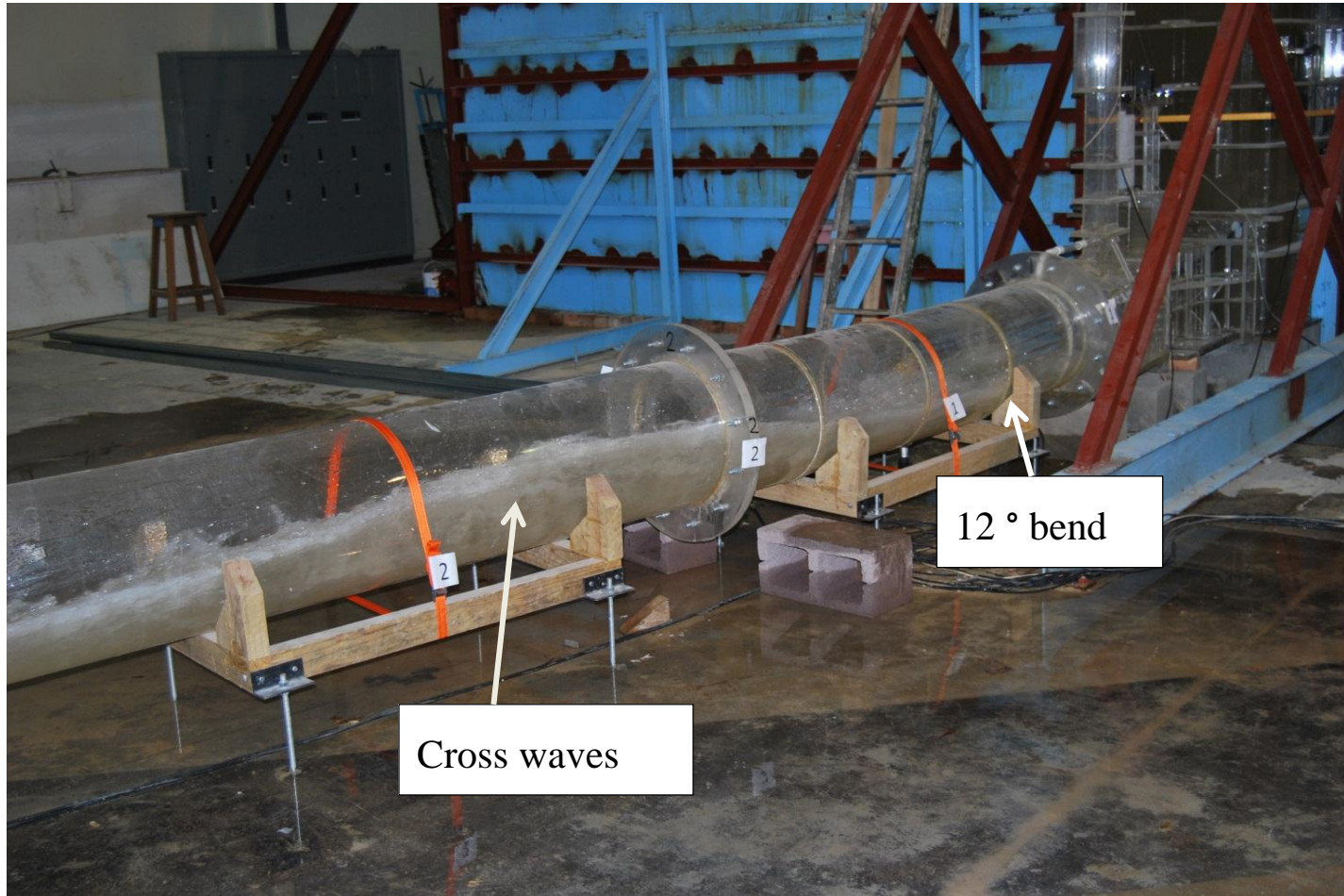


Figure 4B : Flow pattern for 40% emergency gate opening (Physical)



Figure 4A of the CFD model shows the following:

- Water (density 998.2kg/m^3 , shown in blue) in reservoir and wet well upstream of gate
- Air (density 1.225kg/m^3 , shown in red) in air shaft and above the flow in conduit
- Aerated flow (varying density, shown in orange, yellow or green) downstream of gate
- Cross wave formation downstream of 12° bend

Figure 4B for the physical model exhibits similar flow patterns as described for the CFD model above.

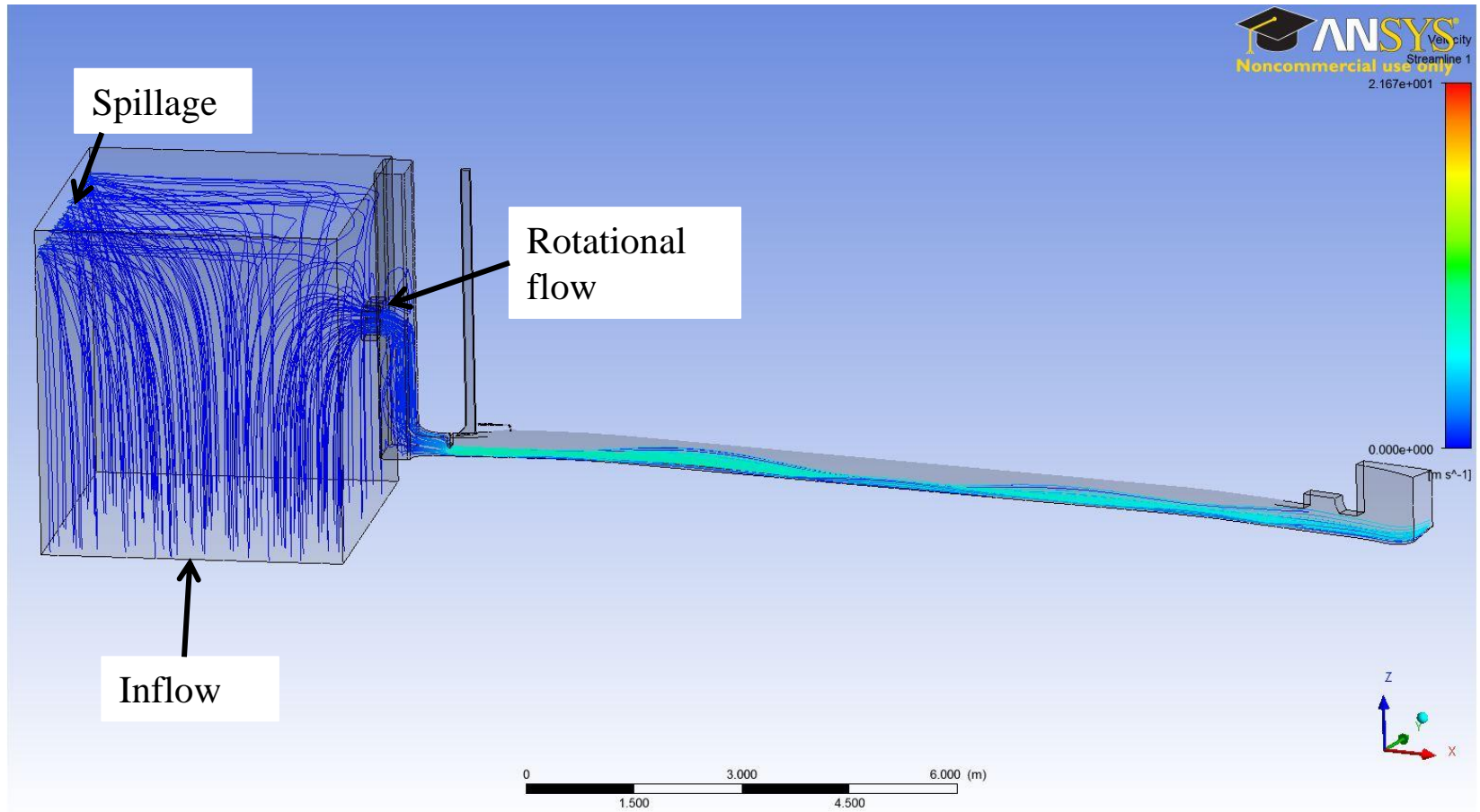


Figure 5 . Streamlines for 40% emergency gate opening

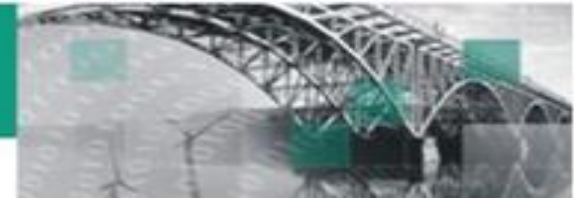


Figure 5 shows the following:

- Streamlines originating from bottom of reservoir
- Spillage of excess flow at side of reservoir
- Varying flow velocities (Blue – 0 m/s, red – 22m/s)
- Rotational flow in wet well

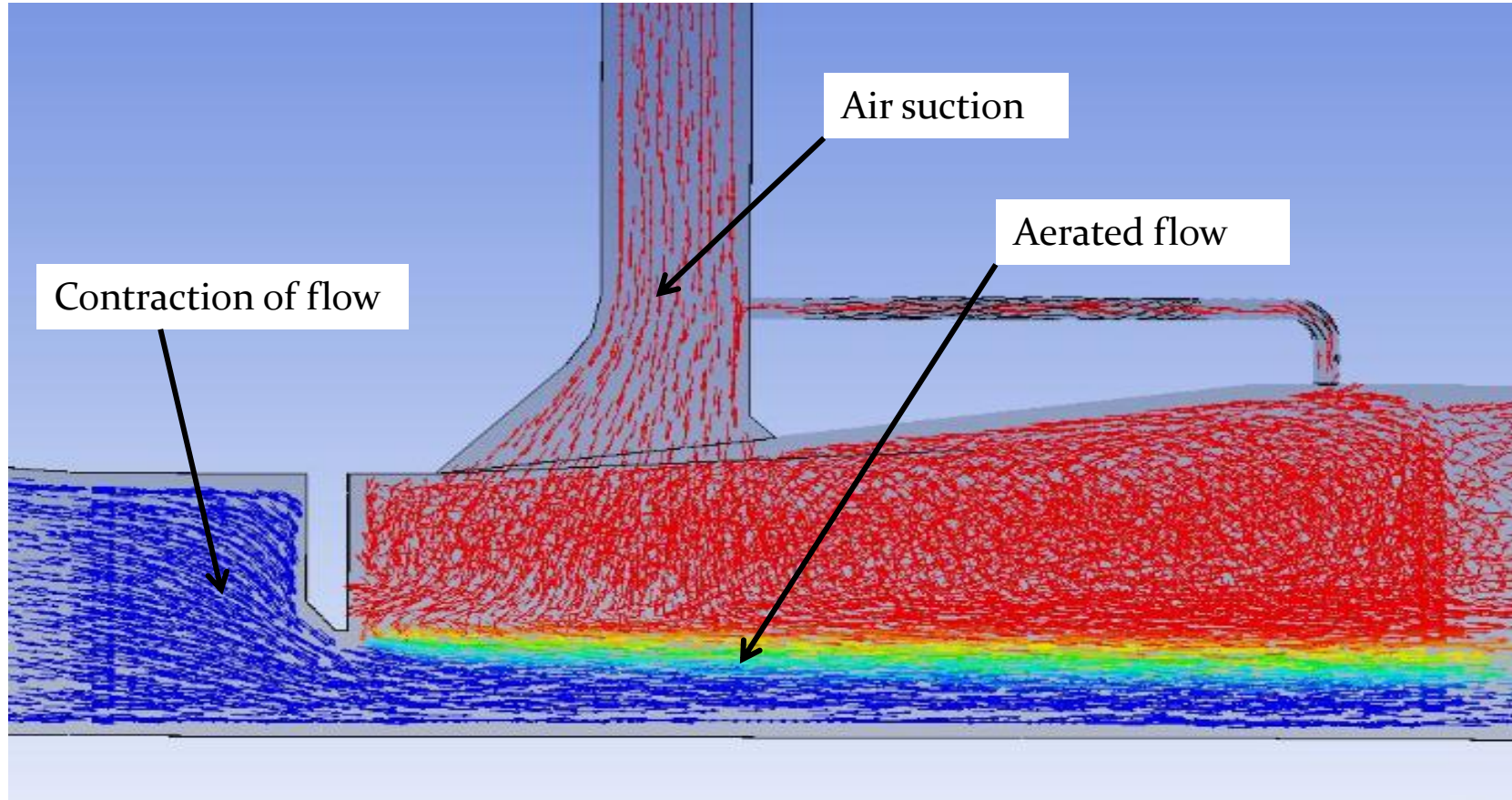
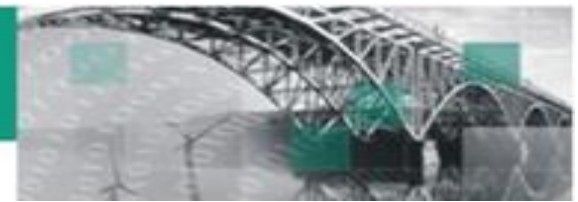


Figure 6B : Velocity vector of flow for 40% emergency gate opening

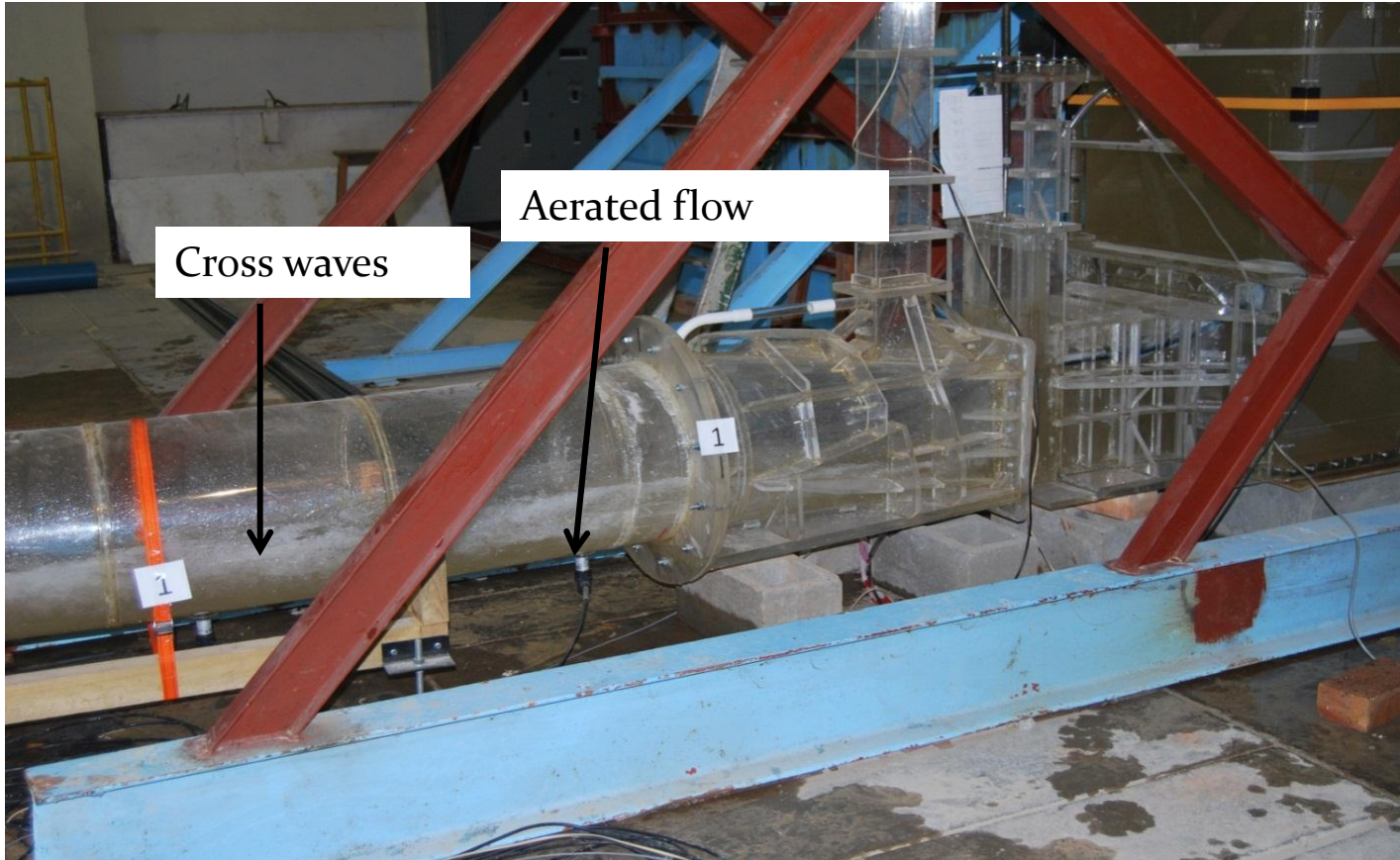
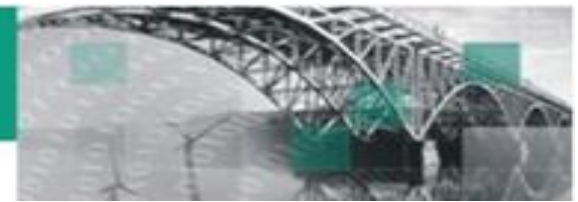


Figure 6B : Velocity vector of flow for 40% emergency gate opening



Figure 6A and 6B shows the following:

- Velocity vectors of flow around the emergency and air shaft region (6A)
- Blue represents water and red represents air (6A)
- Contraction of water upstream of the emergency gate
- Aerated flow downstream of the emergency gate
- Suction of air from the air shaft and above the flow from the gate (6A)

Figure 7 below shows the following:

- Pressure contours around gate region (Blue - -1500Pa, red - 4200Pa)
- Negative pressure at gate lip (0.267m of water below zero)

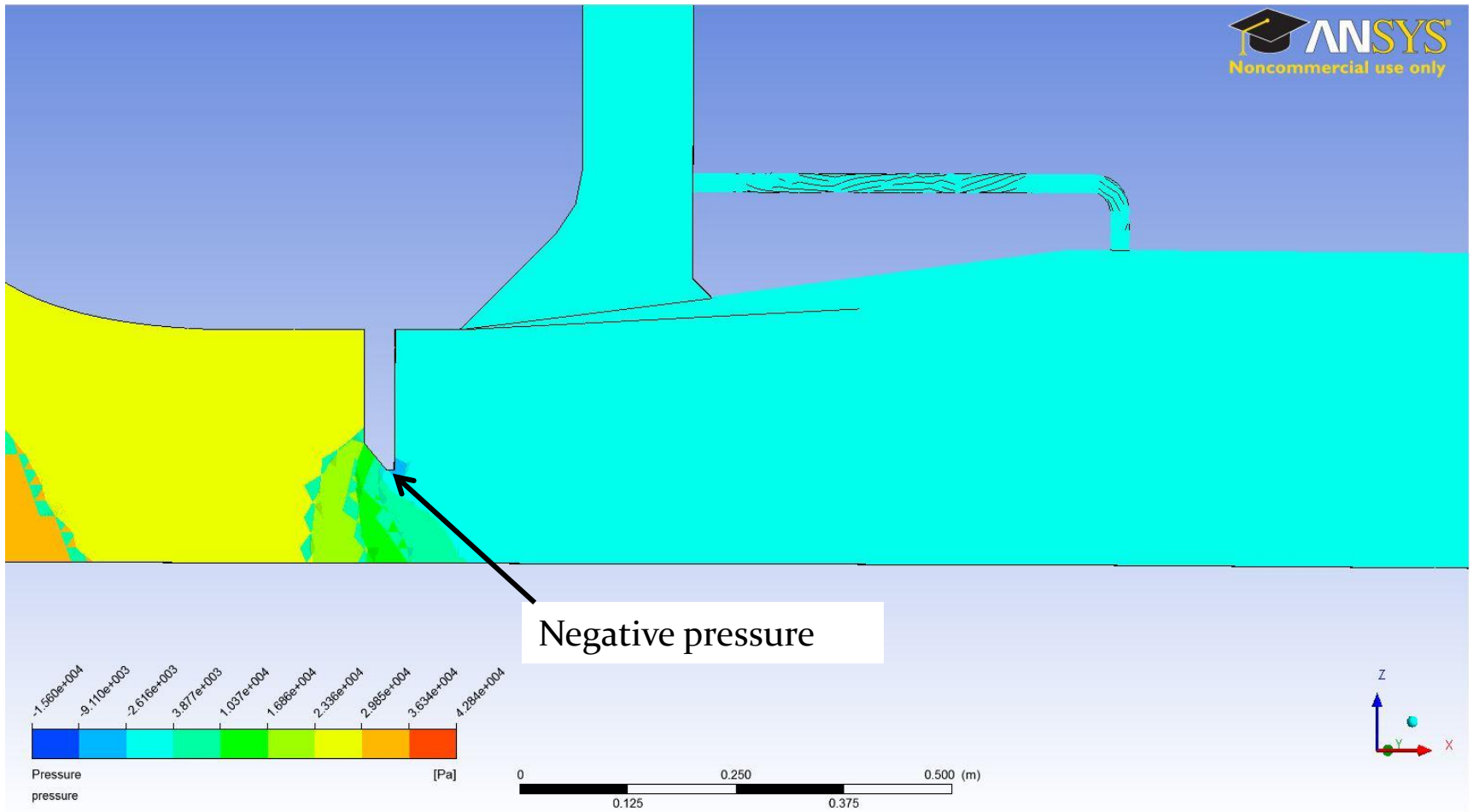


Figure 7 . Pressure contours for 40% emergency gate opening (CFD)

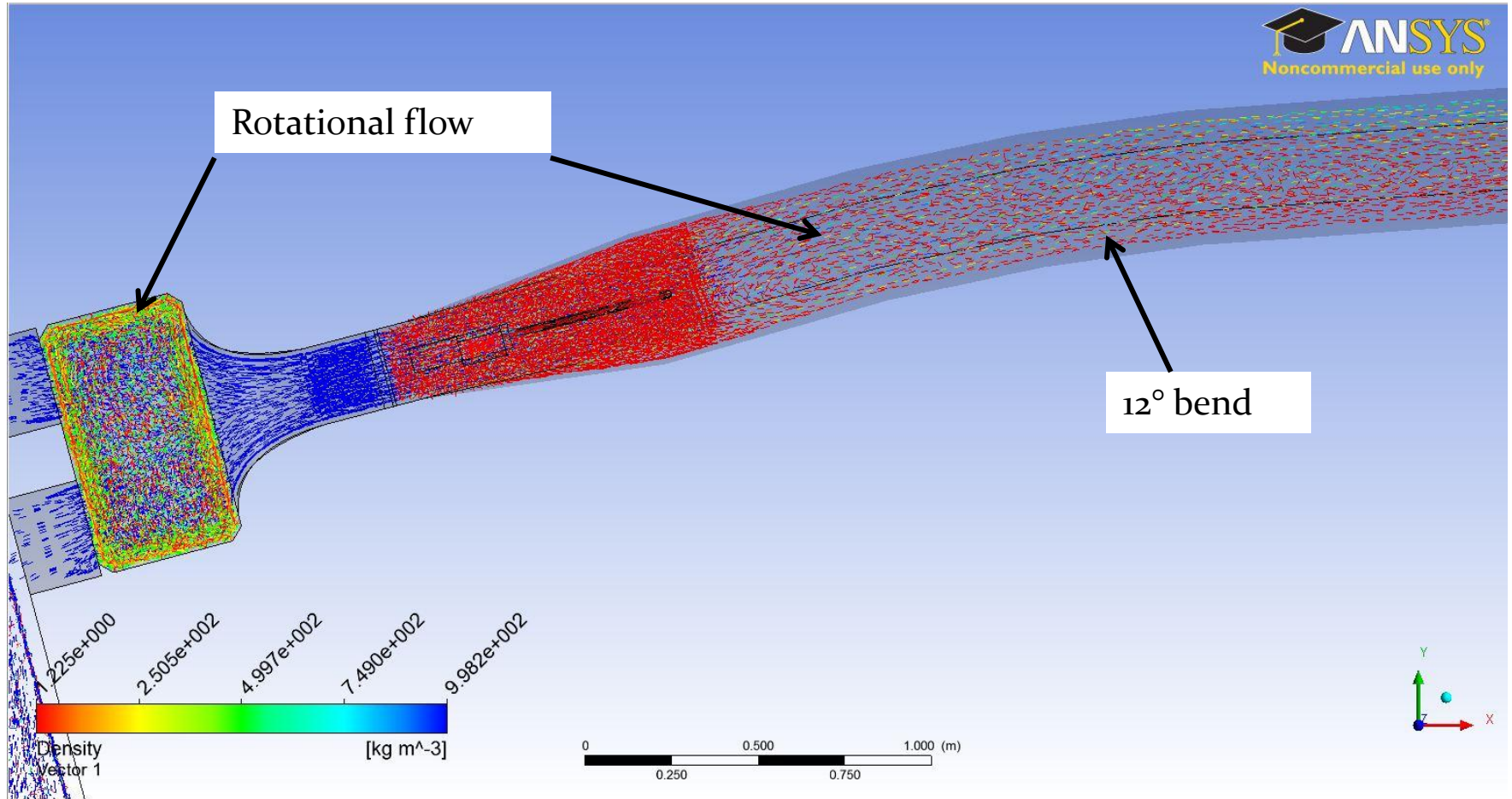
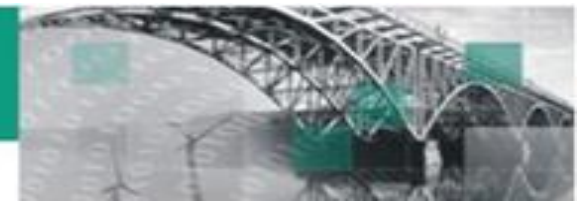


Figure 8 : Plan view of velocity vectors at 12° bend for 40% emergency gate opening (CFD)



Figure 8 shows the following:

- Plan view of velocity vectors of fluid flow in the wet well and 12° bend region
- Red represents air and blue represents water
- Contraction of flow from wet well to emergency gate and expansion from emergency gate to conduit
- Rotational flow in the wet well and region of the bend

Figure 9 shows the following:

- Plan view of velocity vectors of fluid flow in the wet well and 8° bend region
- Red represents air and blue represents water
- Contraction of flow from horseshoe conduit to rectangular radial gate region
- Rotational flow downstream of the bend at the beginning of the constriction

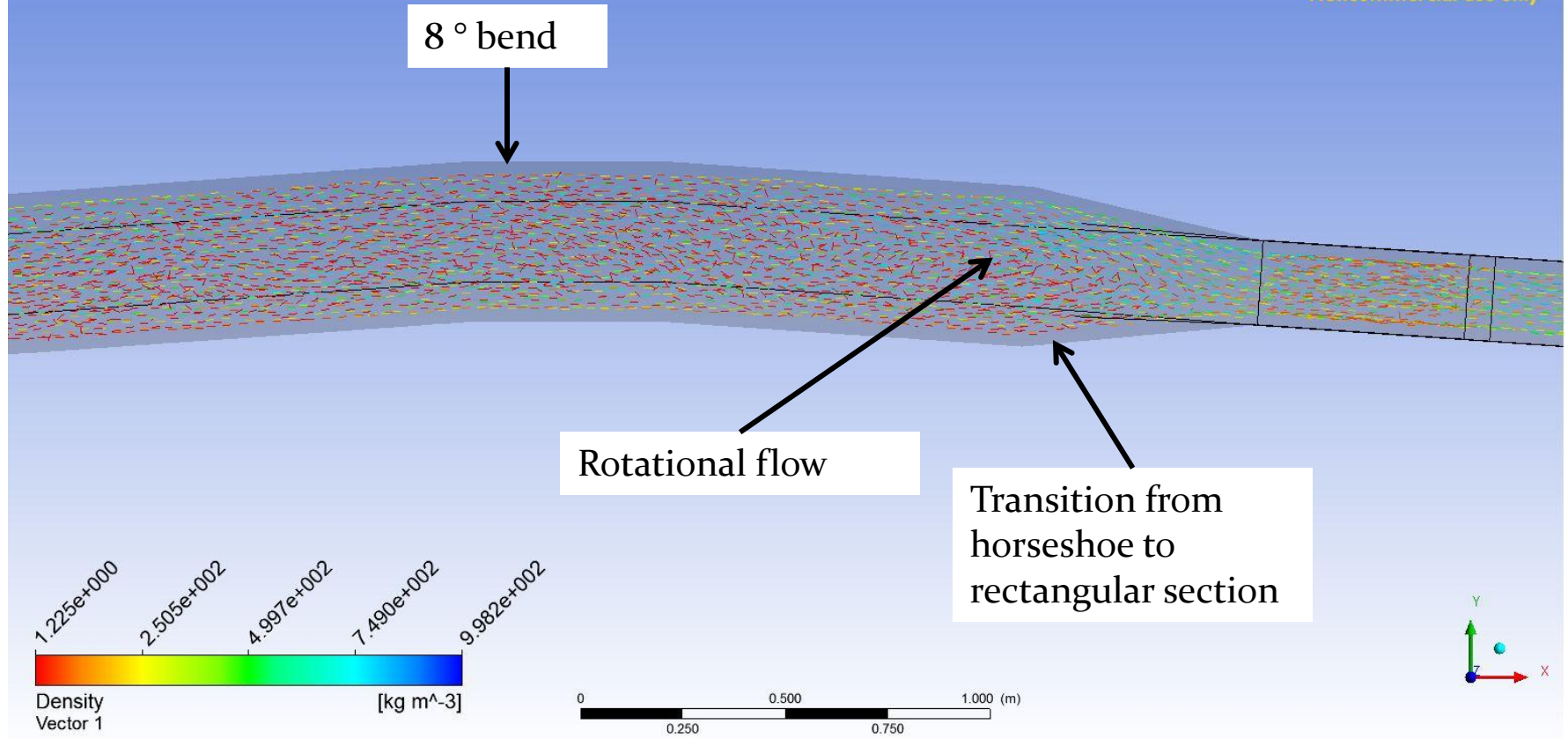


Figure 9 : Top view velocity vectors at 8° bend for 40% emergency gate opening (CFD)



Plot of Emergency gate discharge against Emergency gate opening

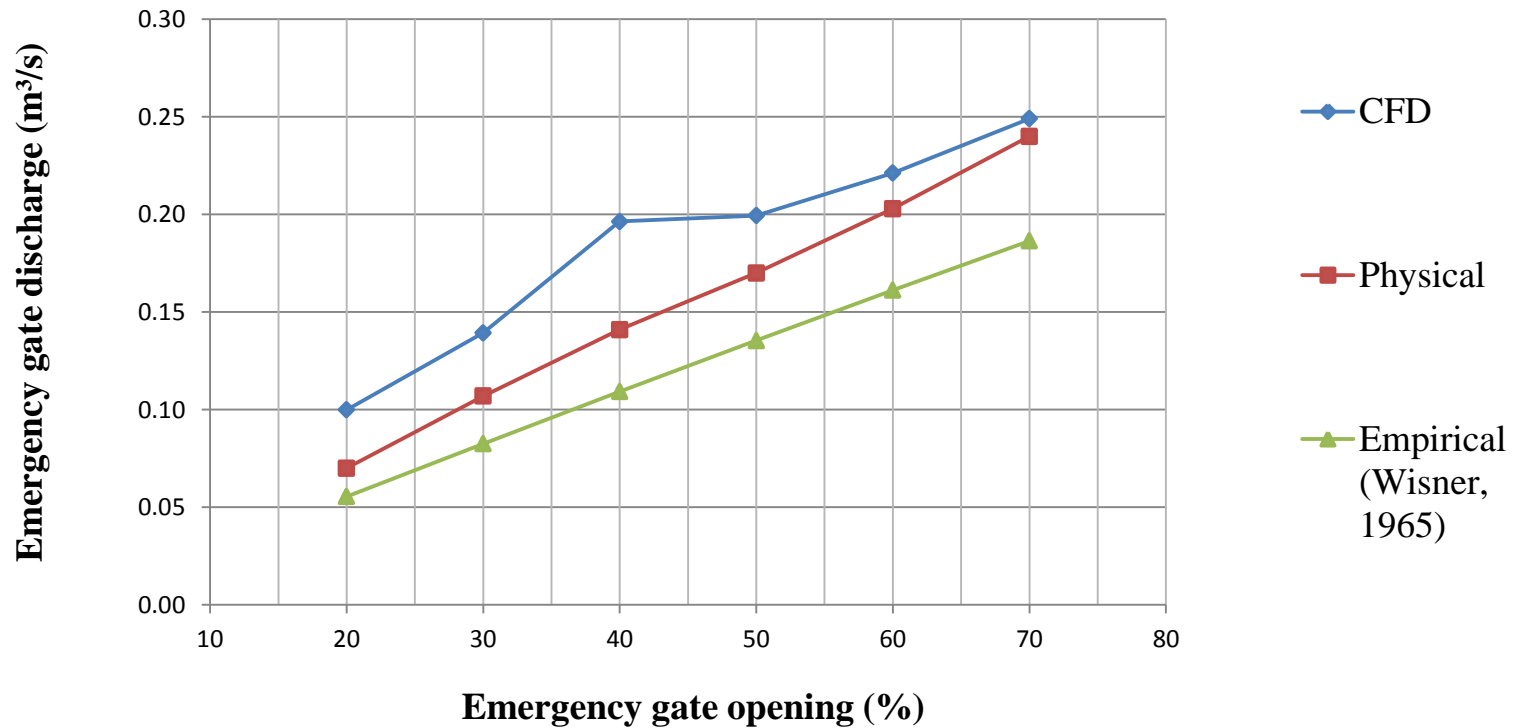


Figure 10: Variation of discharge with different emergency gate openings



Figure 10 shows the following:

- Plot of discharge for the CFD model, the physical model and the empirical calculations (Wisner, 1965) for various gate openings.
- Discharge increases with increasing gate opening

Figure 11 below shows the following:

- Plot of air velocities in air vent for the CFD model, physical model, empirical calculations (Wisner, 1965) and scaled prototype values.
- Air suction decreases with increasing gate opening for CFD, measured and empirical
- Air expulsion decreases with increasing gate opening in prototype
- Note: In the prototype the gate was being closed when air velocities were measured



Plot of Air velocity against Emergency gate opening

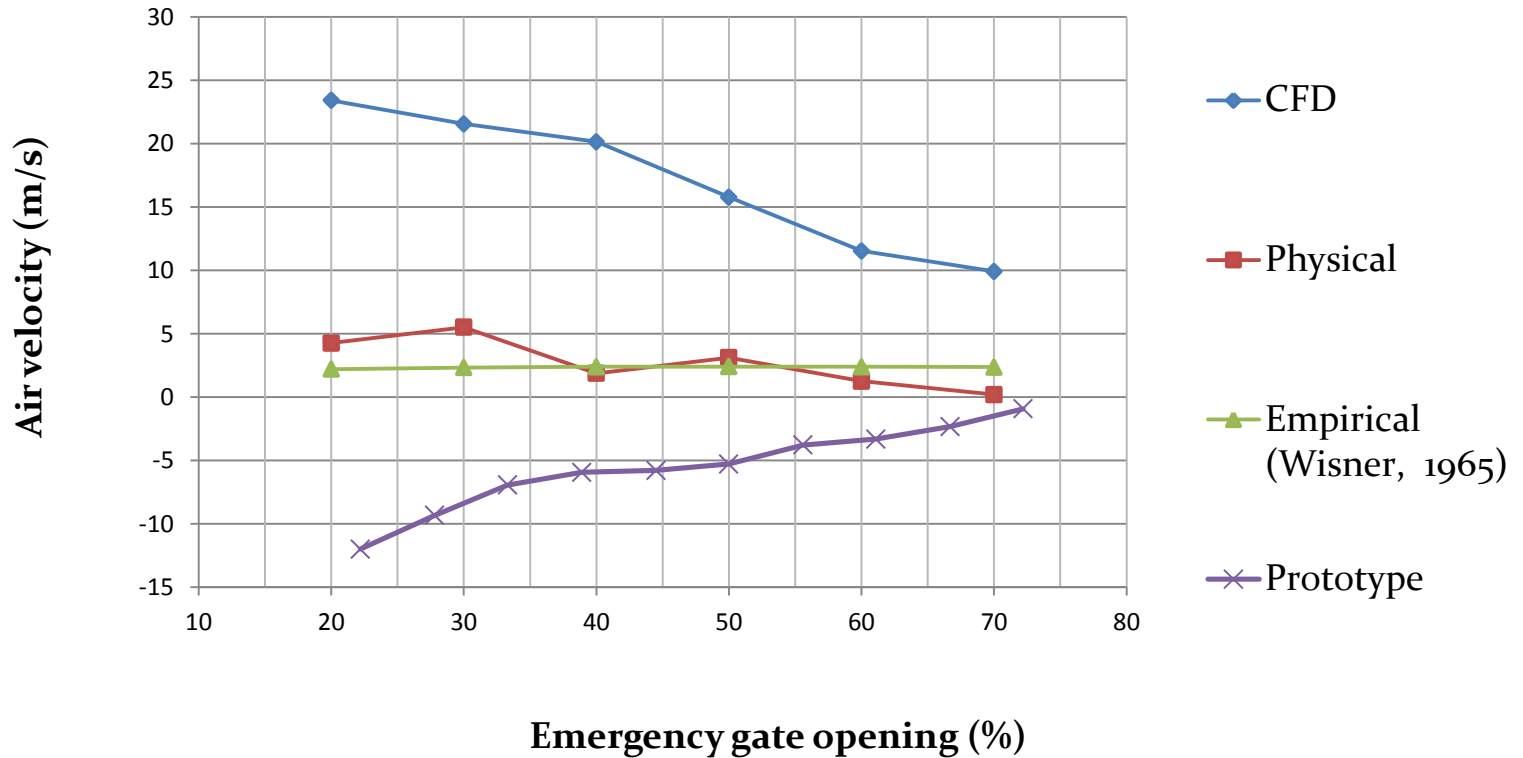


Figure 11: Variation of air velocity in air shaft for different gate openings



Plot of Aeration ratio against Emergency gate opening

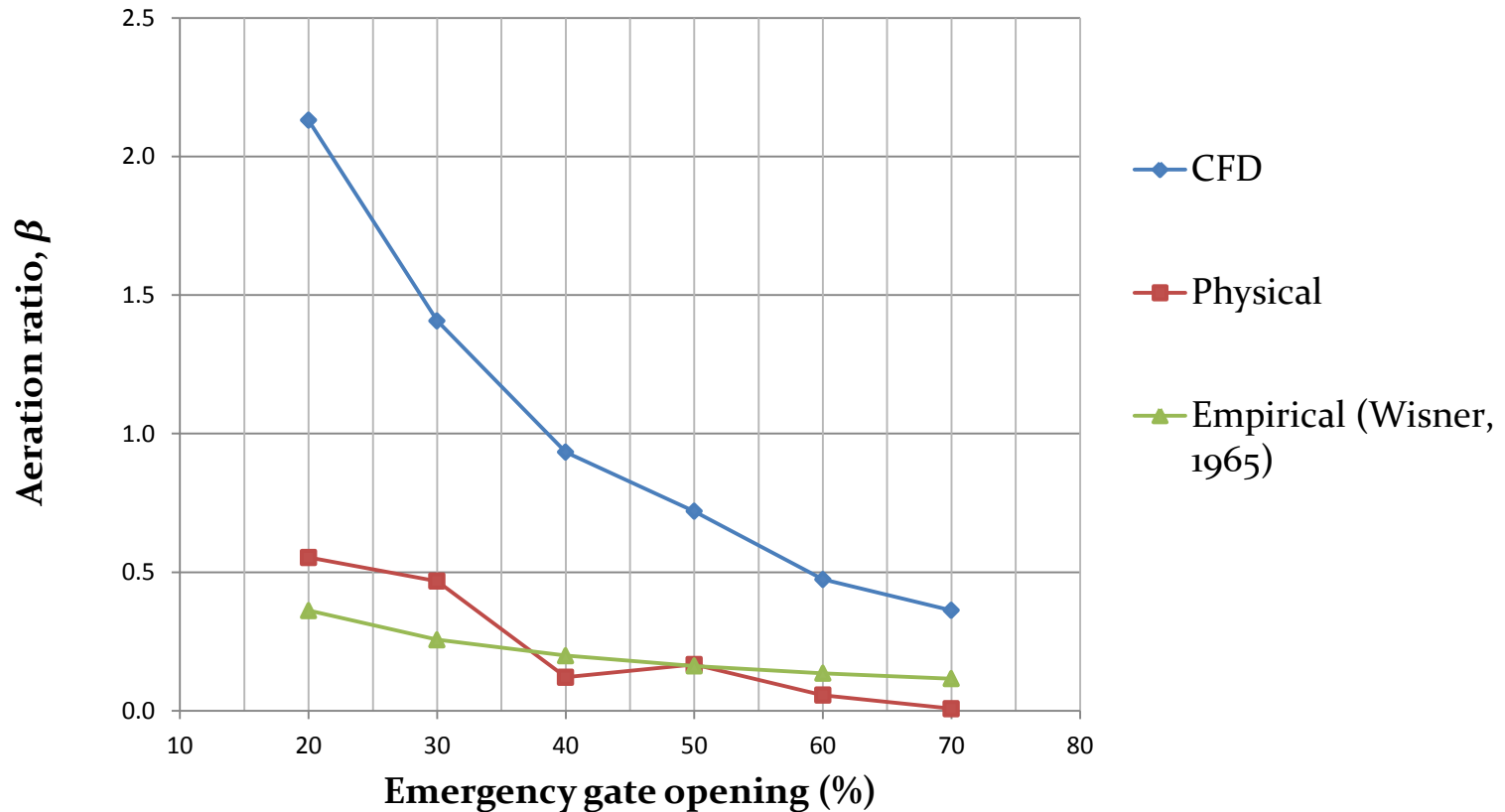


Figure 12: Aeration demand for different emergency gate openings

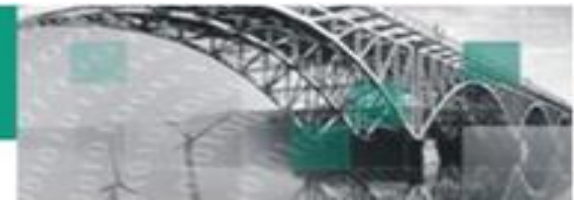


Figure 12 shows the following:

- Plot of aeration demand for various emergency gate openings
- Aeration decreases with increasing gate opening
- Physical model results compare closer to empirical calculations

Figure 13 below shows the following:

- Plot of Froude number for various emergency gate openings
- Results follow similar trend
- Flow is supercritical (Froude numbers are more than 1)
- Froude number decreases with increasing gate opening due to decreasing flow velocities



Plot of Froude number against Emergency gate opening

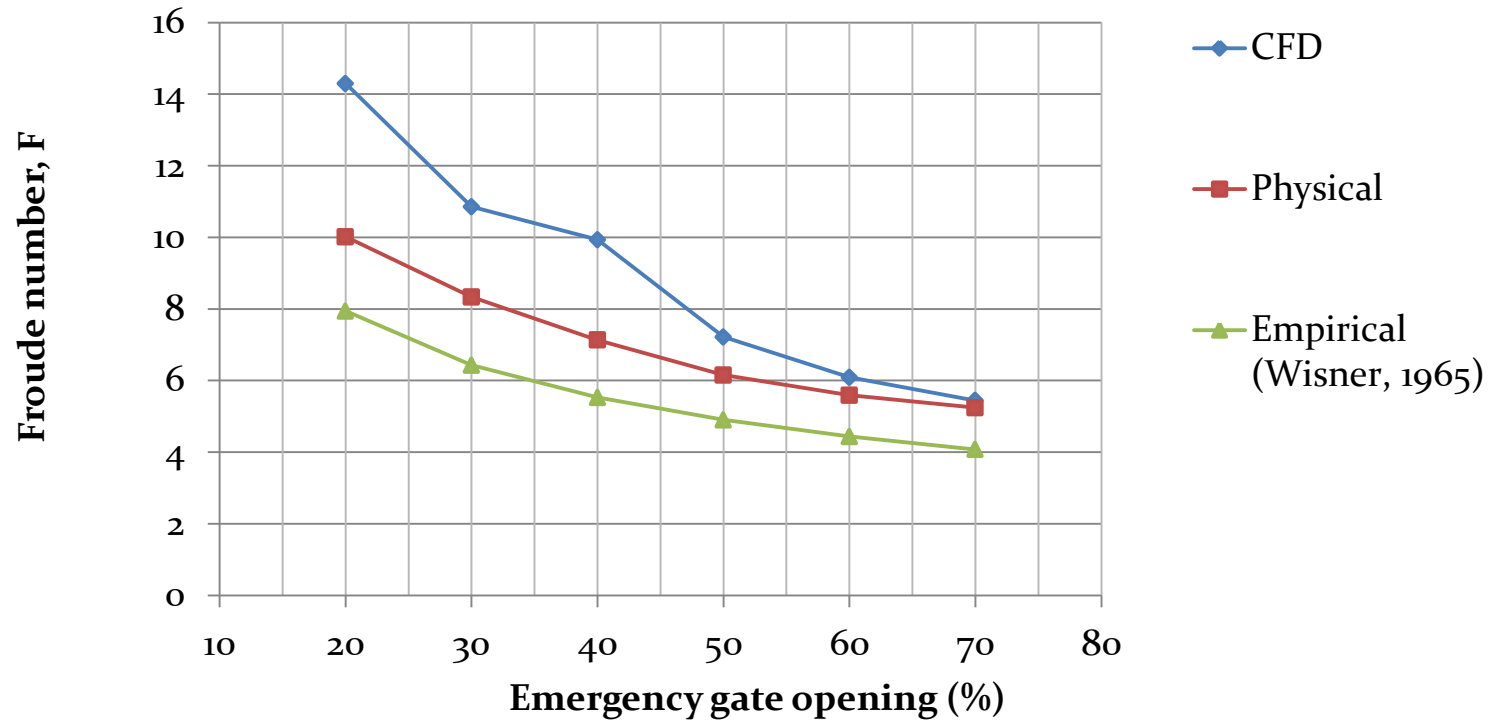
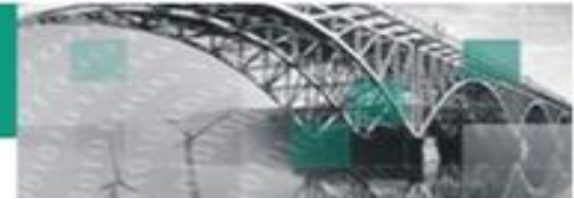


Figure 13. Froude number for various emergency gate openings



❖ *Conclusions*

- Results for CFD were obtained after mass balance
- Lower aeration demand for larger gate openings as conduit begins to flow full.
- Direction of air in the shaft is downward (suction) unlike for the prototype
- CFD and physical model results follow similar trend although CFD model values are higher.
- Negative pressure developed at emergency gate lip
- No sudden air expulsion in air shaft for CFD model



❖ *Recommendations*

- Transient simulations with a dynamic emergency gate
- Increased simulation time
- Finer mesh sizes