Modelling Versus Analytical Calculation of the Loading Chamber

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Abstract
The contributions of small hydropower have grown worldwide substantially in recent years and the potential for future growth is even stronger. In developing countries, small hydro offers perhaps the greatest benefits being the fastest way for rural electrification, improving living standards, stimulating industrial development and enhancing agricultural production. Consequently, the concern of the designers for a sustainable hydraulic design of the small hydropower plants triggered several professionals to refine the design process. One of the important components of a small hydropower layout is the loading chamber. A correct design requires the understanding of the flow behaviour in the basin but also the settlement of fine particles that may wear parts of the turbine and decrease its efficiency and lifetime. The selection of the loading chamber dimensions and the divergent angle of transition zone are important to provide more uniform flow profile and to minimize the separation of flow along the walls of the transition zone. The divergence angle at the entrance of the flow into the basin should be established based on the minimization of the head losses condition to limit the effect due to the sudden expansion of the section at the entrance to the loading chamber. The increased turbulence and the oscillation of the water level due to sudden reduction or increase of the turbine load are raising additional design problems. The paper presents the results obtained by using a mathematical model to study the flow pattern in a loading chamber estimating the process of flow instability in a confined area. To analyze the flow and the influence of the transient regime due to variation of the turbine load on the position of the penstocks in the front wall of the loading chamber and consequently to derive the recommendations for a correct design of the loading chamber, a particular system has been accepted. A significant output of the modelling can be considered the results showing the influence of the valves closing time on the hydraulic transient in the basin. For a selected discharge and gradual closing time of the valves larger than 7minutes, no significant rise in water surface elevation was observed. Appropriate design recommendations derived from the comparison of the results obtained by using mathematical models with the results obtained from a simplified analytical approach and indication from engineering experience, are also presented and discussed.

***Key words*:** remote sensing, fractures analysis, River Nile, Sabaloka dam, Sudan.

1. BACKGROUND

An important role in the operation of a hydropower plant is played by the component designed to compensate the flow and to dampen the effect of the transient waves that appear at a sudden increase or decrease of the power load of the turbines. If for high head power plant the rule is to provide a surge tank, at the small hydropower plant with open channel adduction this component is a loading chamber.

Loading chambers (LC) or impoundment or forebay makes the link between the derivation channel and penstocks. The position of the loading chamber should be as close as possible to the powerhouse to reduce the length of the penstocks and consequently of the head losses and of the magnitude of the water hammer produced in penstocks at sudden variations of the power load.

At the same time the volume of water from the chamber constitute a reservoir where the water supplied by the derivation is collected during the low power demands and used to supply the turbine during the quick increase of power demands until the establishment of the steady regime.

In the study presented in this paper, the fall in water surface elevation and waves produced in an impoundment basin as a result of sudden and gradual opening and closing of the valves of a small hydropower plant are studied using Delft3D (three dimensional) mathematical model- hydrostatic , free surface flow solver.

The system of equations consists of the continuity equation, the horizontal momentum equation, and the transport equation for conservative constituents. The equations are formulated in orthogonal curvilinear co-ordinates or in spherical co-ordinates on the globe. Models with a rectangular grid (Cartesian frame of reference) in Delft 3D are considered as a simplified form of a curvilinear grid. In curvilinear co-ordinates, the free surface level and bathymetry are related to a flat horizontal plane of reference, where as in spherical co-ordinates, the reference level follows the Earth's surface.

2. MODEL SETUP

A particular system has been accepted, to analyze the flow and the influence of the transient regime produced as a consequence of variation of the turbine load on the elevation of the penstocks in the front wall of the loading chamber. It is important to mention that due to the complexity of the transient flow and due to the influence of the turbulence in the process of air entrainment and vortex formation at the penstock inlet, the generalization of the scheme considered it was presently not possible.

The geometrical dimensions and the layout are presented in figure 1. The model was set up as a three dimensional model with a thickness of ten layers. It was run to observe the flow phenomena by considering the influence of the transition zone at the entrance of the impoundment chamber.

The impoundment basin has a total length of 385m, made up of:

a Derivation channel
b Transition
c Impoundment basin or loading chamber

The derivation channel has a slope of 20cm/ km while the impoundment chamber has a slope of 4.8m/km.

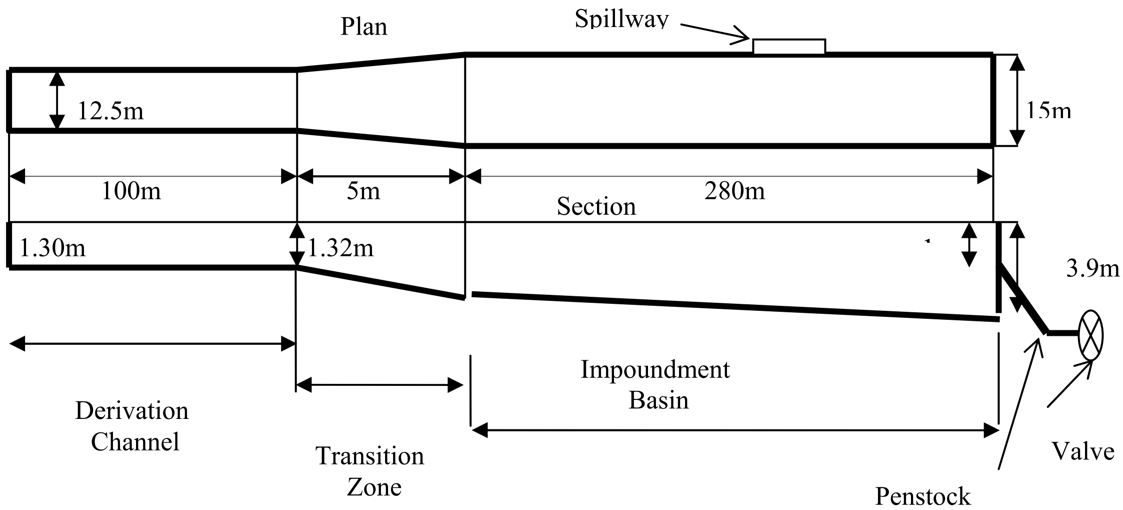

Figure 1: Model geometry

The selection of the dimensions and the angle of expansion of the transition zone are obviously important parameters not only to establish a uniform flow within the impoundment basin but also to minimize the separation of flow along the walls of the transition. Kedhayyer (2006), suggests that the angle of divergent wall of transition can be designed as from 60 and 120 from the centre line if the velocity entering the basin varies between 0.7 and 1.0 m/s. In the particular case selected in this thesis, the derivation channel gradually expands with a vertical to horizontal ratio of 1:4 at the transition to the chamber. To obtain a stable simulation reproducing the variation in time and space of the waves generated by the operation of the valves, models with different grid characteristics were analyzed and compared. Finally a model with a total of 430 cells and main hydraulic characteristics given in table 1, has been selected.

Table 1: Hydraulic parameters of the selected model

Nr	Computational Parameters	Value
1	Length of computational cells in longitudinal direction	385m
2	Width of computational cells in transverse direction before transition	12.5m
3	Width of computational cells in transverse direction after transition	15m
4	Discharge per cell upstream (Inflow)-5cells@3.2m^3/s per cell	3.2m^3/s
5	Discharge through penstock (Downstream)-16,14, 12,10,8or 5m^3/s	varies
6	Discharge through spillway- 0,2,4,6,8 or 11m^3/s	varies
7	Discharge through penstock – first hour of simulation	0
8	Discharge through spillway – first hour of simulation	16m^3/s
9	Initial water level	0
10	Simulation time	7hrs
11	Time step	0.02mins
12	Bed roughness coefficient, Manning's, n	0.013
13	Horizontal eddy viscosity/diffusivity	0.1m^2/s
14	Turbulence(3D model)	k-ε
15	Vertical profile for hydrodynamics	Logarithmic

The grid was generated using the Delft3D-RGFGRID by selecting a uniform layer thickness of 10% applied to the 10 vertical layers. The hydrodynamic grids in vertical and horizontal directions are shown below:

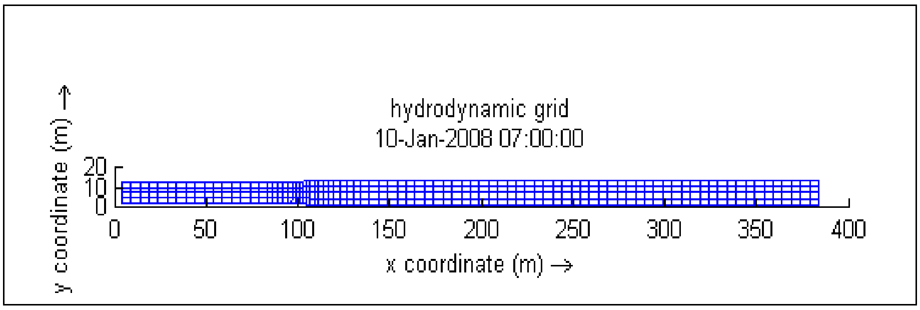

Figure 2: Horizontal Grid

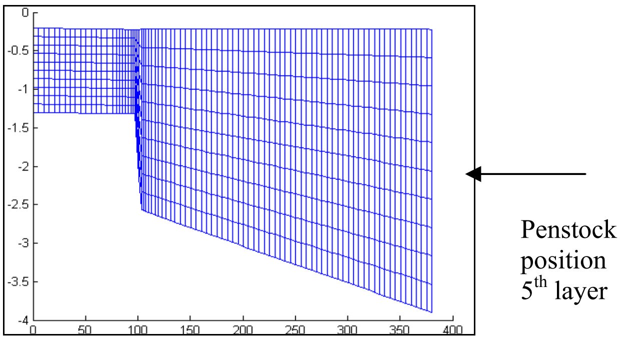

Figure 3: Vertical Grid

The observation points and cross-sections selected to monitor the computational results are shown in figure 4. The lateral spillway provided to discharge the water during closing of the turbines was modelled as a discharge point

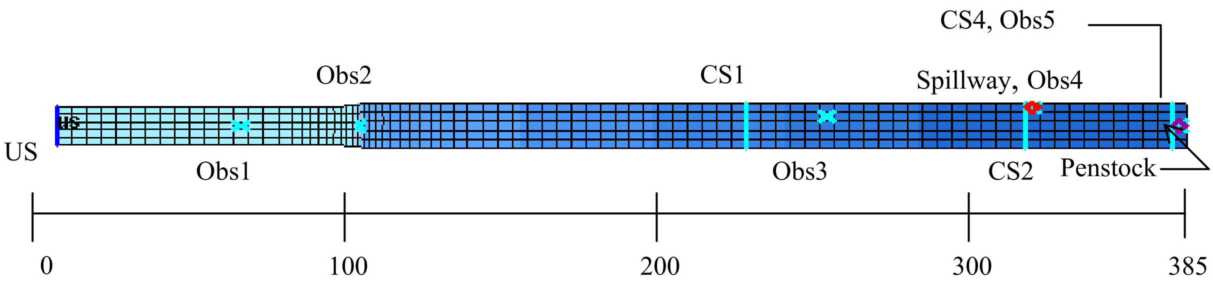

Figure 4: Cross-Section (CS) and Observation Points

Two different boundary conditions are provided in the model.
Upstream flow boundary condition:

$$\frac{\partial Q}{\partial t} = 0$$

Downstream flow boundary condition:

$$\frac{\partial Q}{\partial t} = 0$$

3. MODELLING RESULTS

The results obtained are presented separately for sudden opening and closing of the valves. A number of 36 runs selecting different valve opening and closing times (6 seconds, 120seconds, 180 seconds, 300 seconds, 420 seconds and 600 seconds) such that the inflow upstream (16m3/s) equals the sum of discharge through the lateral overflow spillway and the penstock were performed.

The results of opening of the valves from the turbines for different times as mentioned above are presented in figure 5. It can be observed that the minimum drop in water surface elevation (-0.42m) in the impoundment basin occurred when the penstock is opened instantaneously (six seconds) and -0.22m, only after 10 minutes opening time of the valve.

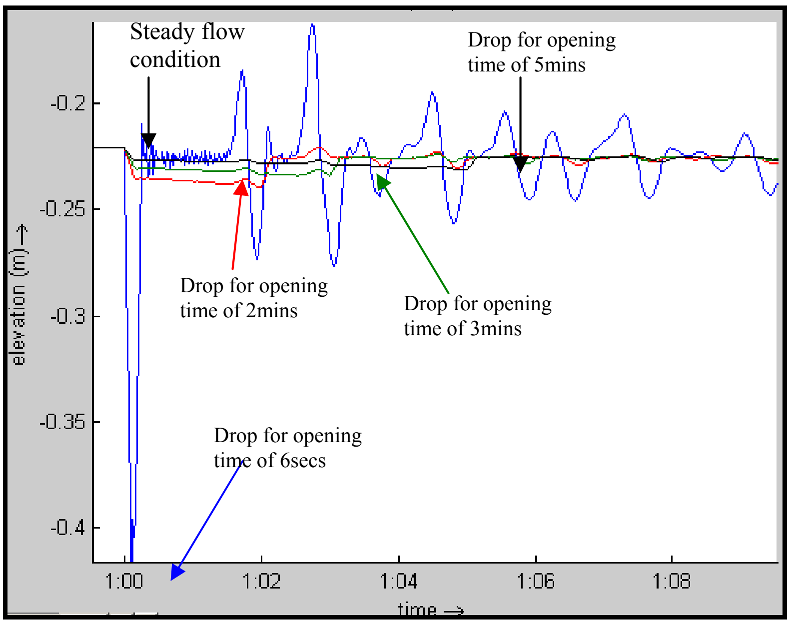

Figure 5: Oscillations of the water level for different opening times at the front wall of the basin.

Another set of runs were performed to identify the variation of the surface water level with discharge for the same opening times. In the case analyzed in this paper it was considered that the power house operates with one turbine with a rated discharge of Q = 16 m3/s.

However, a different situation may take place when more units are selected with smaller discharges per unit. This is actually a preferred situation conferring more flexibility in operation of the power house. Consequently, another analysis was conducted to show the variation of the negative and positive wave if several units with rated discharge of 8, 10, 12 and 14 m3/s are available. The results are presented in figure 6, and show as expected, a significant reduction of the oscillations with the reduction of the discharge.

The situation of sudden and gradual closing of the valves has been analysed considering same set of parameters as selected for opening of the valves. The variation of the water elevation in the loading chamber for different opening times is presented in figure 7 and shows a significant reduction of the wave elevation between the sudden closing of the valve and a closing time of 10 minutes.

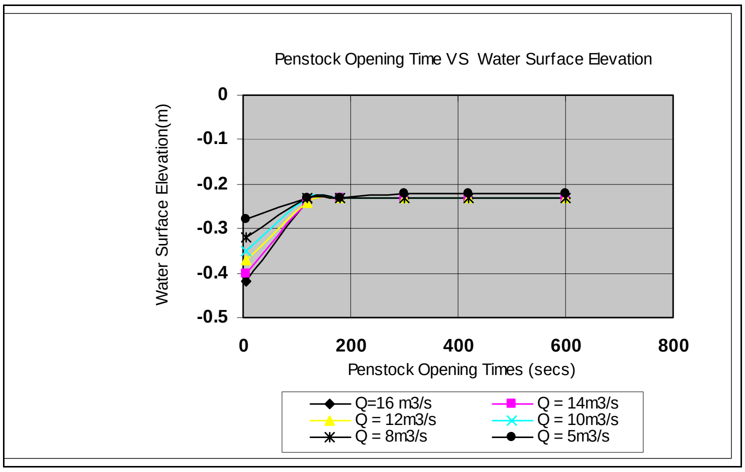

Figure 6: Variation of the water level at the penstock inlet with the discharge of the turbine: opening

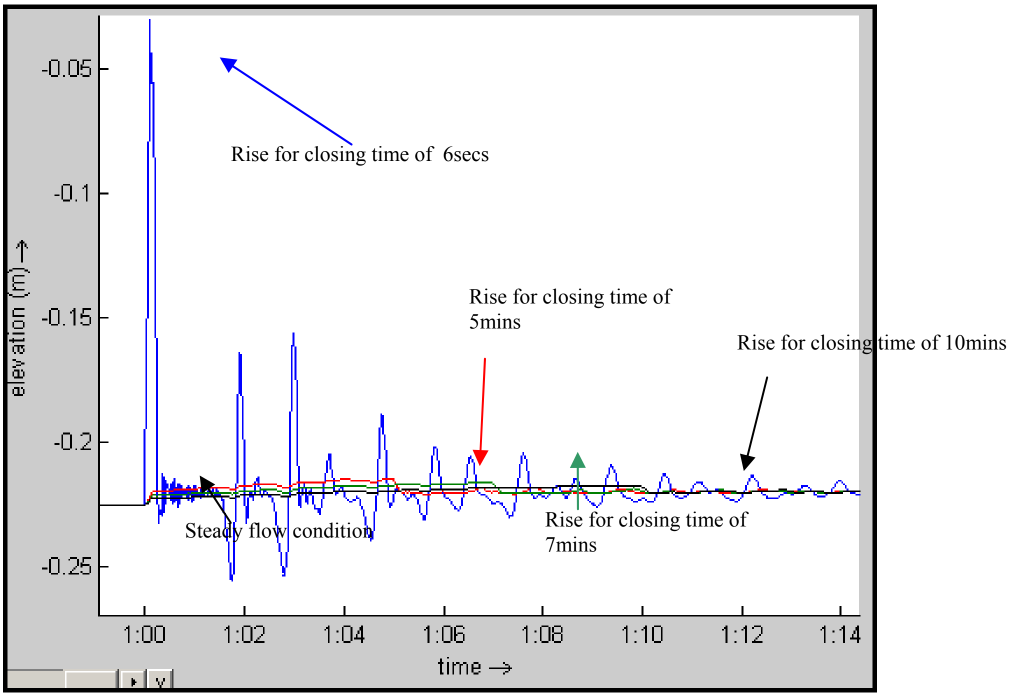

Figure 7: Oscillations for different closing times for Q = 16m3/s

The variation of the water level for different closing times with the discharge of the turbines is presented in figure 8.

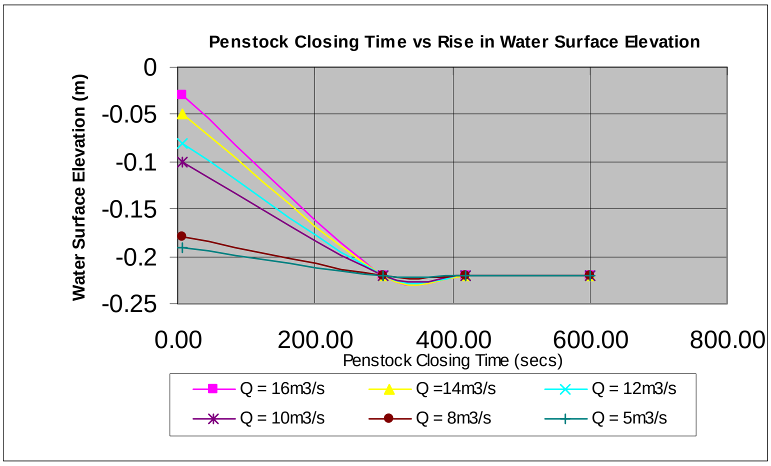

Figure 8: Variation of the water level at the penstock inlet with the discharge of the turbine: closing

In order to validate the k-ε turbulence Delft 3D model, the results from the model were compared with the results obtained using the motion equations. The calculation of the water super elevation was done by accepting a simplified calculation scheme with a uniform bottom slope and a constant cross sectional area. In figure 9 is presented the simplified scheme used for calculation of the maximum level of surge due the sudden to reduction of the discharge.

A similar scheme was used for calculation of the minimum water level in the case of the sudden opening of the valve.

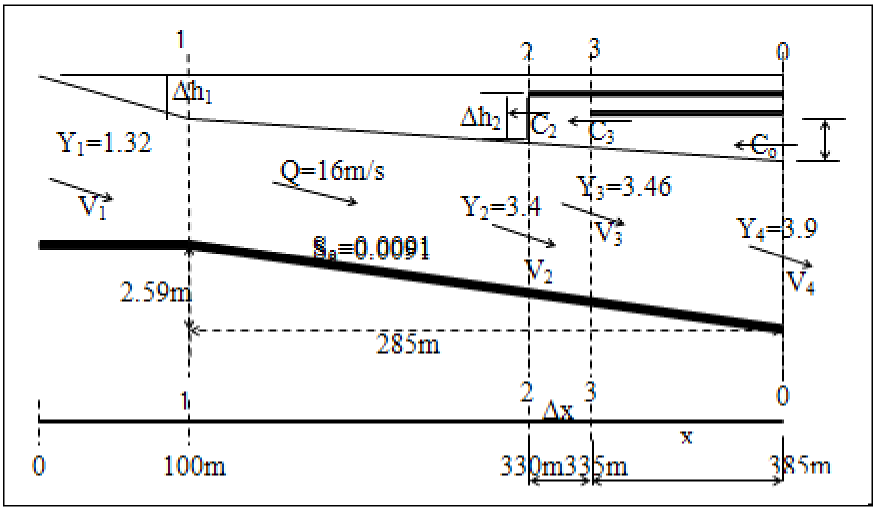

Figure 9: Simplifies scheme for calculation of the maximum level of surge at the reduction of discharge

4. CONCLUSIONS

The evaluation of the model solution for the penstock closure shows that the rise in water level due to fast (full) closing (6secs) of the valves for a discharge of 6m3/s is 0.20 m, figure 6. The simplified analytical solution gave a similar result, a rise of 0.17m. The difference is negligible especially with the assumption that the solution by calculation is not very accurate due to simplified calculation scheme accepted.

However, it must be highlighted that the model gives more details and possibility to analyze several opportunities such as operation rules for valves or links between the magnitude of the oscillations in the loading chamber and the number of the turbines

A significant output of the modelling is the influence of the valve closing time on the hydraulic transient in the basin. For the same discharge, 16m3/s, and with gradual closing of 10mins, no significant rise in water surface elevation was shown by the model. It is clear that closing the valves gradually can significantly reduce the transient in the impoundment basin.

Water in the impoundment basin must be kept at a certain level above the top of the penstock, to prevent air entering the pipe. The submergence depth obtained from running the model does not agree with the figures obtained from the empirical works of Gordon, Knauss, Nagarkar and Rohan (8.22m, 4.43m, 19.07m and 6.02m). The empirical formulas are based on the avoidance of vortex formation and seem not realistic for the submergence of the penstock as resulted in this study.

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