Slipways guide walls design by linkage of the 2-D shallow water models and the PSO

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ABSTRACT: An innovative approach is presented in this study to find the optimal shape of the guide walls of a spillway. More specifically, the length and shape of the guide walls are determined by linking a 2D depth-averaged model for the flow to a particle swarm optimization model. The experimental data of Karkheh dam is then used to benchmark the applicability of the approach. The numerical results show that this numerical approach succeeds in calculating a guide wall configuration which is more economical than that obtained by physical model study.

1 INTRODUCTION

Guide walls are important components of spillways. They are usually designed to increase the performance of the spillways and related hydraulic structures. A well designed guide wall directs flow from the approach channel to the spillway's control structure in such a smooth manner that not only is the energy loss minimized but uniformly distributed flow is also achieved at the spillway's control structure (USBR 1987).

Poorly designed guide walls dramatically decrease a spillway's discharge coefficient which in turn results in the need for greater spillway head and consequently a more expensive dam. Moreover as a result of nonuniform approaching flow, oblique waves may be set up in the chute. The supercritical nature of the flow in the chute then amplifies the amplitude of the cross waves. The amplified cross waves along the chute not only require higher chute side walls, but also increases the risk of the cavitation on the chute surface (Falvey 1990). Furthermore these waves produce pulsating flows in any downstream stilling basins, leading to poor downstream energy dissipation. In fact, high energy flows may be swept out of the stilling basin and cause excessive erosion in the downstream river (USBR 1987). This erosion may structurally damage the stilling basin itself or even threaten the stability of the dam if the erosion extends as far as the dam toe.

In practice, if a physical model study is undertaken – which is usually the case for large projects – the shape of the guide walls are determined through a trial and error procedure. In this procedure, different shapes of the guide walls are model tested until the acceptable flow condition is reached. Although the resulting flow condition satisfies design requirements, the optimum shape of the guide walls is not necessarily guaranteed. In fact the exhaustive and painstaking nature of the tests may prevent designers from searching for a more economical length of the walls. Optimization is effectively precluded.

However, in the absence of a model study, the shapes of the walls are typically designed by applying design criteria available from standard texts and engineering manuals. Of course, such basic criteria may not result in the best design, and thus numerical alternatives may then be particularly helpful.

Fortunately advances in computer industries and numerical analysis have made the numerical analysis of many hydraulic engineering problems possible. Neary et al.(1999) successfully employed a three dimensional turbulence model to analyze flow around a side intake. Tingsanchali and Maheswaran (1990) used a 2D depth-averaged turbulence model to discover flow nature near groynes. Molls and Chaudhry (1995) applied a 2D depth-averaged turbulence model to analyze a wide variety of hydraulic problems including flow in a channel with hydraulic jump, flow in a channel contraction, flow near a spur-dike, flow in an 180^{o} channel bend, and a dam break simulation. They also compared the numerical results with experimental data and concluded that there were in satisfactory agreement.

This paper is not intended as a contribution to the numerical modeling literature, but rather to present an alternative-numerical design approach to a costly physical model study. The optimum shape of the guide walls is iteratively obtained by modeling the flow using the 2-D shallow water equations and searching alternative wall geometries using a particle swarm optimization (PSO) approach.

2. 2D DEPTH AVEARAGED EQUATIONS

Many hydraulic engineering problems can reasonably be assumed to be 2D in nature. This is also the case in the spillway approach channels in which flow width is considerably larger than flow depth. In such cases, it is usually reasonable and appropriate to use 2D flow equations for the analysis.

In absence of the wind-induced shear stress and Coriolis effects, the depth averaged mass and momentum equations for 2D flow are as follows:

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}(u.h)+\frac{\partial}{\partial y}(v.h)=0 \qquad (1)$$

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-g\frac{\partial h}{\partial x} \qquad (2)$$

$$+\frac{1}{\rho h}\left[\frac{\partial}{\partial x}\left(\varepsilon_{xx}h\frac{\partial u}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_{xy}h\frac{\partial u}{\partial y}\right)-\frac{gu}{C_z^2 h}\left(u^2+v^2\right)^{0.5}\right]$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-g\frac{\partial h}{\partial y} \qquad (3)$$

$$+\frac{1}{\rho h}\left[\frac{\partial}{\partial x}\left(\varepsilon_{yx}h\frac{\partial v}{\partial x}\right)+\frac{\partial}{\partial y}\left(\varepsilon_{yy}h\frac{\partial v}{\partial y}\right)-\frac{gv}{C_z^2 h}\left(u^2+v^2\right)^{0.5}\right]$$

where h=depth of flow, t=time, u,v=depth-averaged velocity components in the x- and y- directions, respectively, ρ=water density, ε_{ij}=the eddy viscosity acting in the *i*-direction on a plan that is perpendicular to the j-direction (with $i,j=x,y$), and C_z=the Chezy coefficient.

No analytical solution is available for the above equations, so the numerical method should be employed to solve them. In this paper, a finite element open source model, HSCTM-2D, developed by Hyter et al. (1995) is used for the numerical solution.

3. PSO APPROACH

In the recent decades, evolutionary optimization approaches have attracted scientists and engineers because they provide an alternative to traditional optimization techniques such as the nonlinear-gradient-base optimization methods. The recent popularity of any evolutionary optimization approach is attributed to the fact that it is often too difficult, or even impossible in some cases, for a traditional approach to solve the current scope of scientific problems. This is primarily due to their high complexity and nonlinearity, discontinuity of search space, nondifferentiable objective functions, imprecise arguments, and function values (Back et al. 1997). Although the evolutionary approaches do not guarantee that a global solution will be found, experience has shown that global solutions are indeed usually captured.

The fact is that intelligent cognition is derived from the interaction of individuals in a social environment. This understanding has helped researchers in the field of social intelligence (SI) to establish the idea that socio-cognition can be effectively applied to develop stable and efficient algorithms for optimization.

One of the most interesting optimization methods that have been formed on the basis is the PSO approach developed by Kennedy and Eberhart (2001). In PSO, potential solutions or “particles” move through the problem space by considering searches that are in some sense near to where current optimum particles have currently been positioned.

Jung (2005) extensively applied this method to a water distribution system optimization issues and showed that PSO not only exhibits fast convergence for the uni-modal functions, but also has the strongest global convergence, effectively escaping poor local optima for multi-model functions. Jung and Karney (2006) applied the PSO technique to find the optimal combination and positions of different surge protection devices to protect a given water distribution system against the harmful effects of transient events. They also integrated PSO with Inverse Transient Analysis (ITA) for the purpose of calibrating transient models and for leak detection in a small water distributaries network. The authors (2004) showed that the PSO technique can be effectively used to achieve a reasonable match between measured (simulated) and predicted pressure traces in the network.

Detailed formulation of the PSO approach is presented next along with a description of how the method is coupled to the 2D modeling approach.

4. PROBLEM DEFINITION & FORMULATION

As schematically shown in Figure 1, the guide walls consist of two parts, curved and straight parts. The curved part reduces the width of flow from W1 in the approach channel to W2 in the spillway’s control structure. The flow is next uniformly distributed across the section in the straight part of the structure.

Of course, this flow transformation should be done in such a smooth manner that no flow separation occurs on or along the guide walls. In the absence of flow separation – that is, for the case of well-designed guide walls – irrotational flow can be assumed in both zones. Since the shape of streamlines in an irrotational flow can be well described as elliptical shapes, it is promising to assume the curved part of the guide walls as one quarter of an ellipse.

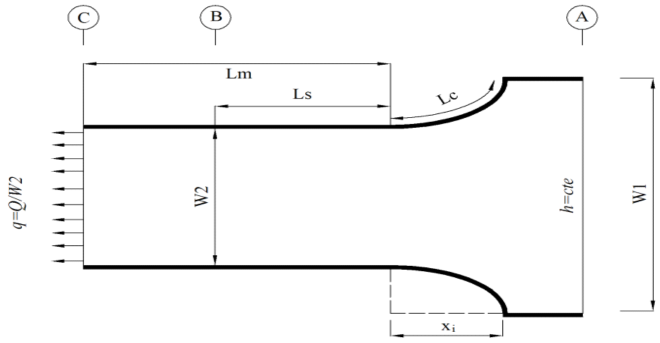

Figure 1. An schematic layout of spillway’s guide walls

Indeed the size of ellipse affects flow in the whole system. Ellipses with larger perimeter direct flow more gradually to the straight part and achieve uniformly distributed flow in a shorter distance of the straight part. Thus the objective of an economical design is to find the size of the ellipse so that the total length of the guide walls is minimized. For a symmetric system, as shown in Figure 1, this can be formulated as follow.

$$Minimized\ \ f = L_C(x_i) + L_S(x_i) \tag{4}$$

It can be seen that $L_C(x_i)$ is not an analytical function and should be determined numerically. This makes the use of analytical optimization method impossible, but favors the PSO approach considered here.

As a first step, a group of trial solutions or “particle” is randomly generated. In this case each particle contains exactly one dimension, the radius of the ellipse in the curved part (x_i). The fitness of each particle is then calculated from equation 4. To do this, the length of both curved and straight part needs also to be specified. Having set the radius of the ellipse for a particular particle, the length of the curved part can easily be calculated. However, the calculation of the straight part’s length $(L_S(x_i))$ is not as straightforward, but can be determined through 2D flow modeling.

As can be seen in Figure 1, to do the numerical analysis, constant head and uniformly distributed flow is assumed at the upstream (section A) and at the downstream (section C) boundary conditions respectively. Whatever the shape of the curved part is, the downstream boundary should be located far enough from the end of the curved part to assure that the assumption of uniform flow at that boundary is reasonable.

The flow is first analyzed and the depth of flow and the velocity vectors are obtained at the computational nodes. The level of flow uniformity is then determined in the subsequent cross sections of the straight part. The cross section with the acceptable flow uniformity, say section B, determines the end of the straight part.

Many different approaches can be employed to quantify the level of flow uniformity across the section. With this in mind that uniform flow is reached at a section where the velocity vectors across the section become essentially parallel, in this paper the standard deviation of the angle of velocity vector at the computational nodes made with the longitudinal axes of the channel, α, is used to evaluate the level of flow uniformity at this section.

In every iteration, each particle is then updated by the two "best" values. The first one, which is denoted by *pb* is the least cost solution that has achieved thus far for any particular particle. The second "best" value, which is tracked by the particle swarm optimizer, is the least cost value obtained so far by any particle in the population. This best value is the current global best and denoted by *gb*. After finding these two values, the particle updates its velocity and position based on the following equations:

$$v_i = wv_i + c_1 r_1 (pb_i - x_i) + c_2 r_2 (gb - x_i) \tag{5}$$

$$x_i = x_i + v_i \tag{6}$$

where $i = 1,2,..,N$ and N = size of population; w = internal weight; C_1 and C_2 = learning factors ; r_1, r_2 = random values in the range of 0 and 1.

The first equation is used to calculate the ith particle’s new position by considering three terms: the particle’s previous velocity, the distance between the particle’s current position and from its own best position, and the distance between the particle’s current position and the swarm’s previously best experienced position. The second equation is then used to determine the new position of the particle using this newly obtained velocity.

4. NUMERICAL RESULTS

To justify the applicability of the proposed approach the guide walls of Karkheh dam is considered in this study. Karkheh earth dam with the total volume of 7 billion cubic meters is the largest dam in Iran. Figure 2 depicts the spillway’s guide wall of the dam. As can be seen the curve parts of the walls consists of two circular arcs with different radii of curvature.

The sizes of the curve and straight parts were optimized through an extensive physical model study. In this study the performance of the guide walls was tested for the maximum probable flow (PMF) that is 18500 m^3/s. The obtained results show that the total length of each wall is 100 m. For this discharge the flow depth in the approach channel measured on the model was 20 m.

Using this information, the guide walls are designed by the proposed approach. To make sure that the same level of flow uniformity is achieved in both the original design and the proposed approach, the performance of the original design is evaluated using a 2D analysis.

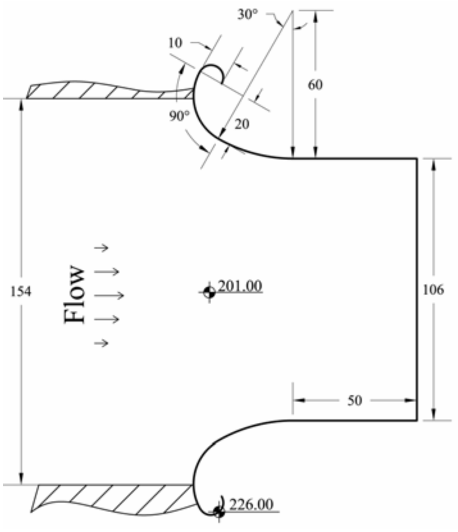

Figure 2. An schematic layout of Karkheh dam guide walls

The numerical result shows that α =0.01 is reached at the end of the walls; this value is taken as a benchmark for the proposed design approach as well.

Figure 3 shows the least guide walls solutions obtained from the PSO approach during 100 iterations. As can be seen the optimal solution is reached after 46 iterations. At this point the total length of guide wall is 58 m which is appreciably less than that in original design (100 m).

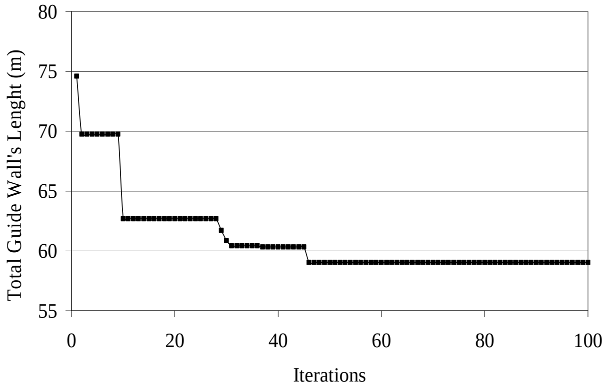

Figure 3. The PSO convergence curve

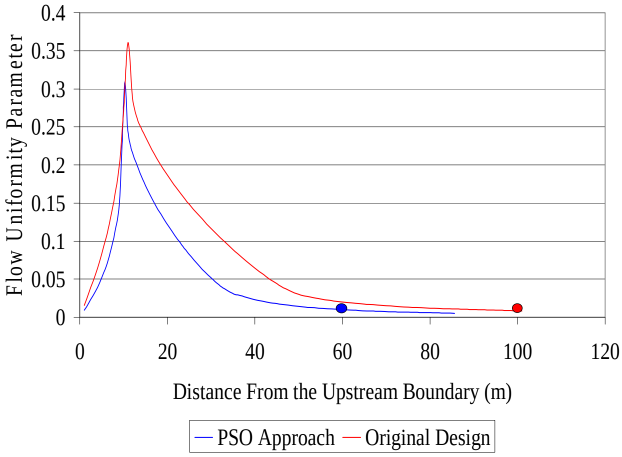

Figure 4. Variation of the flow uniformity parameter along the guide walls for the original design and the proposed approach

To compare the performance of the original design to the proposed approach, the parameter α along the guide walls is shown in Figure 4 for two cases.

It can be clearly seen that for a particular level of uniformity, say α =0.01, the flow approaches uniformity much more quickly in the proposed approach than in the original design. The better performance of the proposed approach is mainly due to using the elliptical rather than circular arcs within the curved zone. This obviously justifies why the elliptical arcs are extensively used in hydraulic engineering transition problems.

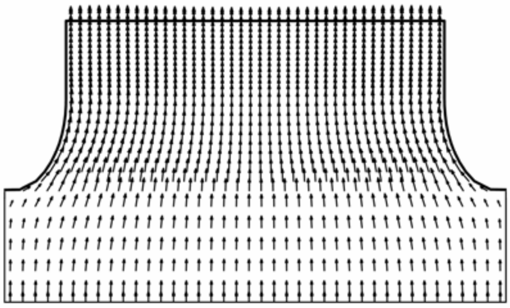

Figure 5. Flow pattern across the proposed guide walls

Flow pattern through the guide walls obtained from the proposed approach is also shown in Figure 5. This figure graphically demonstrates the performance of the proposed guide walls and their effectiveness in establishing uniform flow at the end of the guide walls.

4. SUMMARY AND CONCLUSIONS

An innovative approach is presented to determine the optimal shape of the spillways guide walls. In this approach a 2D depth averaged model is linked to a PSO approach to search for least length guide walls that achieve certain hydraulic goals. Assuming flow through the guide walls follows elliptical arcs, the shape of the curved walls is taken as a quarter of the ellipse.

The approach is then applied to determine the optimal guide walls of Karkheh dam, and the results are compared with those obtained from the physical model study. The comparison reveals that the guide walls obtained by the proposed approach are more efficient and economical than that obtained from physical model study. This is mainly because in the proposed method the elliptical rather than circular arcs are used in curved part of the walls.

This paper argues that, in the absence of a physical study, the proposed approach can be effectively employed as an alternative design tool. The approach can be also incorporated into the physical model study in order to accelerate the painstaking nature of final experimental design and confirmation.

Finally it should be emphasized that although the proposed approach is applied on a very simple case in which the guide walls are symmetric and there are just one decision variable, the method can be also effectively applies on the case having unsymmetrical guide walls and several decision variables.

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