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HUMAN LIFE SAVING BY SIMULATION OF DAM BREAK USING FLOW-3D (A CASE STUDY: UPPER GOTVAND DAM)

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ABSTRACT
Dam break analysis plays a very important role in the risk assessment of dams. Large dams pose significantly higher risks to the people and property downstream of the dam as compared to smaller dams. So the flooding risk due to the possible failure of large dams is more crucial. The simulation of exceptional events characterized by high hydraulic and hydro-geologic risk is an actual problem for the scientific community, working in the topic of environmental protection. These failures have caused severe devastation in the valleys downstream both in terms of lives lost and widespread damage to infrastructure and property. In this study, dam break modeling for very large dams has been focused. For this purpose, Upper Gotvand dam, located on Karun river in Iran, has been taken into consideration. With a height of about 182 m, which is one of the largest earth and rock fill dams in the world. Most simulation studies for the dam break problem are currently attempted using one-dimensional models, and we investigate here the possibility of the simple example of the collapse of a dam is used with a finite element analysis. Moreover, the risk zones in the dam's downstream are known. This study would be useful for the dam break analysis and the risk assessment of existing & planned dams in Iran as well as in other parts of the world. Also, the findings of dam break modeling are helpful in the risk assessment of dams. The flooding risk could be quite high due to the failure of large dams. This study proposes the Emergency Action Plan (EAP) of a very large earth and rock-fill dam to save the human life.

KEYWORDS: Human life saving; Shallow water equations; Dam-break simulation; Finite elements method; EAP.

INTRODUCTION
Emergency plans had to be prepared for every dam higher than 20 m and with a reservoir volume over 15 Mm^3. At that time, the numerical simulation of dam-break problems could be accomplished only with one-dimensional tools and accordingly these were used to predict the spread of the flood wave (Hervouet 2000). Since 1994, however, new regulations have demanded an updating of existing emergency plans for large dams. Emergency Response Plans now have to be prepared by the local authority after consulting the relevant mayors and dam operators. The scope of the Emergency Response Plan includes:
- The identification of potential risks;
- A list of protective measures and mechanisms to implement them;
- Definition of the responsibilities of local government agencies and other organizations involved;
- Dissemination of information to the public.

As a consequence of this new law, a risk analysis of many dams must be completed. Although many of these studies, particularly those relating to hydroelectric power stations in narrow upland valleys, could be completed with a one-dimensional program, a small but significant number of problems demanded a two-dimensional approach. These include flood waves spreading in large valleys or those that ultimately reach the sea via a flat coastal plain. In both these cases, widespread, and relatively shallow inundation results in a flow field that is significantly 1D in nature and which is amenable to simulation using the shallow water or Saint Venant equations. Given the complexity of dam-break hydraulics, it is also probable that more and more two-dimensional studies will have to be completed in the future (Hervouet 2000).

Review of numerical methods for dam break.
A brief review of the numerical methods used in the dam break problem has been done, although it is not the objective of this work. Numerical simulation models are powerful tools to assess the impact of floods due to dam failure events. Different codes are available for numerical simulations of floods caused by dam failures. At present, classical methods

and central difference schemes dominate the software products for the shallow-water system of equations. Some years after their adoption for solving problems in gas dynamics, upwind schemes have been successfully used for the solution of the shallow water equations, with similar advantages. Historically, upwind schemes were developed specifically for the solution of the Euler equations, but there is no reason why the techniques involved cannot be applied for the solution of other systems of conservation laws.

FEM, FVM or FDM?

Several techniques are available in literature, to solve the two-dimensional shallow water equations for the simulation of free-surface flows transients. These include finite difference methods (FDM), finite element methods (FEM) and the finite volume methods (FVM) (Valiani et al 1999). A finite element method (FEM) discretization is based upon a piecewise representation of the solution in terms of specified basis functions. The computational domain is divided up into smaller domains (finite elements) and the solution in each element is constructed from the basic functions. The actual equations that are solved are typically obtained by restating the conservation equation in weak form: the field variables are written in terms of the basic functions, the equation is multiplied by appropriate test functions, and then integrated over an element. Since the FEM solution is in terms of specific basis functions, a great deal more is known about the solution than for either FDM or FVM. This can be a double-edged sword, as the choice of the basic functions is very important and boundary conditions may be more difficult to formulate. Again, a system of equations is obtained (usually for nodal values) that must be solved to obtain a solution. Comparison of the three methods is difficult, primarily due to the many variations of all three methods. FVM and FDM provide discrete solutions, while FEM provides a continuous (up to a point) solution. FVM and FDM are generally considered easier to program than FEM, but opinions vary on this point. FVM are generally expected to provide better conservation properties, but opinions vary on this point also. The implementation of the model is based on the commercial FEM package Comsol Multiphysics, which reduces the programming effort required to a minimum.

Numerical problems of the Shallow Water Equations.

The numerical solution of the shallow water equations for flood waves propagation over real domains poses three specific problems, (Valiani et al 1999). The first problem is the simulation of the fronts or abrupt water waves that can be represented numerically as a propagating discontinuity. This problem can be considered as solved since the late eighties or early nineties. The second problem derives from abrupt changes in bathymetry. As long as the bottom surface remains sufficiently smooth, most numerical techniques provide an accurate solution of the flow, but if the bottom surface is very rough the majority of methods fail. The last problem especially arises when these schemes are applied to study the wave front propagation over dry bed. In fact, during the simulations of this work, as we said before, some difficulties are encountered simulating dry bed condition for the appearance of negative depths or velocity overshoots; therefore, our principal focus has been the wet case. Furthermore, the hyperbolic character of the shallow water equations that makes finding solutions to these equations is difficult. Hyperbolic equations admit discontinuous as well as smooth or classical solutions. Even for the case in which the initial data is smooth, the non-linear character combined with the hyperbolic type of the initial of the equations can lead to discontinuous solutions in finite time. The non-linear character of the equations also means that analytical solutions to these equations are limited to only very special cases. Numerical methods must be used to obtain solutions to practical problems. Therefore, numerical techniques which admit discontinuities in the solution, secondary shocks, reflections of waves, dry bed and obstructions are necessary for the solution of the shallow water equations. The method of characteristics, finite differences, finite elements and Godunov-type schemes can be used to solve the shallow water equations (Zoppou and Roberts 1991).

GOVERNING EQUATIONS

Before describing the shallow water equations, it needs to be specified that these are not the only equations used to solve the dam-break problem. Therefore, using the approach (Quecedo et al 2004), where the authors compared two mathematical models for solving the dam-break problem, the Navier-Stokes equations are also a possible candidate. As in many engineering problems, simulation of dam break can be done with alternative mathematical and numerical models with different levels of approximation. Quecedo compared two methods based on (i) solving the Navier–Stokes equations and (ii) using a depth integrated model which is discretized using a Taylor–Galerkin scheme. These mathematical models are based on assumptions such as disregarding air trapping in the former or vertical accelerations on the latter, and their range of application depends on them. The validity of the shallow water approach was based on comparisons of the model against problems with a known analytical solution, which has been done by many researchers over the past years.

If failure takes place onto a wet bed, the shallow water results can be considered reasonable in comparison to those obtained using the Navier–Stokes approach. If the free surface curvature is high, the shallow water approach miss predicts the pressure. Thus, it should not be used to calculate, for instance, stresses on structures. In spite of the shortcomings of the shallow water approach when applied to dam break problems, the computational effort required by other methods, such as the Navier–Stokes Level-Set algorithm presented herein, in actual problems makes the shallow water approach attractive for large computational domains. The Navier–Stokes approach would be used for the analyses of small areas when knowledge of the three dimensional structure of the flow is needed.

The 1D Saint-Venant's-SWE are the following:

$$\frac{\partial z}{\partial t} + \frac{\partial (zv)}{\partial x} = 0 \qquad (1)$$

$$\frac{\partial (zv)}{\partial t} + \frac{\partial (zv^2)}{\partial x} + g.z.\frac{\partial z}{\partial x} + g.z.\frac{\partial z_f}{\partial x} - v_f.\frac{\partial^2 (zv)}{\partial x^2} + g.z.S_f - E.\frac{\partial^2 (zv)}{\partial x^2} = 0 \qquad (2)$$

Or is the compact form:

$$\frac{\partial z}{\partial t} + \nabla.(zv) = 0 \qquad (3)$$

$$\frac{\partial (zv)}{\partial t} + \nabla.(zvv^T) + g.z.\nabla.z_s - v_f.\nabla(zv) + g.z.S_f - E.\nabla(zv) = 0 \qquad (4)$$

Where z is the thickness of the water layer (m), v is the velocity (ms^{-1}), g the gravity constant ($m\ s^{-2}$), Sf is the friction term (explained later) and υ_c the kinematic viscosity ($m^2\ s^{-1}$). The wind effect is not present in the equations.

NUMERICAL MODELLING THE DAM-BREAK WAVE.

Assumptions.

The basic assumption is that a failure and the resulting flood wave can reasonably be modeled using analytical techniques. Existing computer models have been used to recreate actual failures with a close representation to observed crests. However, unrealistic results can be obtained without a careful analysis. In this model, it has been assumed that the dam failed completely and instantaneously. This 'main' assumption of instantaneous and complete breach (the breach is the opening formed in the dam when it fails) was used for reasons of convenience when applying certain mathematical techniques for analysing dam-break flood waves. The presumptions are somewhat appropriate for concrete arch-type dams, but they are not suitable for earthen dams and concrete gravity-type dams.

- Earthen dams, which exceedingly outnumber all other types of dams, do not tend to completely fail, nor do they fail instantaneously. Once a developing breach has been initiated, the discharging water will erode the breach until either the reservoir water is depleted or the breach resists further erosion. The fully formed breach in earthen dams tends to have an average width (b) in the range ($h_d<b<3h_d$) where h_d is the height of the dam. Breach widths for earthen dams are therefore usually much less than the total length of the dam as measured across the valley.
- Concrete gravity dams also tend to have a partial breach, as one or more monolith sections formed during the dam construction are forced apart by the escaping water. The time for breach formation is in the range of a few minutes.

Figure 1. Upper Gotvand Dam.

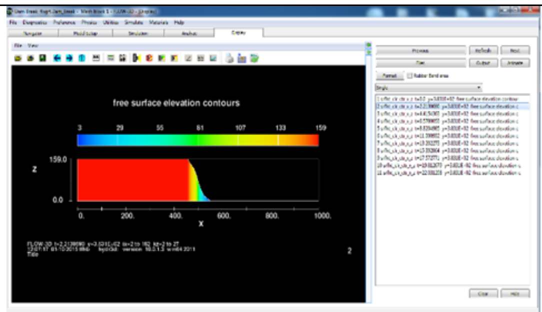

Figure 4a. Water surface and velocity layer at t=2.2 s.

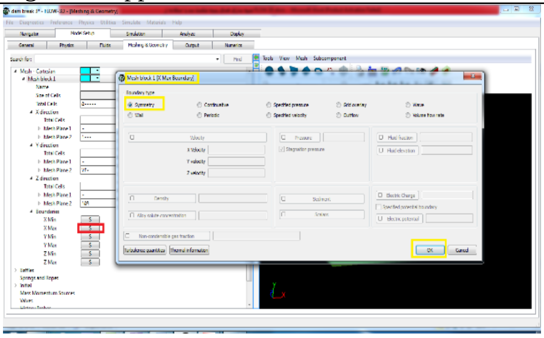
Figure 2. Definition of boundary condition.

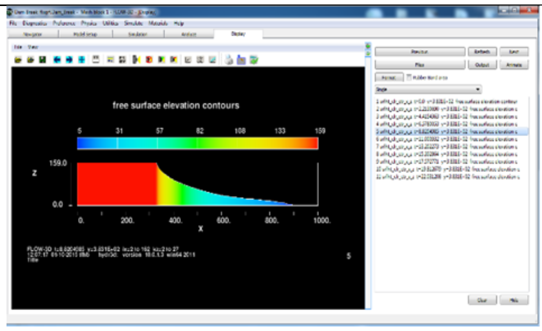

Figure 4b. Water surface and velocity layer at t=8.8 s.

Figure 3. The stability of numerical analyses.

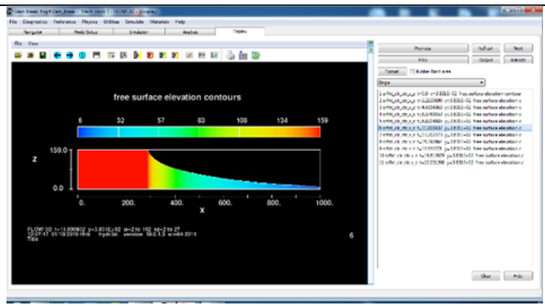

Figure 4c. Water surface and velocity layer at t=11.0 s.

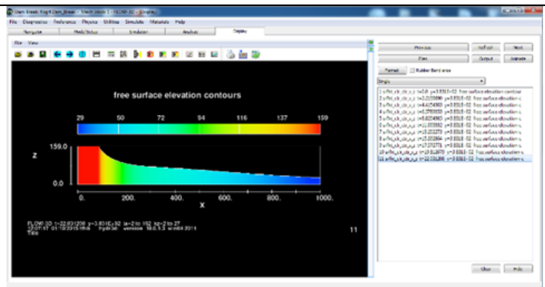

Figure 4d. Water surface and velocity layer at t=22.0 s.

Upper Gotvand Dam.

Gotvand dam is the most downstream one of a cascade of 11 large dams on Karoun River (South of Iran). Karoun is the largest river by discharge in Iran and just after the Gotvand dam traverses the Khuzestan plain, the main agricultural area in the south of Iran, before discharges into the Persian Gulf. Gotvand Dam is a rockfill dam with a height of 182 meters mainly built to generate hydroelectric power and provide flood control. The average annual runoff volume at the dam section is about 13.3 billion m3 and the reservoir capacity with a length of 90 kilometers is about 5.1 billion m3 at the maximum normal operation elevation (234 masl) (see Fig. 1). In this paper, dam break analysis is done by Flow 3-D software on Upper Gotvand Dam, according to above-mentioned theory. The modelling steps and the results are discussed in the following.

Numerical Modelling by Flow 3-D.

The Volume-of-Fluid (VOF) method for tracking fluid interfaces and the FAVOR(TM) method for the description of geometry can be combined in a shallow water model of Flow-3D. FLOW-3D is a finite-difference, transient-solution program that solves the conservative form of the Navier-Stokes equations over a non-uniform Cartesian grid. The origins of the FLOW-3D model can be traced back to Los Alamos National Laboratory and the research of C. W. Hirt. Research by Hirt and others lead to creation of the SOLA-VOF, NASA-VOF, and RIPPLE programs, which are documented in several publications (Torrey, et al. 1987; Kinnmark I. 1988). The free-surface algorithm they developed, called the Volume-of-Fluid (VOF) method, tracks movement of the free surface by calculating the fraction of fluid (in this case, water) in each computational cell.

Solution domain, boundary, and initial conditions

The dimensions of the solution domains were 1000 m long and 159 m high for SWE model. As initial conditions, a 200 m long and 159 m high volume of fluid was defined as a reservoir and no volume of water was described at downstream from dam, due to dry bed. All channel and obstacle surfaces were assumed smooth. The time steps □t were determined according to the Courant-Friedrichs-Lewy condition. In the numerical computations, the upstream boundary was set as wall due to no flow into the reservoir and constant reservoir length. The downstream boundary was outflow since the downstream end of channel was open over dry bed. The lower boundary was set as wall. The upper boundary was set as symmetry to account for the atmospheric pressure on the free surface (Fig. 2). In Flow 3-D, if the upper boundary is taken as symmetry, atmospheric pressure can be effective on the free surface of water. Since the water surface is defined by VOF, zero shear stress and constant atmospheric pressure were applied as boundary conditions over the air-water interface (Fennema R.J & Chaudhry M.H. 1990). The channel sidewalls were chosen as symmetry, implying no flux and shear of any property across it. The k-ε turbulence model provided logarithmic velocity distributions in the boundary layer, called the wall function. The no slip condition was defined as zero tangential and normal velocities.

Constants and stability of numerical modeling

In this model, we call 'constants' the variables that are independent of the geometry. Constants are global, that is, they are the same for all geometries and subdomains. It is expressed as the dynamic viscosity divided by the density of the fluid. Kinematic viscosity is a measure of the resistive flow of a fluid under the influence of gravity. Kinematic viscosity (Greek symbol nu: $\nu_c = \mu / \rho$) has SI units ($m^2 s^{-1}$). The kinematic viscosity of water at 23ºC is 10^{-6} m^2/s, and that is the value we assume for our model. This viscosity term is negligible; it has no influence although is has been taken into consideration. At the Earth's surface, denoted g, is approximately 9.8 m/s^2 (meters per second squared). Stability of analyses is shown in Figure 5. This figure shows that the selected parameters and constants are suitable to run the dam break analysis on Upper Gotvand dam safely to get the correct results.

Time stepping.

A vector of times starting at 0.0 with steps of 0.5 up to 22.1 is selected. The relevant time span depends on the model's dynamics. The absolute and relative tolerances control the error in each integration step. Roughly stated, the relative error is less than the relative tolerance if the solution is large, and the absolute error is less than the absolute tolerance for the corresponding solution component if the solution is small. In particular, there is no accuracy at all when the solution is less than the absolute tolerance. In the 'Time steps taken by solver' edit field, for the 'Free' option selected, the solver chooses its time steps arbitrarily; in other words, it ignores the 'Times' list when selecting them. We fetch all these explanations from the 'Comsol Multiphysics User's Guide'. The rest of the parameters are the default values.

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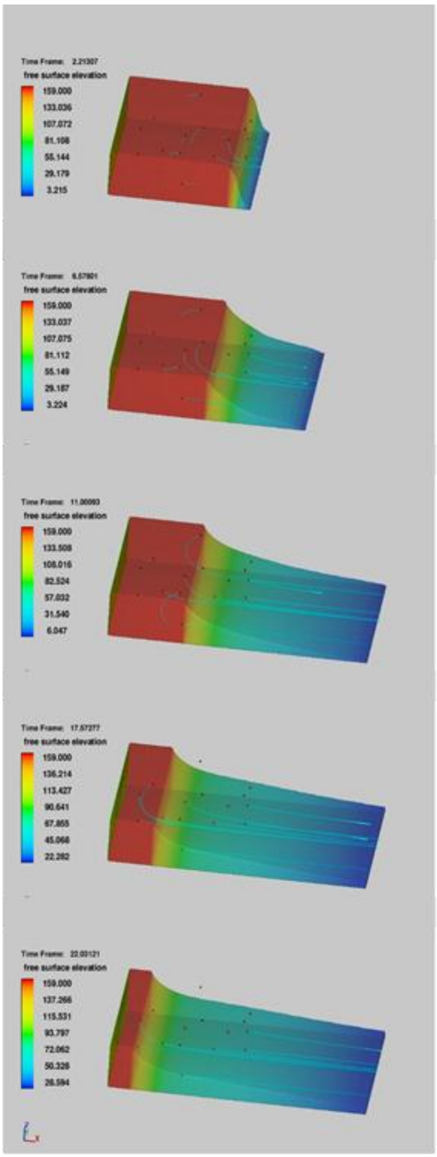

Figure 5. Hydraulic jump during the simulation.

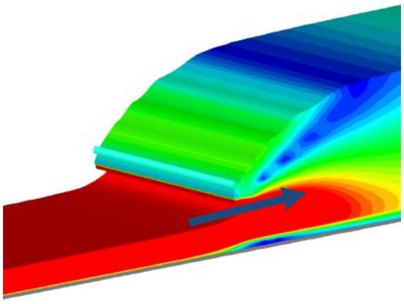

Figure 6. The numerical solution at pseudo-steady state, contoured by velocity magnitude.

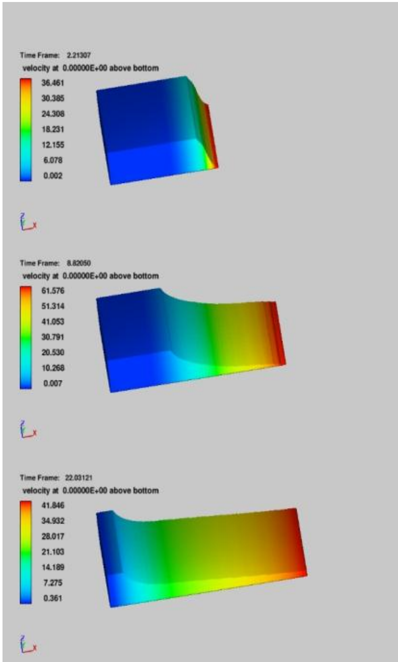

Figure 7. The distribution of velocity (m/s).

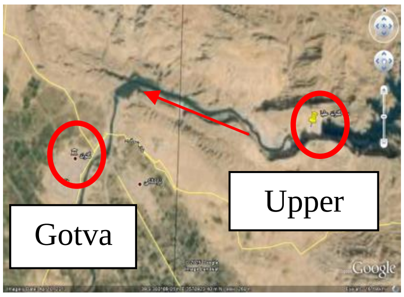

Figure 8. Location of Gotvand City on the dam's downstream.

RESULTS

The simulation runs for 22.1 seconds (when the waves reach to the 1000 m of the domain and pass it). The following figures show the water surface and the bed profile at four output times toward the beginning of the simulation (only cross sections are shown in Figure 4a to 4d). The simulation clearly shows that the flow reaches the 1000 m of the down-stream during 9.5 s. Also, the reservoir shrinks from the front after 2.2 sec. One of the most fundamental and ubiquitous aspects of free-surface hydrodynamics is the hydraulic jump. The hydraulic jump represents the turbulent transition between super and sub-critical flows. Laboratory data recording observed water levels of hydraulic jumps at several Froude numbers are reported in Rahman and Chaudhry (1998). Results were compared to Rahman and Chaudhry's water surface elevation data. Simulated results were transient, and the location of the jump was observed to oscillate over time. As the location of the jump moved, the length of transition varied depending upon if the jump was moving upstream or downstream. Results presented in Figure 5, the numerical solution at pseudo-steady state, contoured by velocity magnitude. Pacific Northwest report is typical for the numerical model. It should be noted that this was also observed in the laboratory results, and reported values were averaged over time. Upstream and downstream of the jump, the model calculated the reported water depth to within 0.01 m. The same jumps are presented in this research as shown in Figure 6. According to the simulation's data, the velocity and its distribution in the different layers of the realized water from the reservoir are shown in Figure 7. As shown in Figure 7, velocity in reservoir is changed 0.002 to 0.361 m/s during first 20 sec after the dam break. It means increasing the velocity 180 times during the dam break simulation. In the front of flood, velocity is increased from 36.5 to 41.8 m/s at the same time. On the other hand, flood can reach to 1.0 Km of the downstream of Upper Gotvand dam during only 10 sec. With this assumption that the velocity of flood is constant equal to 41.8 m/s, the flood of dam break will be reached to the near city of dam, Gotvand City, before 6 min and Shoshtar city will be under flood before 10 min, from the dam break time. (see Figure 8).

The Emergency Action Plan for Human Life Saving

A vital issue in dam safety is the protection of the dam's downstream. The development of a comprehensive dam breach analysis and emergency action plan will help the authorities to minimize the damages resulting from dam breach disasters. The total storage volume of Upper Gotvand dam is about 5.1 billion m3 and it is very important because this dam is the final dam on Karun river after 9 large dam on the upstream (Figure 9).

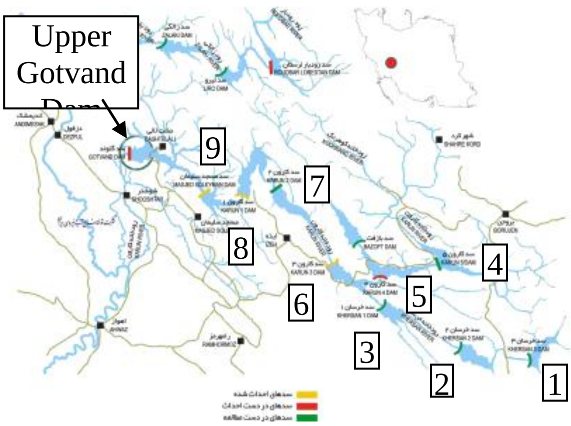

Figure 9. The distribution of velocity (m/s).

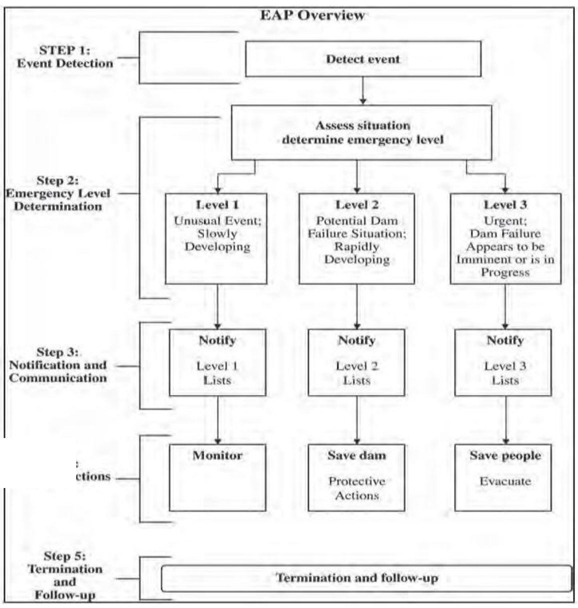

Figure 10. The proposal EAP for Large dam.

They not only play as the most important roles of water resource management but also the flood control of the dam's downstream. With the characteristics of the steep slope in downstream river, the flood will travel more quickly when dam breaching. With 4.5 million people living around the downstream basin, the crowded population will shorten the response time, complex the coordination and enlarge severe damage as well. With years of effort pushed by the central government, the templates of EAP had been developed and applied at many reservoirs with good result. This would be a good experience to share. The EAP specifies actions the dam owner should take to moderate or alleviate the problems at the dam. It contains procedures and information to assist the dam owner in issuing an early warning and notification to appropriate emergency management authorities of the emergency situation. It also contains inundation maps to show emergency management authorities critical areas for action in case of an emergency. When people live in an area that could be flooded due to the failure of a dam, an emergency potential is assumed to exist. An emergency, in terms of dam operation, is an impending or sudden uncontrolled release of water which could result in flooding of downstream property with the potential risk to human life. The EAP must clearly specify the dam owner's responsibilities to ensure effective, timely action is taken should an emergency occur at the dam. For this purpose, Figure 10 is recommending to define the steps of EAP for large dam.

CONCLUSION

One of the main goals of this study was to show the important of a dam break analysis on the large dam. This capacity has been proved even though it has been done using a simple and idealized case. For this purpose, theory of dam break is discussed and numerical simulations are done on Upper Gotvand dam with 182 m high in Iran. In parallel with the rapid development of computer technology within the last 20 years, dam break and flood simulations have stepped from the use of simplified models to one dimensional channel network models and finally to expensive two-dimensional models. The trend is to minimize the expert work in favor of computer resources. A framework for a dam break analysis is summarized, where the current practice is presented according to the ICOLD (International Commission On Large Dams) recommendations. The flood wave caused by a dam failure can result in the loss of human lives and have a severe economic impact. Therefore, significant efforts have been carried out over the years to produce methods for determination of the extent and timing of the flood wave. In this study, dam break modeling for very large dams has been focused. For this purpose, Upper Gotvand dam, located on Karun river in Iran, has been taken into consideration. With a height of about 182 m, which is one of the largest earth and rock fill dams in the world. Most simulation studies for the dam break problem are currently attempted using one-dimensional models, and we investigate here the possibility of the simple example of the collapse of a dam is used with a finite element analysis. The hydraulic analysis of the dam break problem from a different point of view has been done in this work. Moreover, the risk zones in the dam's downstream are known. This study would be useful for the dam break analysis and the risk assessment of existing & planned dams in Iran as well as in other parts of the world. Also, the findings of dam break modeling are helpful in the risk assessment of dams. The flooding risk could be quite high due to the failure of large dams. This study proposes the Emergency Action Plan (EAP) of a very large earth and rock-fill dam to save the human life.

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