Numerical Investigation of Dam-Break Flow over a Bottom Obstacle Using Eulerian Finite Element Method

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Abstract— *Dam-break flows can cause major destructions in case settlements located at the downstream area. Since many people live in the settlements, investigations regarding the dam-break flow have great importance. Dam-break flow characteristics can become various based on different downstream conditions. In this study, an investigation was made relating to the dam break flow in a channel with symmetrical triangular-shaped bottom obstacle using Finite Element Method (FEM) formulation. Numerical results of the present study were compared with experimental results. It was concluded that numerical and experimental results are in good agreement.*

Keywords— *Dam-Break, Finite Element, Eulerian, Free Surface Flow.*

I. INTRODUCTION

Dams are important engineering structures with main purposes such as water supply and energy generation. In case of dam-break, the large amount of water can cause catastrophic floods at the downstream area. For this reason, determination of the characteristics of dam-break flow such as the flow depth and wave propagation velocity have great importance.

Due to difficulties in obtaining field data, many experimental and numerical studies were carried out to investigate dam-break flow phenomenon. Some researchers carried out experimental studies using horizontal rectangular channel [1], straight and curved channels [2-3]. Some researchers conducted experimental works, in the presence of obstacles and over a bottom sill, adopting image processing as a measurement technique [4-5].

Due to difficulties in experimental studies, numerical models have become important to investigate the dam-break flow characteristics in recent years. Most of the early numerical studies used shallow water equations (SWE) to describe the flow [6-7]. Developments in computer technology have made it possible to use advanced numerical

methods based on Computational Fluid Dynamics (CFD) codes. Vasquez and Roncal [8] were investigated sudden dam-break flow using CFD modeling software. Some researchers used SWE and Reynolds Averaged Navier-Stokes (RANS) equations to investigate dam-break flow with dry and wet conditions [9-10]. Aurelli et al. [11] compared the SWE based numerical solution of dam-break flow over the bottom obstacle with experimental data. Some researchers used a numerical model based on Finite Volume Model (FVM) to investigate the effect of lateral channel contraction on dam-break flow [12-13]. Ozmen-Cagatay et al [14] used numerical models based on SWE and RANS equations to validate their own experimental data of the dam-break flow in a channel with a symmetrical triangular-shaped bottom obstacle.

Numerical models related to dam-break studies play an important role in understanding hydrodynamics properties of dam-break flow. However, these numerical models need to be validated by comparing with various experimental data. Therefore, the purpose of this study is to investigate the performance of numerical model based on Finite Element Method (FEM) formulation in the dam-break flow phenomenon. In order to overcome extreme deformation feature of fluid, Eulerian formulation was used to define a reference frame in FEM analysis. To determine the performance of the numerical method, numerical data were compared with experimental data [14].

II. EXPERIMENTAL SETUP

Experimental studies were conducted by Ozmen-Cagatay et al. [14] using a rectangular smooth horizontal channel having the dimensions of 8.90x0.30x0.34 m with glass bottom and walls. The plate representing the dam was located at 4.65 m from the channel entrance. The initial water level of the reservoir, h_0, was 0.25 m. The downstream channel was initially kept dry at downstream of the breach. A symmetrical triangular-shaped bottom

obstacle with 1.0 m base length and 0.075 m height was located at 1.50 m downstream from the dam site (Fig. 1a). Dam-break model was represented through a mechanism allowing the sudden removal of the vertical rigid plastic plate with 4mm thickness. A steel rope having 15 kg was attached to the plate. By releasing of rope from 1.50 m

above the ground, the plate was instantaneously removed (Fig. 1b). It was determined that the removal time between 0.06 s and 0.08 s. In the literature, this time is required to be shorter than $1.25(h_0/g)^{1/2}$ where h_0 is the initial flow depth in the reservoir and g is the acceleration of gravity so is considered as 'sudden removal' [15].
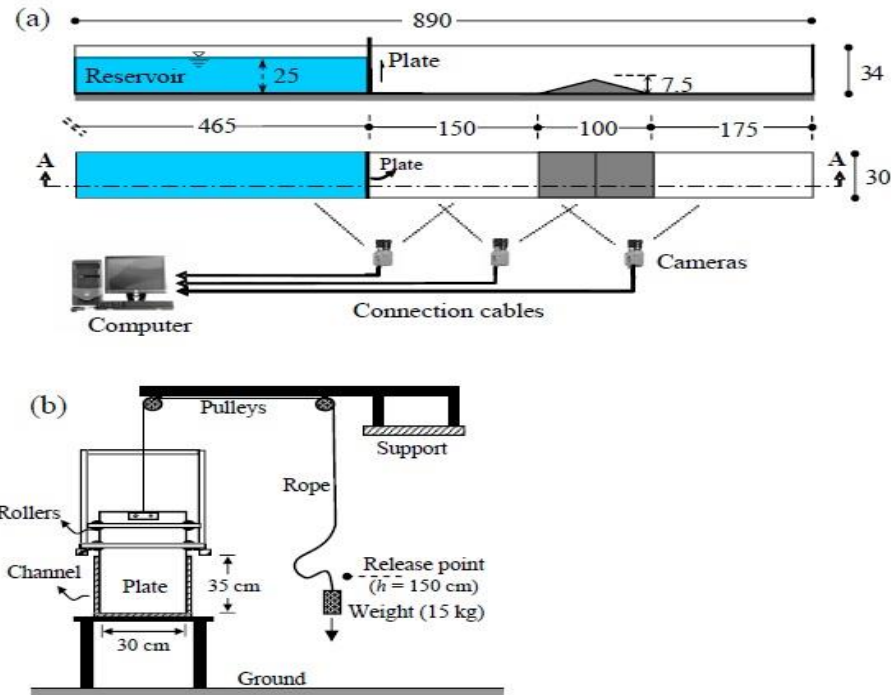

Fig.1:a) Experimental Setup b) Scheme of Dam-Break Mechanism, lengths in (cm)[14]

Image processing method, which contains three CCD cameras, a frame grabber card and a computer, was used to determine time evolution of water levels. The recorded video using three CCD cameras transferred to a computer

and separated to frames. Then, filters and threshold values were used to better identify water surface. There are 6 measurement points (P1-P6) in the experiment and, their locations are shown in Figure 2.
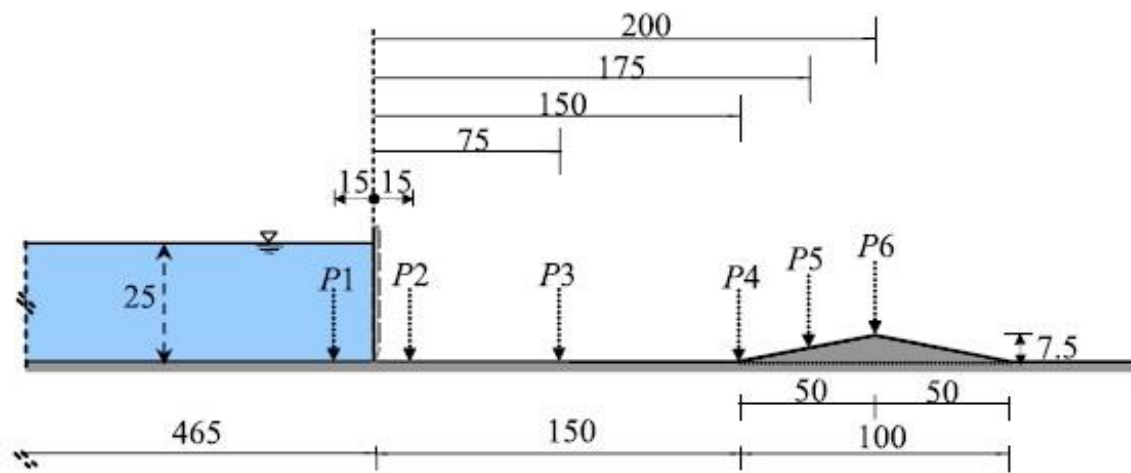

Fig.2: The measurement locations of the stage hydrographs, lengths in [cm] [14]

III. NUMERICAL MODEL

In FEM, there are two different formulations to describe reference frame; Lagrangian and Eulerian. In the Lagrangian formulation, materials are fixed to meshes and deform together. In the Eulerian formulation, meshes are fixed to space and, materials can move through meshes freely. Eulerian Analysis technique in ABAQUS/Explicit [16] is an effective tool for applications involving extreme deformation with these features and was used in this study to model dam-break flow.

Throughout the Eulerian analysis, the material ratio in the elements is determined by the value of "Eulerian Volume Fraction (EVF)". While EVF=1 value represents the fully filled element, EVF=0 value represents the fully void element.

In this model, the water was modeled as a Newtonian, viscous and nearly incompressible using the linear Mie–Grüneisen equation of state (EOS);

$$p = \frac{\rho_0 C_0^2 \eta}{(1-s\eta^2)}\left(1 - \frac{\Gamma_0 \eta}{2}\right) + \Gamma_0 \rho_0 E_m \qquad (1)$$

where $\eta = 1-\rho_0/\rho$ is the volumetric compressive strain and, parameters Γ_0 and s are the material constants. p is pressure and E_m is the internal energy per unit mass. C_0 defines the velocity of sound through water and, ρ_0 is initial density.

Parameters used to define EOS material and viscosity value are listed in Table 1.

Table.1: Material properties of water

ρ_0	1000 kg/m^3
C_0	1500 m/s
S	0
Γ_0	0
μ	0.001 Ns/m^2

Eulerian domain with 7.5x0.01x0.26 m sizes was created using ABAQUS software and, water with 0.25 m height was assigned as material at up to 4.65 m beyond the channel entrance as in accordance with experimental setup (Fig. 3). To discrete Eulerian domain, EC3D8R type elements with 0.01x0.01x0.01 m sizes were used. There is one element at y-direction to provide 2D analysis condition.

As the initial condition of pressure, the hydrostatic pressure was applied to water. Gravity force providing the movement of water was applied to the whole model. There is no inflow in the model and only one outflow is assigned to end of the channel.
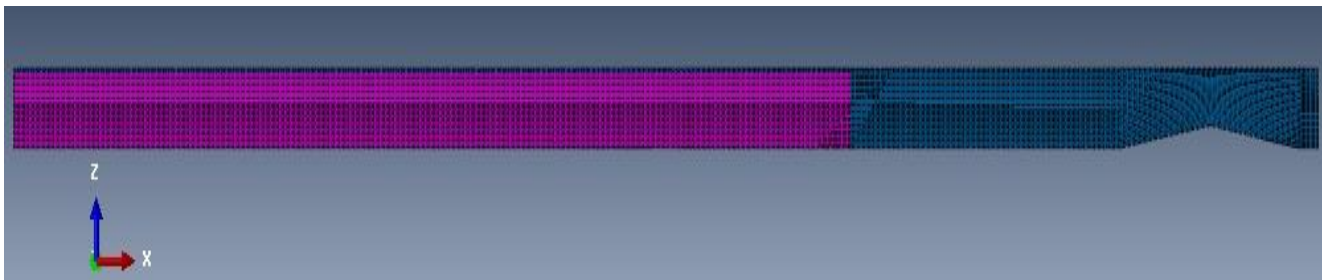

Fig.3: Water (Purple) Assignment inside Eulerian Domain (Blue)

IV. RESULTS AND DISCUSSION

Eulerian Analysis was run for 17s and, velocity magnitude values at various times were shown in Figure 4. By sudden remove of the plate, flood waves started to move in the dry bed. When flood waves arrived to triangular-shaped hump, a part of the wave was reflected. It was seen that a bore appeared travelling to upstream direction, whereas the other part traveled towards downstream of the hump. In numerical results, plunging type wave breaking was seen because of flood wave reflection from the hump, while spilling type wave breaking was seen in upstream direction during the experiment [14]
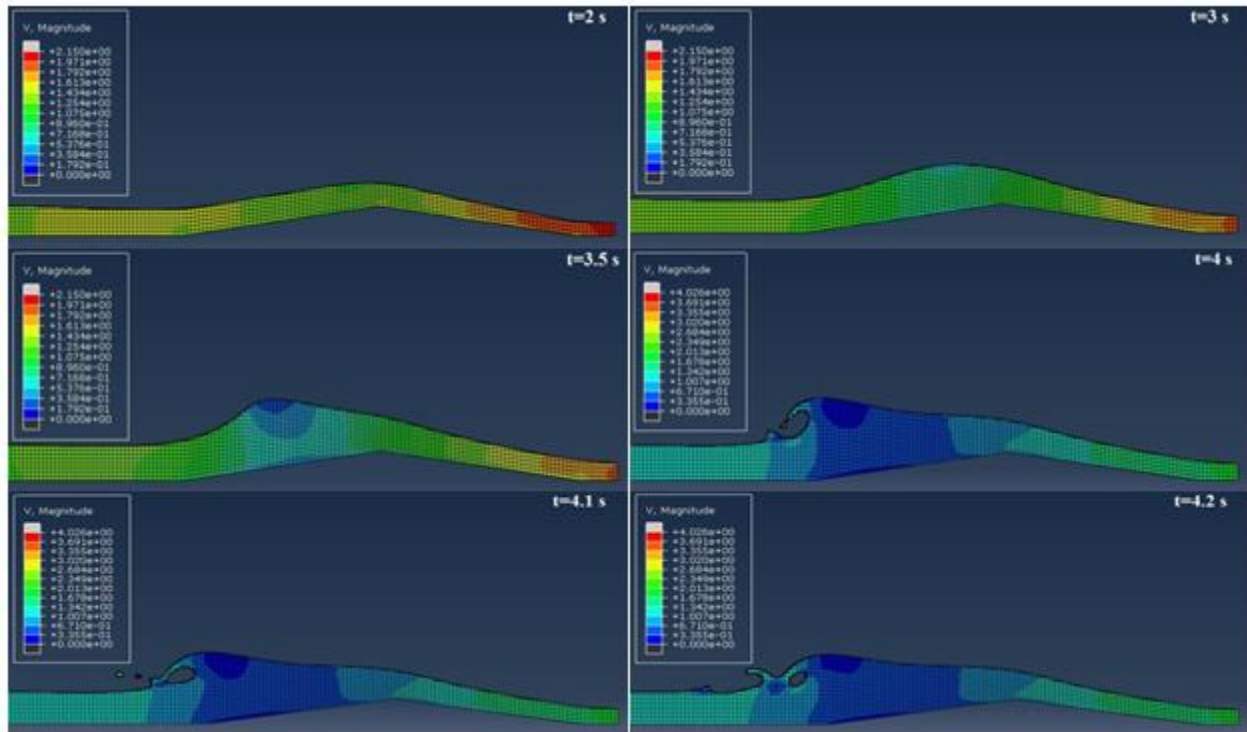
Fig.4: Computed Velocity Magnitudes at 2s, 3s, 3.5s, 4s, 4.1s and 4.2s

Fig. 5 shows the comparison between experimental results obtained by Ozmen-Cagatay et al. [14] and present numerical study results through non-dimensionalized time evolution of water levels for all sections from P1 to P6. The time, t, was multiplied by $(g/h_0)^{1/2}$ to obtain dimensionless time, T. Water level, h, divided to initial water level, h_o, to obtain dimensionless water level. In Eulerian FEM analysis, water levels at measurement points were calculated using EVF values in elements.

When the plate was instantaneously removed, an abrupt drop was observed in water level at the P1 point. After that, rising in water level at other points (P2-P6) was started to be seen respectively. Because of reflection waves, abrupt rising in water level was seen at all measurement point except P6.

It was seen that there is a good agreement between numerical and experimental results at P1, P2, P3, P4 and P5 measurement points until abrupt rising in water level caused by reflection waves. It is observed that the experimental data profiles are smoother than numerical data profiles. Although depth values are in good agreement until abrupt rising, numerical results are below the experimental results after the rising. However, the numerical results are above the experimental results at the abrupt rising stage. The results are in good agreement generally. However, it is

obvious that the experimental reflected wave fronts are faster than the numerical results at all stages.

This discrepancy can be due to the determination mechanism of the water level through the Eulerian Volume Fraction (EVF). The water level is determined using fill rate of the mesh. The mesh founded on the water surface fills up to its any level. Since the below meshes are filled with water completely, their ratio is 1. Sum of the heights of the full meshes below and the partially filled mesh on the top is the volume value of the measuring point. The fill rates of the meshes illustrated in Figure 6.
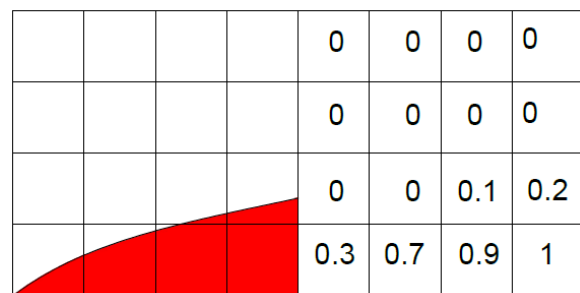

Fig.6: Determination of the fill rates of the meshes (Representative Values)

Then, the volume value divided by area of the bottom surface of the element to obtain the approximate water height. As it can be seen, the mesh size affects the

determination of the water level significantly. It was considered that finer mesh can increase both sensitivity of analysis and, the accuracy of calculation of water level from

EVF value. Since the finer mesh means smaller mesh size, the measurement of the water level can be performed more accurate by the Eulerian FEM.
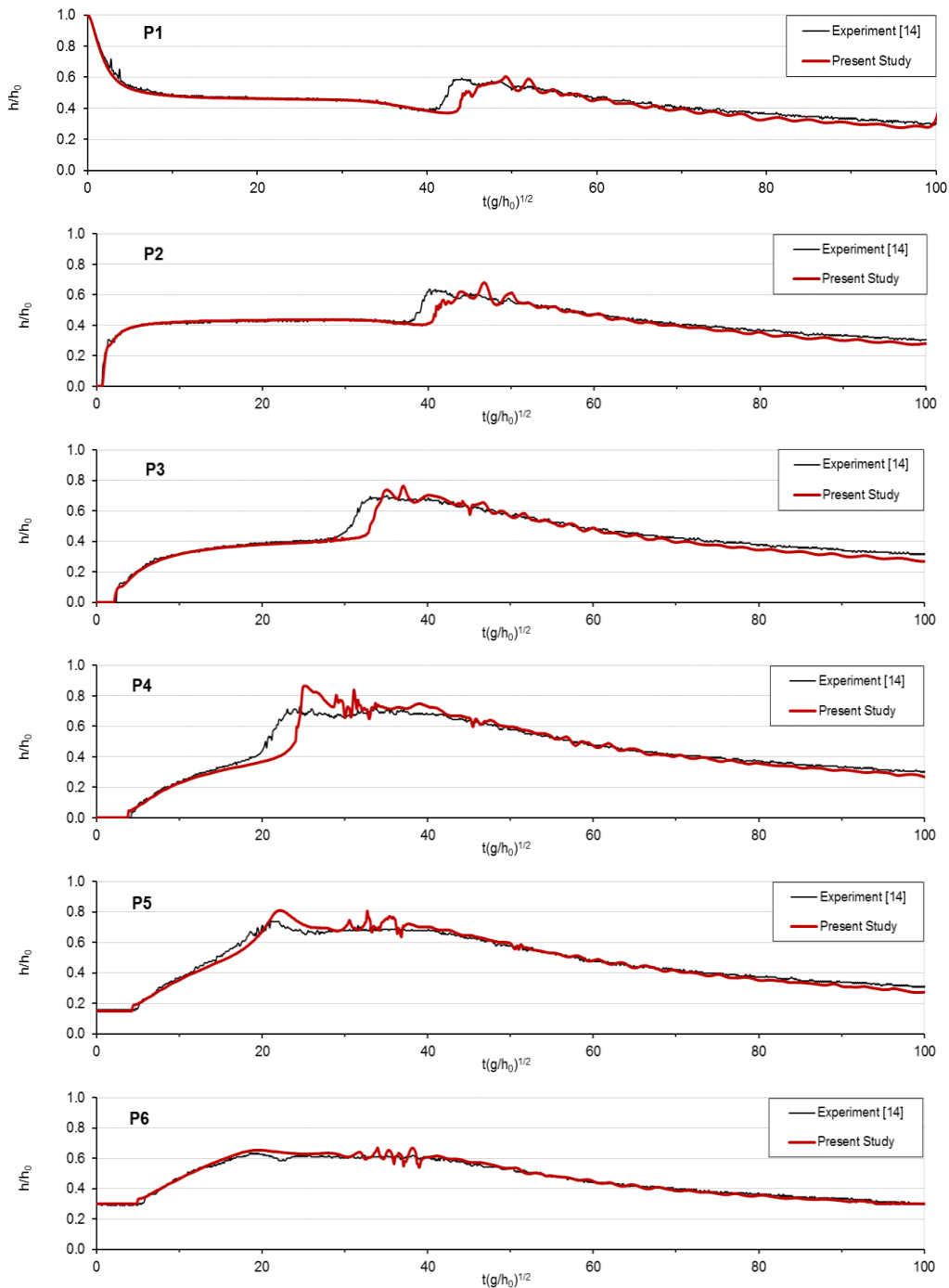

Fig.5: Comparison between experimental data and present study (FEM) results for the time evolution of water level at the dimensionless distance from P1 to P6.

V. CONCLUSIONS AND SUMMARY

In this study, FEM with Eulerian formulations was used to investigate dam-break flow in a channel with a symmetrical triangular-shaped bottom obstacle. Numerical and experimental results were compared using water levels at six measurement points. Image Processing Method was used to obtain water levels in the experiment.

The experimental and numerical study showed that presence of any obstacle in downstream affects flow pattern significantly. Rising in water level and wave reflection in downstream are important effects of obstacle in this experiment. Generally, there is a good agreement between numerical and experimental results until rising in water level caused from wave reflection. Also, after the wave reflection occurs, fluctuations were observed in numerical model results.

It is considered that using better mesh structure can improve numerical method accuracy. In future works, effect of different mesh structures can be investigated. Also, it is considered that the lack of any turbulence definition in Eulerian FEM reduced the accuracy of the model to some extent.

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