Hydrodynamic Pressure on Culvert Gates during an Earthquake

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ABSTRACT: Culverts are essential parts of the lock and navigation structures. They transfer water between upper and lower chambers, lakes, rivers and/or ocean side of the navigation system. A system of bulkheads and valve gates control the transfer of water in these culverts during operation and maintenance. These gates are designed to withstand the hydrostatic and transient pressure loads. A phenomenon that is, however, usually overlooked in the design is the hydrodynamic pressure that is built up in the system during an earthquake. This pressure is caused by the seismic acceleration and could be higher than hydrostatic pressure in a severe earthquake. In this paper a set of simulation results using Abaqus/Explicit are presented for hydraulic culvert models to investigate the pressure caused by an earthquake. The pressures predicted by these simulations are compared with two simple solutions being used in contemporary seismic design. The results of the simulations are presented in form of a parametric study on the effect of culvert tunnel length, venting geometry, dimension and topology of the vents, existence of notch at the vent opening, and also the cavitation effect. These studies were performed using scaled Tabas earthquake acceleration as the input seismic motion.

1. Introduction

Culvert valve and bulkhead gates are subject to substantial hydrodynamic water pressure loading during an earthquake. In some cases this pressure is ignored in the design of these gates and the supporting structures. In regions with lower seismicity, this simplification could be acceptable, especially if the static head of water is substantial. The hydrodynamic pressure, however, is large during a strong ground shaking and could become a substantial part of the design load. An example is Menjil 1990 earthquake in Iran where the hydrodynamic force damaged a radial gate in the intermediate level spillway of the Sepid Rud buttress dam (Jalalzadeh, 2000).

Besides, in current seismic analysis practice, wherever this hydrodynamic pressure is considered to be important, the seismic pressure according to Westergaard solution (Westergaard, 1933) is used. Westergaard solution results in adequate factor of safety in dam gates and gates of surface spillways (Sasaki, 2007). However, the results of a few Abaqus/Explicit simulations for that are presented here demonstrate that the Westergaard solution does not provide adequate factor of safety for some pressured water systems.

In this paper the governing pressure wave equation are briefly introduced alongside with water-structure interaction and the cavitation limit. Then a progressive analysis for the problem of interest is presented. In a progressive analysis, sophisticated models and simulations follow simplified analysis based on established technique. This step-by-step increase in the sophistication of the analysis helps with building up confidence in the final results.

The progressive analysis in this work starts with the simple Westergaard solution. The pseudo-static Wieland analysis is presented as the next step in sophistication. Finally, the explicit (nonlinear) finite element analysis using Abaqus/Explicit is presented as the most sophisticated model. A comparison of these different solutions and the limits on applicability of these solutions is also presented.

Abaqus/Explicit analysis results are presented as a parametric study on 2D simulations. This study illustrates the effect of different parameters in the culvert geometry in determining the maximum pressure on the culvert valve gate.

The progressive analysis and the parametric study presented here are the basis for the 3D Explicit Finite Elements simulations of the design cases in Tetra Tech.

2. Statement of the Problem

Figure 1 shows the schematics of the problem of interest. This picture shows an enclosed culvert tunnel that is connected to the bottom of a chamber in one end and is closed-off by a valve gate on the other end.

There may be one or more vents in the culvert in between the chamber and the valve gate as is shown here. The culverts have maintenance bulkhead slots in the area of the gates, which have a free water surface at the top. Although these have a limited area, they provide some venting of the pressures generated during the seismic event.

The objective is to design the valve gate so that it can withstand the hydrodynamic pressure caused by seismic acceleration.
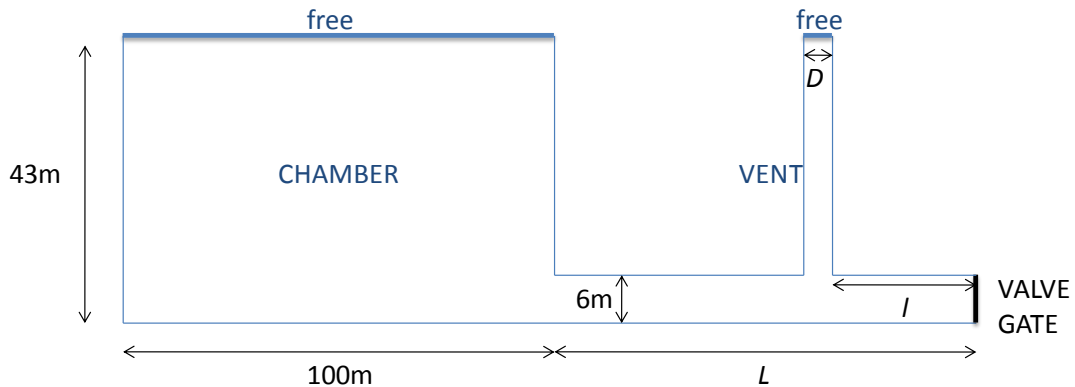

Figure 1 – Schematic of the problem of interest, which is used in the parametric study presented in this paper.

3. Mathematical View

Here is a brief mathematical description of the pressure wave problem (DASSAULT SYSTEMS, 2011). The wave equation is

$$\frac{\partial^2 p}{\partial x^2} + \frac{\partial^2 p}{\partial y^2} + \frac{\partial^2 p}{\partial z^2} = \frac{1}{c^2}\frac{\partial^2 p}{\partial t^2}, \quad c = \sqrt{K/\rho_w}$$

In the above equations, p is the gauge pressure and c is the speed of the pressure wave. K is water bulk modulus and ρ_w is water density. The pressure at the water surface remains zero.

The interaction on water-structure interface is governed by $\frac{\partial p}{\partial n} = -\rho_w \ddot{u}_n$ where n is the normal to the interface and $\ddot{u}_n$ is the component of the structural acceleration in the normal direction.

In the time history analysis with cavitation the minimum gauge pressure is set to -0.101 MPa based on the average atmospheric pressure at the sea level.

4. Analysis Progression

The Analysis progression starts with the Westergaard Solution that is an appropriate approximation for the case of (close to) zero vent length (L in Figure 1). The next step on sophistication is using the pseudo-static analysis introduced by Wieland (Wieland solution). This solution is intended for the cases without vent. Finally Abaqus/Explicit simulation is presented which is the most sophisticated method of analysis.

4.1   Westergaard Solution

It is accepted in civil engineering to estimate the hydrodynamic pressure on the rigid reservoir dams by the Westergaard hydrodynamic pressure equation, which is

$$p_d = 0.875\rho_w gk\sqrt{H.h}$$

where p_d is the hydrodynamic pressure (MPa), $g = 9.81\,\mathrm{m/s^2}$ is the gravity and k is the design seismic coefficient. The value of k is two third of the peak ground acceleration in terms of g (i.e. $k = \frac{2}{3}\frac{PGA}{g}$). H is the total depth of the water reservoir and h is the depth from the reservoir water surface to the point of action of hydrodynamic pressure.
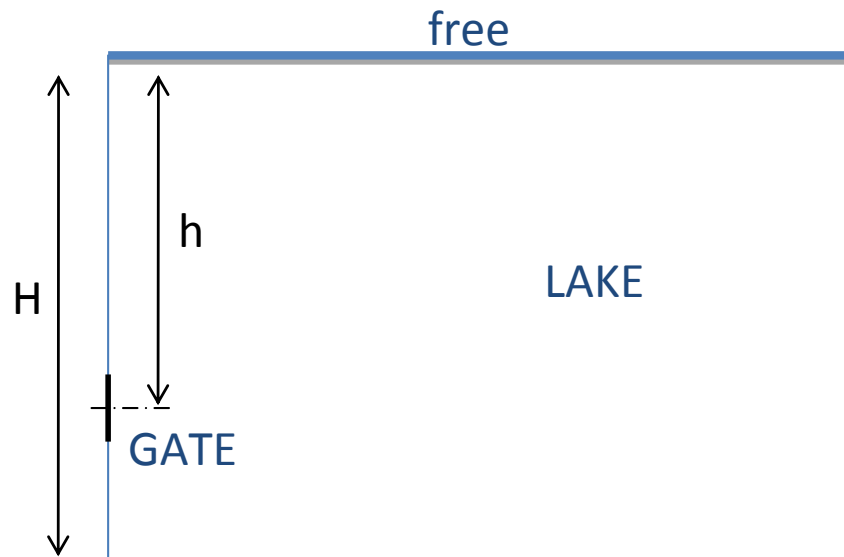
Figure 2 – Schematics for the Westergaard solution.

4.2 Wieland Solution

Wieland (2005) introduced a pseudo-static solution for the hydrodynamic water pressure in long tunnels. This solution uses elastic acceleration response spectra in estimating the pressure at the gate at the end of a pressure tunnel or penstock. The hydrodynamic pressure is calculated to be

$$p_d = (8/\pi^2)\gamma_w.L.S_a(T_1,\zeta)$$

L is the length of the tunnel, T_1 is the main period of the pressure wave propagation in the tunnel, and ζ is the damping ratio.

4.3 Explicit Time History Analysis

The explicit method of time history analysis is selected here to capture the wave propagation characteristics of the solution. The explicit dynamics analysis procedure in Abaqus/Explicit (DASSAULT SYSTEMS, 2011) is based upon the implementation of an explicit integration rule together with the use of lumped element mass matrices. The program automatically selects the time stepping to ensure stability and convergence.

Water in the chamber and the culvert is modeled with acoustic elements simulating the properties of water. The element used in Abaqus/Explicit is AC3D8R, an 8-node linear acoustic brick.

4.4 Applicability of Different Solutions

Westergaard solution is credible for the case of rigid gates on dam lakes and channels walls. Wieland solution is a simple solution for the case of long enclosed tunnels, culverts and penstocks. Explicit Time History analysis is the most versatile solution presented here.

5. Case Studies

5.1   The model

A group of 2D culvert models were simulated using Abaqus/Explicit to investigate the importance of the parameters that affect the maximum hydrodynamic pressure observed at the valve gate location. The parameters that were studied were the effect of culvert tunnel length, venting, dimension of the vents, existence of notch at the vent opening, and setting a minimum to the water pressure (cavitation effects).

Figure 3 shows a representative model in Abaqus/CAE. Note that a rigid valve gate transfers the acceleration to the culvert.
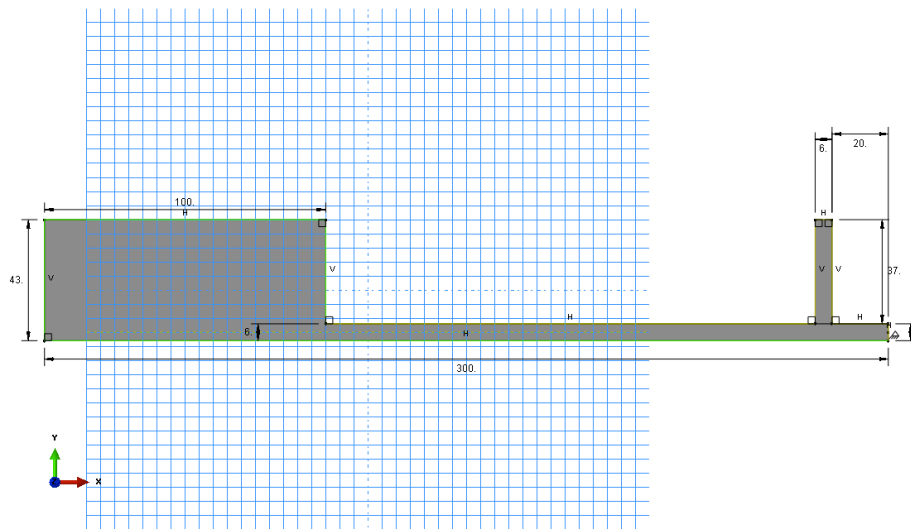

Figure 3 – Picture of a typical model examined in this parametric study (case #4)

5.2   Seismic Loads

These studies were performed using scaled Tabas earthquake as the seismic motion. It is Tabas seismic record that is scaled to Peak Ground Acceleration of 4.18 m/s^2.

Figure 4 presents the acceleration time history and Figure 5 shows the Pseudo-acceleration response spectra for this motion.
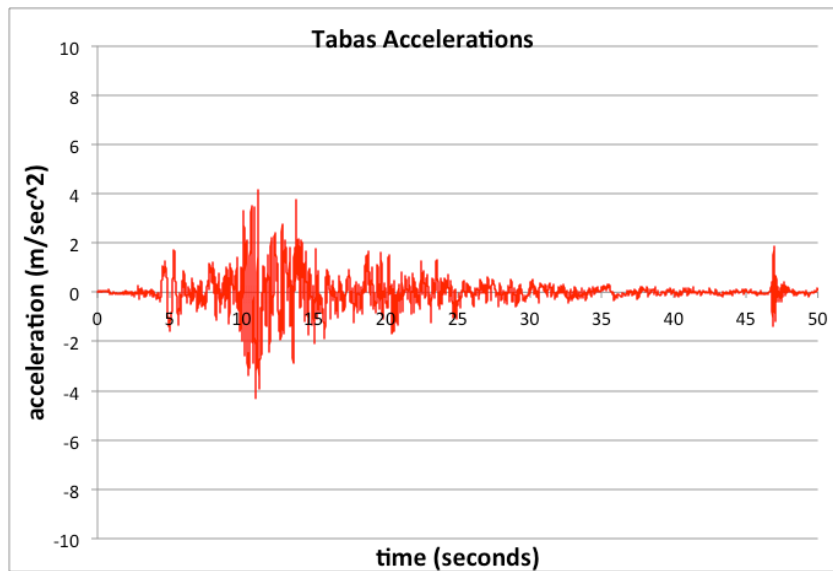
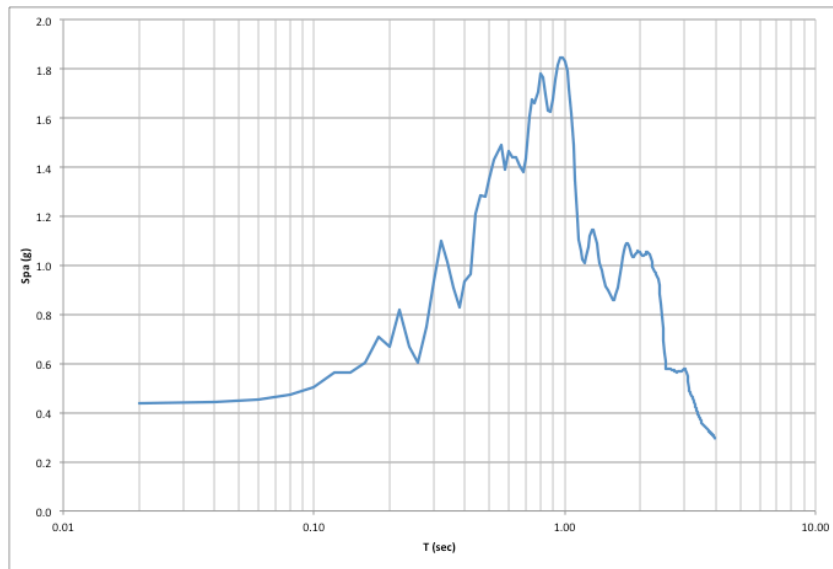**Figure 4 – Acceleration time histories for scaled TABAS earthquake.**

Figure 5 – Pseudo Acceleration Spectra (PAS) for Tabas earthquake (5% damping).

5.3   The Simple Solutions

5.3.1   Westergaard Solution

Westergaard pressure for a gate center could be calculated using Westergaard equation with $H = 43\,\text{m}$ $h = 40\,\text{m}$, and $PGA = 0.52g$. Hence $p_d = 0.12\text{MPa}$.

5.3.2   Wieland Solution

Figure 6 presents the pressure at the end of tunnel (gate) location as is calculated based on the acceleration response spectra for Tabas earthquake (Figure 5).
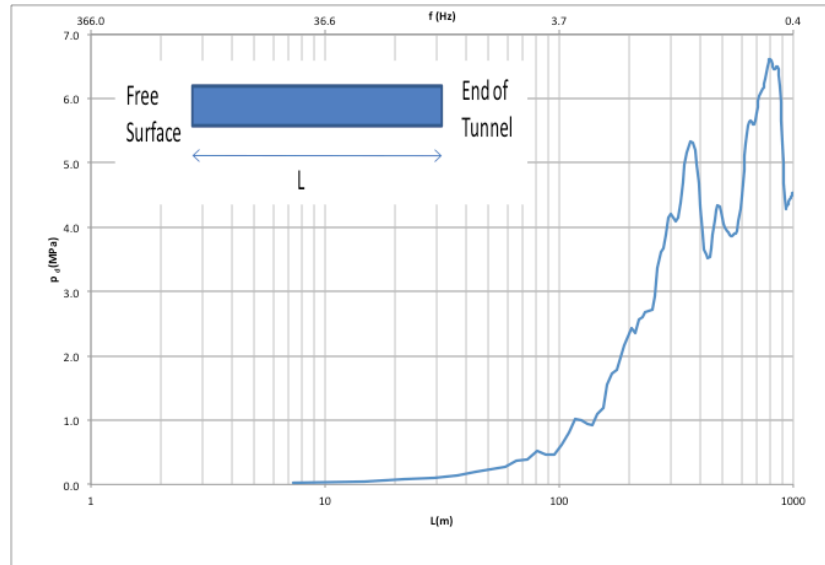

Figure 6 – Gate pressure at the end of the tunnel for Tabas earthquake (5% overall damping) calculated using Wieland solution.

5.4   Parametric Studies

Table 1 shows the values of the parameters and also the maximum pressure observed in each case and its corresponding main frequency. Figure 7 to Figure 15 in the Appendix show the geometry and the pressure distribution in each of these cases.

5.4.1   Culvert Length Effect

Checking rows 1 to 3 of Table 1 shows that for $L = 1$m, Westergaard Solution is 45% overestimate. For $L = 100$m and $L = 200$m, however, it gravely underestimates the correct hydrodynamic pressure.

Figure 6 shows that Wieland solution is lower than the Abaqus/Explicit results at these lengths, which reflects the effect of damping besides the approximate nature of this solution.

5.4.2   Venting and Geometry of Vents Effect

Adding a vent with the same width as the culvert depth decreases the pressure substantially. Decreasing the vent size, however, increases the maximum pressure observed at the gate center. Note that the gate pressure stays significantly higher than Westergaard estimate in all cases. These observations are presented in cases 4,5, and 6.

Moving the vent away from the valve gate increase the maximum pressure observed at the gate center as is shown in case 7. Adding a notch to the lower part of the vent, while keeping its free surface constant, won't change the pressure significantly. This is observed by comparing case 6 and case 8.

5.4.3   Cavitation Effect

Case 9 is a re-run of case 6 with set cavitation limits ($p_{t,\min} = -0.101\mathrm{MPa}$). This limit had reduced the maximum pressure observed at the valve gate.

Table 1 – Parametric studies on culvert geometry, venting and cavitation. P_{max} is the maximum pressure at the center of the gate.

Case	L (m)	l (m)	D (m)	P_{max} (MPa)	f_1 (Hz)
1 – gate at chamber		-	-	0.085	8.5
2 – intermediate tunnel	100	-	-	1.95	3.3
3 – long tunnel	200	-	-	2.85	1.7
4 – case #3 with large vent	200	20	6	0.42	3.1
5 – case #3 with vent	200	20	2	0.95	2.5
6 – case #3 with small vent	200	20	1	2.33	2.2
7 – case #3 with far vent	200	100	1	2.50	2.0
8 – case #4 with notched	200	20	6	0.46	3.0
9 – case #6 with Cavitaion	200	20	1	1.31	-

6. Summary and Conclusion

A progressive analysis is presented here that was intended for estimating the seismic hydrodynamic pressure on culvert valves. This analysis starts from the simple Westergaard analysis, is followed by more refined Wieland solution, and is finalized by nonlinear time history analysis in Abaqus/Explicit.

The magnitude of the hydrodynamic pressure depends on the earthquake peak ground acceleration, and also frequency content of the earthquake. It is also a function of geometry, shape and length of the culvert tunnel and the shape and area of the vent openings.

The Abaqus/Explicit solution presented here is the most versatile one except for the shortcoming that it doesn't include damping. Hence, except when cavitation is active, there is no damping of energy. Among the simpler solutions, the Wieland solution includes a uniform damping as implemented in the response spectra.

7. References

1. DASSAULT SYSTEMES and Simulia, 2011. Abaqus Analysis User's Manual.
2. Jalalzadeh A.A., Fouladi N.C., 2000. Measures on gated spillway of Sefidrud and Marun dams – case studies. Proc. 20th Int. Congress on Large Dams, China
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4. Sasaki, T., Iwashita, T., Yamaguchi, Y., 2007. Calculation Method of Hydrodynamic Pressure in Seismic Response Analysis of Gates. The Tirthy-Ninth Joint Meeting of UNJR, Japan
5. Westergaard, H.M., 1933. Water pressures on dams during earthquakes. Transactions of ASCE 98, 418-433.
6. Wieland, M., 2005. Hydrodynamic Pressures. International Water Power and Dam Construction, 18-24.

8. Appendix

The following pictures illustrate the maximum hydrodynamic pressure distribution in the 9 parametric studies. The maximum pressure at the center of the gate is reported in Table 1.
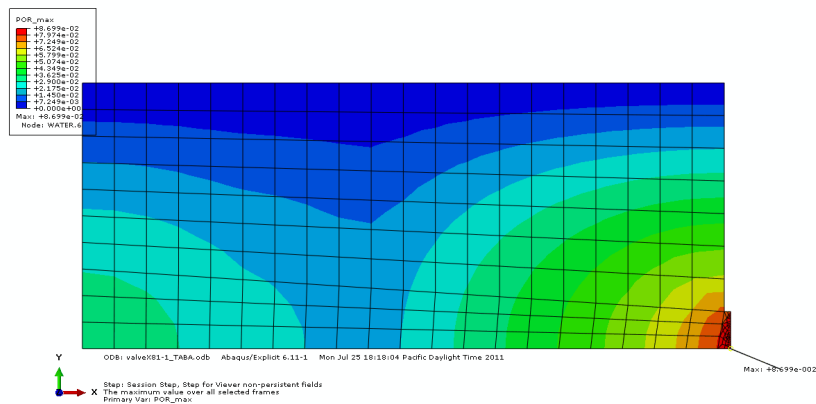

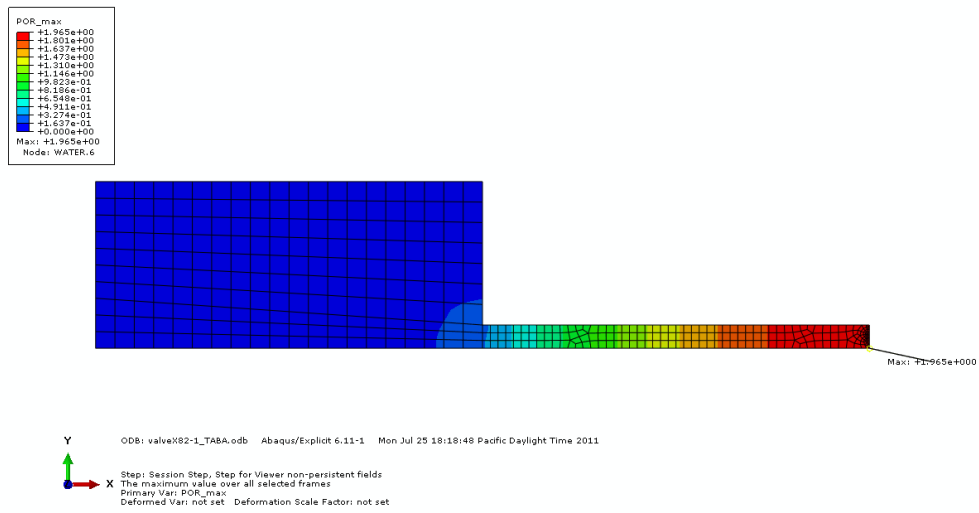**Figure 7 - Maximum hydrodynamic pressure distribution in case 1.**

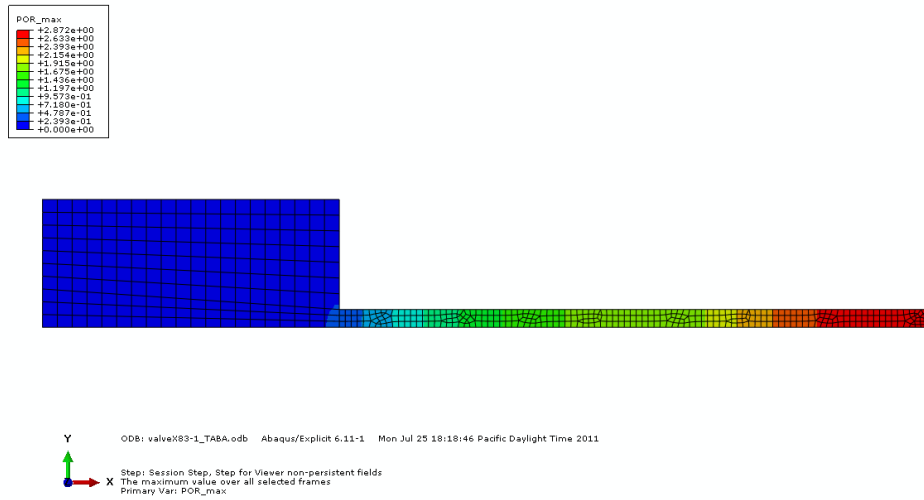**Figure 8 - Maximum hydrodynamic pressure distribution in case 2.**

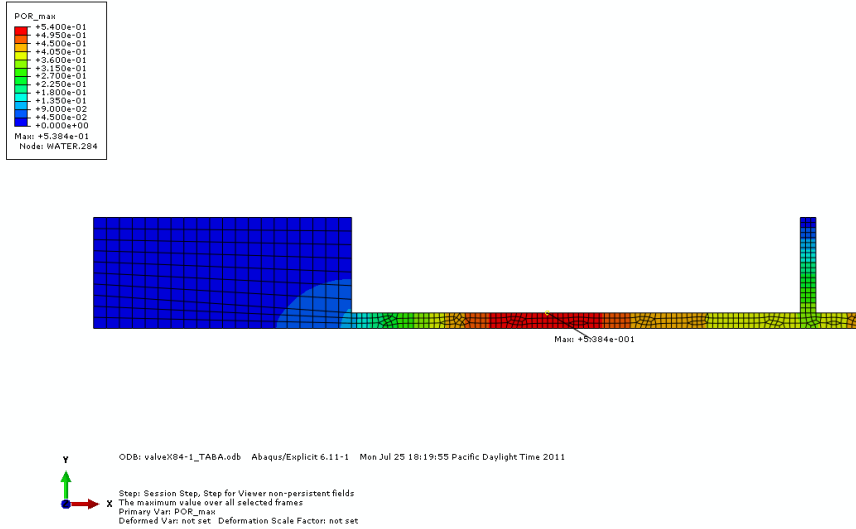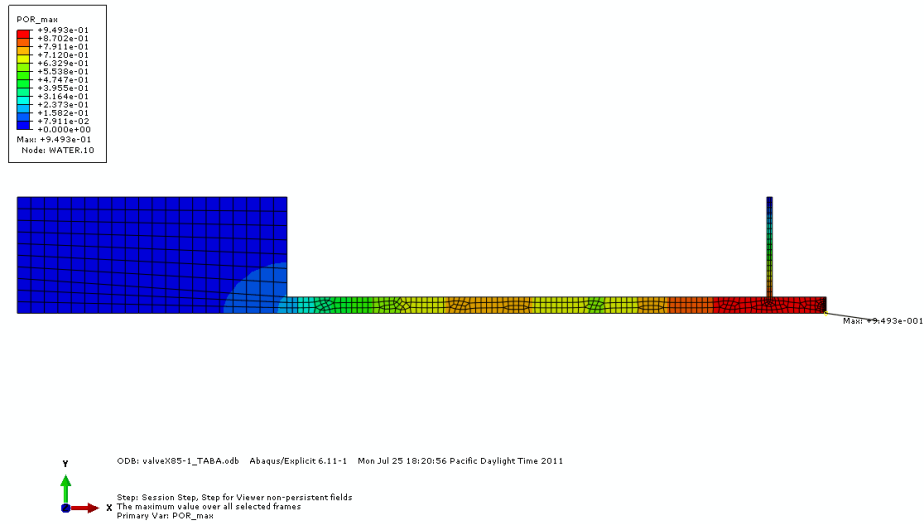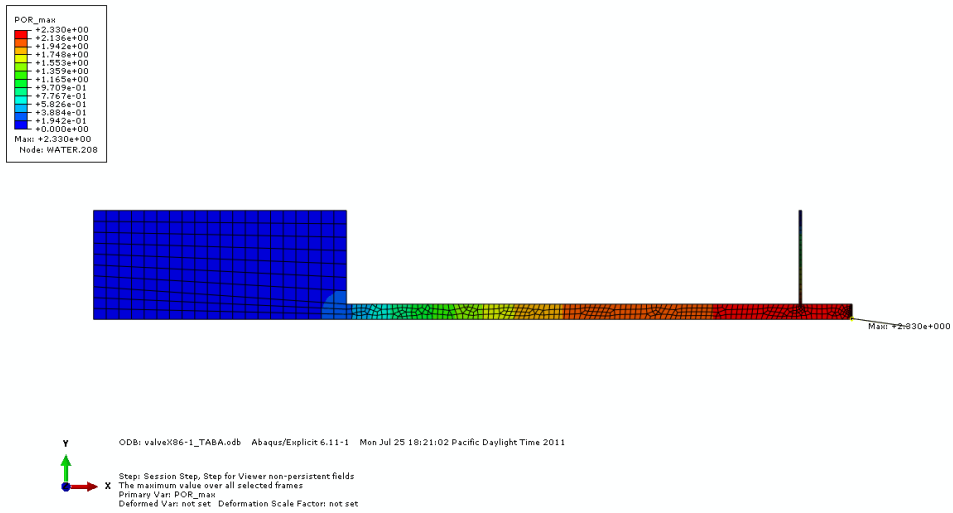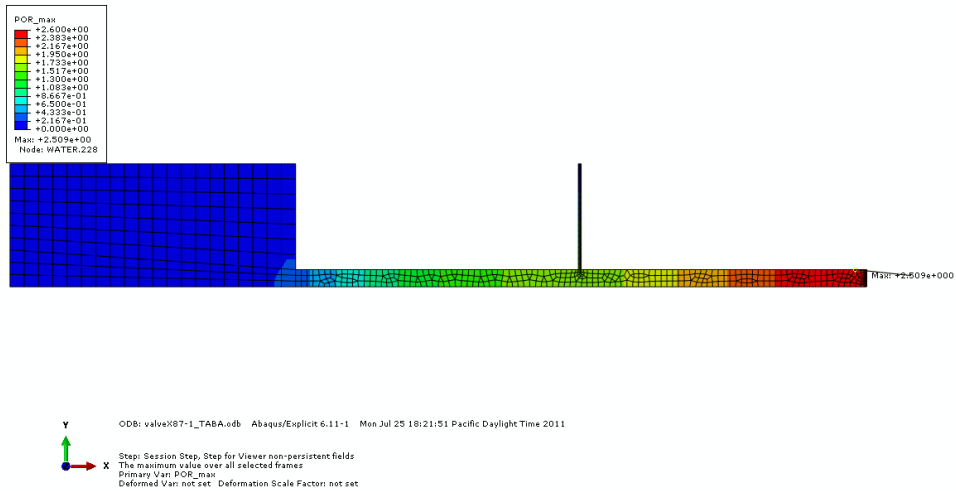**Figure 9 - Maximum hydrodynamic pressure distribution in case 3.**

POR_max
+5.400e-01
+4.950e-01
+4.500e-01
+4.050e-01
+3.600e-01
+3.150e-01
+2.700e-01
+2.250e-01
+1.800e-01
+1.350e-01
+9.000e-02
+4.500e-02
+0.000e+00
Max: +5.384e-01
Node: WATER.284

Max: +5.384e-001

ODB: valveX84-1_TABA.odb   Abaqus/Explicit 6.11-1   Mon Jul 25 18:19:55 Pacific Daylight Time 2011

Step: Session Step, Step for Viewer non-persistent fields
The maximum value over all selected frames
Primary Var: POR_max
Deformed Var: not set   Deformation Scale Factor: not set

Figure 10 - Maximum hydrodynamic pressure distribution in case 4.

POR_max
+9.493e-01
+8.702e-01
+7.911e-01
+7.120e-01
+6.329e-01
+5.538e-01
+4.747e-01
+3.955e-01
+3.164e-01
+2.373e-01
+1.582e-01
+7.911e-02
+0.000e+00
Max: +9.493e-01
Node: WATER.10

Max: +9.493e-001

ODB: valveX85-1_TABA.odb   Abaqus/Explicit 6.11-1   Mon Jul 25 18:20:56 Pacific Daylight Time 2011

Step: Session Step, Step for Viewer non-persistent fields
The maximum value over all selected frames
Primary Var: POR_max

Figure 11 - Maximum hydrodynamic pressure distribution in case 5.

POR_max
+2.330e+00
+2.136e+00
+1.942e+00
+1.748e+00
+1.553e+00
+1.359e+00
+1.165e+00
+9.709e-01
+7.767e-01
+5.826e-01
+3.884e-01
+1.942e-01
+0.000e+00
Max: +2.330e+00
Node: WATER.208

Max: +2.330e+000

Figure 12 - Maximum hydrodynamic pressure distribution in case 6.

POR_max
+2.600e+00
+2.383e+00
+2.167e+00
+1.950e+00
+1.733e+00
+1.517e+00
+1.300e+00
+1.083e+00
+8.667e-01
+6.500e-01
+4.333e-01
+2.167e-01
+0.000e+00
Max: +2.509e+00
Node: WATER.228

Max: +2.509e+000

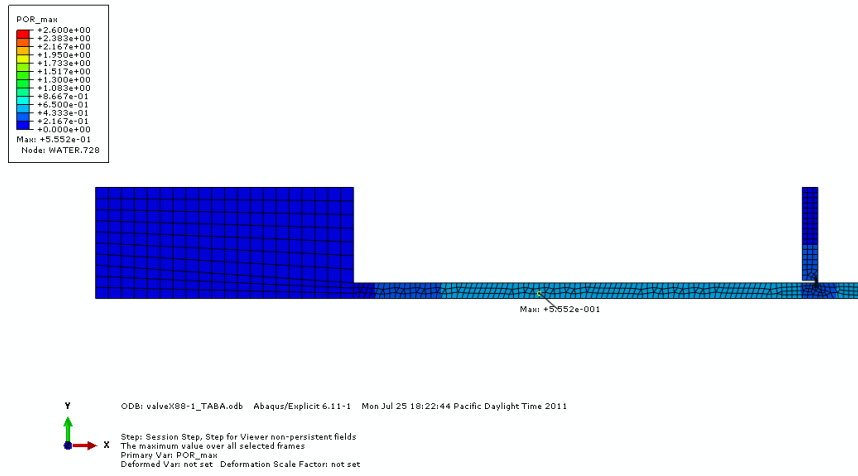**Figure 13 - Maximum hydrodynamic pressure distribution in case 7.**

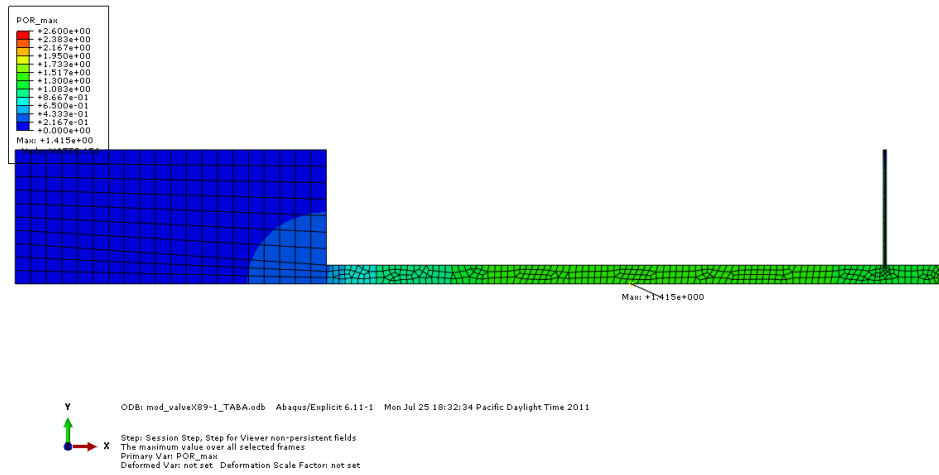**Figure 14 - Maximum hydrodynamic pressure distribution in case 8.**

Figure 15 - Maximum hydrodynamic pressure distribution in case 9.