Computational examination of fluid–structure interaction problems in dams

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Abstract

An examination of dam components subjected to explosive loading involves various levels of the fluid–structure interaction (FSI) due to the different types of structures included in the problem. Large concrete gravity dams respond very slowly compared to the blast loading period and, thus, only limited localized FSI typically occurs. Thinner reinforced concrete walls on powerhouses and relatively thin arch-type dams are typically affected by more pronounced FSI when loaded by blast. At the opposite extreme from the gravity dam, steel gates respond almost instantaneously to blast loading. Consequently, very severe FSI is observed as the loading and the gate structure greatly affect each other. Determining when to use explicit calculations for solving problems including FSI becomes essential when considering the best approach to solving this problem. By coupling an Eulerian fluid flow solver to a Lagrangian solid solver, many problems, where complicated FSI is important, can be more accurately simulated. This form of coupling involves the passing of information between the two types of solvers, typically on a timestep basis: in this case between the fluid dynamics code and the structural mechanics code. This paper provides an overview of some of the numerical results from a study to determine damage to dam components due to nearby upstream underwater detonations.

Keywords: Fluid–structure interaction; Numerical modeling; Explosive loading

1. Introduction

Continuing research on the effects of explosive detonations on dam structures has led to the use of 'coupled codes' to simulate complicated fluid–structure interaction (FSI) problems. This form of coupling involves the passing of information between two types of computational solvers: in this case between a fluid dynamics code and a structural mechanics code. Analysis of relatively low stiffness or flexible structures, such as the steel gates used in many dam systems, involves highly complex interaction between the loading imparted on the structure and its response. As a stiffer structure is considered, the effect of FSI decreases, and many times a simpler transfer of pressure time histories from a fluid dynamics code into a structural mechanics code may be accurate enough for the circumstances. A massive gravity dam may be treated as a rigid boundary when calculating the explosive environment generated by a detonation, especially when the global response of the dam is the primary concern. When a close-in detonation occurs against any structure, breaching and/or cratering types of behavior must be considered. Both of these behaviors typically have a large interaction between the structure and the blast loading, leading to the use of coupled codes to solve the problems. The stiffness of the surrounding fluid – in this case water – and the flexibility of the structure determine the necessity of using numerical coupled codes to solve the FSI problem.

2. Approach

A brute force approach was attempted by modeling each structure type (from flexible steel gates to almost rigid concrete dams) using the coupled code DYSMAS [1]. Close-in detonations were initially examined and complemented with several explosions at larger distances to determine a loading environment against the structures. These simulations were used to aid in the development of an engineering level model by numerically validating the damage curves generated by that simplified model. Once critical areas were established by

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the engineering model, according to damage inflicted on the structure due to a detonation of some charge weight at some standoff, those particular scenarios were simulated using the coupled code approach, unless the standoff was large enough so that the shock wave was basically planar when it reached the structure. Several calculations were performed moving a charge away from the structure and comparing the pressures seen by the structure with those generated by simpler engineering level models. Again different ranges were important when comparing a stiff concrete structure with a flexible steel structure.

Once several calculations were performed with large concrete structures and a large standoff, it was apparent that the coupled calculations, while providing some FSI, did not enhance the accuracy enough to warrant the use of time-expensive coupled calculations. This was especially true once the charge was moved more than two charge diameters away from the structure. When the detonation occurred either in contact or close-in (typically considered under two charge diameters) to the structure a crater was generated, and the coupling of the fluid and blast provided by the coupled codes computed a more accurate simulation of that behavior. At that point, uncoupled calculations were performed using the PC-based code REFMS [2] engineering level loads or fluid-only DYSMAS loads calculated using a rigid wall for a structure. Once the loads were generated they were applied as pressure boundary conditions to ParaDyn [3] simulations of the structural response. These uncoupled or one-way coupled calculations ran considerably faster than the fully coupled versions, as each of these codes is considerably faster when used in a stand-alone fashion. REFMS calculations took only a couple of minutes to run, followed by a four to six hour structural calculation in ParaDyn. This is much shorter compared with a coupled calculation in DYSMAS that typically took approximately five days on 76 processors to compute out to the same point in real time.

3. Discussion

Each component was numerically subjected to an underwater close-in detonation approximately halfway up the vertical face of the structure. The accompanying figures show the resulting pressure contours in the water and the structural model. A considerable amount of FSI was observed in the steel gate calculations, as shown in Fig. 1. This shows the centerline of the gate, along with pressure contours in the upstream water. A formed

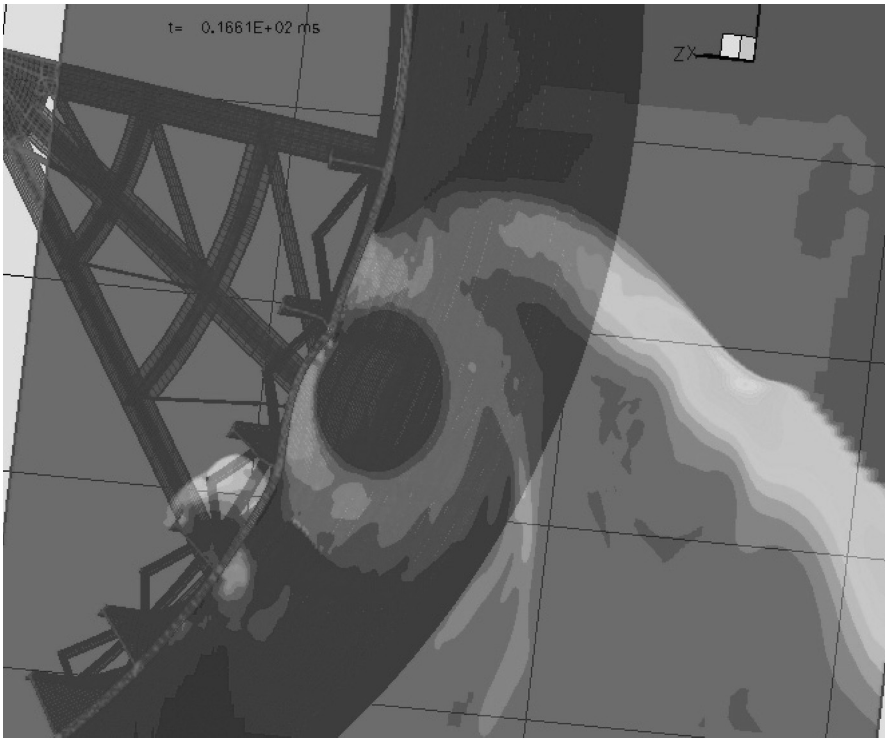

Fig. 1. Interaction of pressure contours and steel tainter gate.

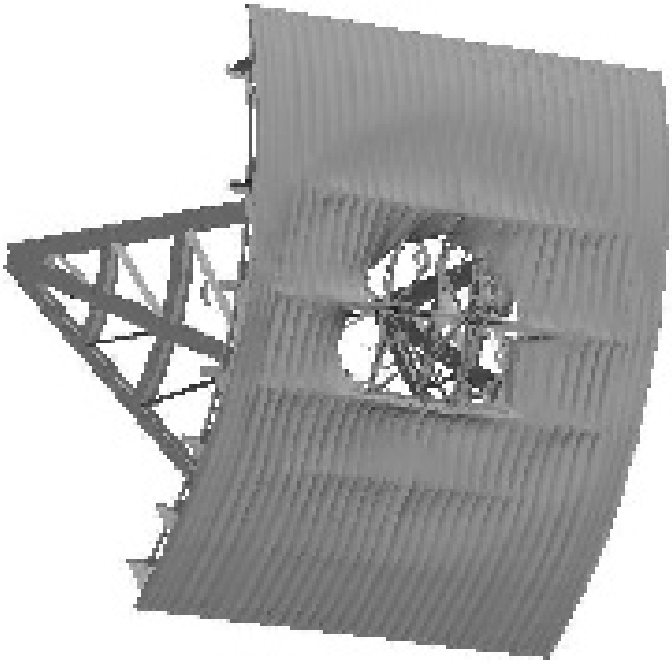

Fig. 2. Resulting damage to tainter gate from in-contact detonation.

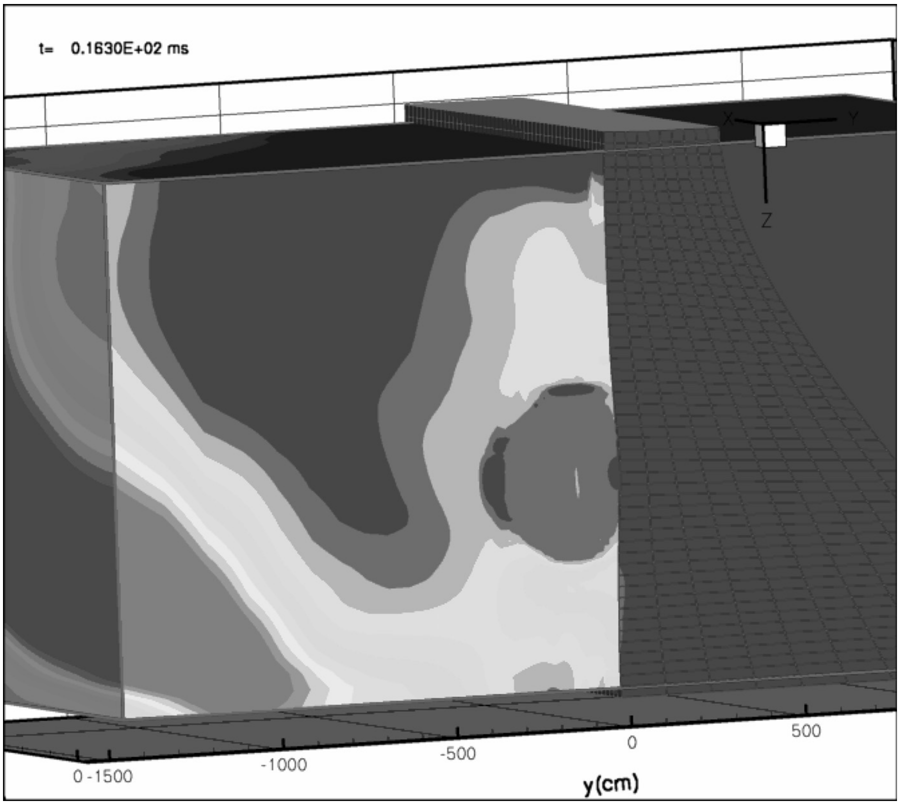

Fig. 3. FSI for large concrete structure surrounded by pressure contours.

bubble location is clearly seen directly adjacent to the gate. It is easily seen that the detonation has already caused a considerable response in the gate, which, consequently, has affected the applied loading. If the gate was rigid, the reflected pressure would be approximately twice the incident pressure, but the responding gate, while still reflecting some of the pressure, causes pressure cutoffs at a very early time near the detonation location, greatly lowering the peak pressures as well as the impulse imparted onto the gate. After approximately 30.0 ms, this leads to the structural damage to the steel gate seen in Fig. 2. This figure only contains the structural damage without picturing the pressures in the surrounding water.

Concrete dam components act much more like a rigid surface, as seen in Fig. 3. This shows a view similar to Fig. 1, but includes a concrete dam component subjected to the detonation. As before, pressure contours can be seen in the water, but now the structure is not responding as fast, and therefore not affecting the blast environment other than acting as a reflecting surface. This is purely dependent on the structural mass available, because if a thinner concrete target is considered, as pictured in Fig. 4, a breach and catastrophic deformation occurs within a short time. Figure 4 exhibits the time progress of a detonation in contact with a thin concrete panel, such as would be seen in a typical dam powerhouse. It is clearly shown where a section of the panel bubbles out – or breaches – almost immediately in the top-right view, and also a large global motion is also apparent for the panel. The bottom two views of Fig. 4 show the altered pressure distribution within the breach. This particular material model did not contain a failure mechanism and, therefore, was not allowed to act as a physical breach. The pressure was, consequently, held in and reflected by the thin panel. Had it actually been a concrete structure, the pressure would have been ejected through the breach from the backside of the target. However, the large mass contained within gravity dams makes them very resistant to early time global deformations. While this generally has been known for some time, the current simulations are allowing the detailed responses of the FSI scenarios to be predicted.

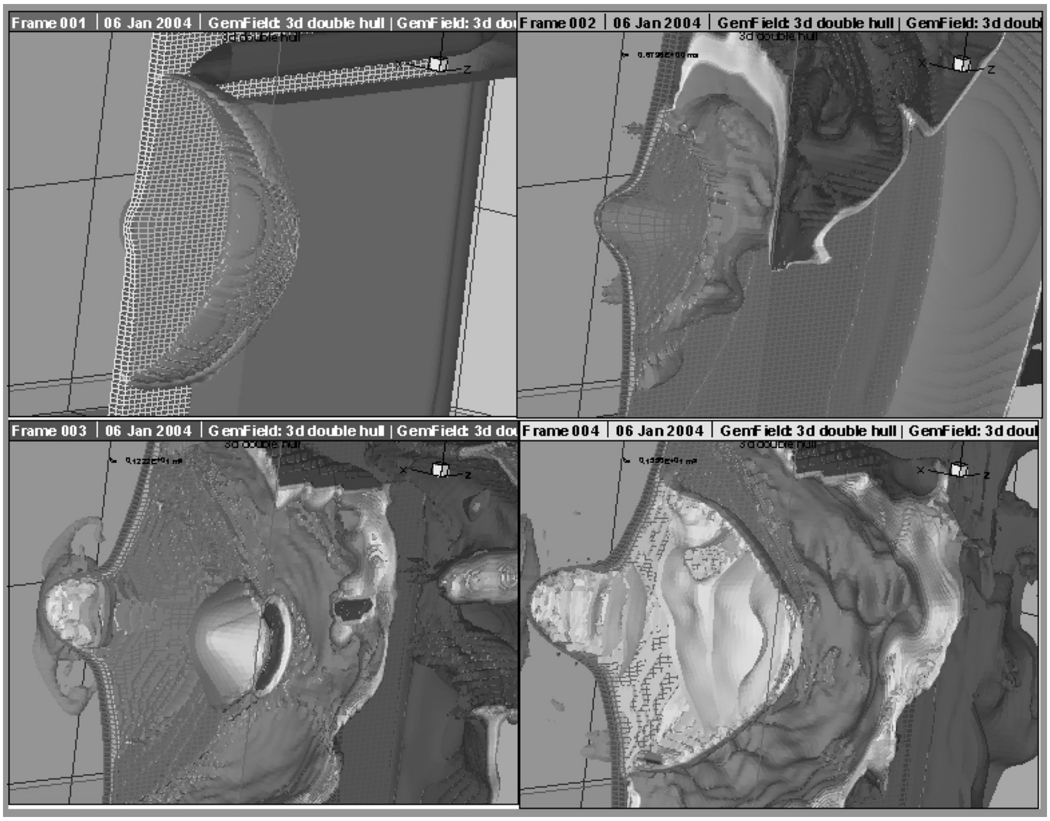

Fig. 4. Time progression of underwater contact detonation and breach through a thin concrete panel.

4. Conclusions

Ongoing simulations further capabilities to numerically examine the FSI problem concerning explosive attacks to dam components. Determining when FSI is needed to simulate the behavior of the structure as well as the importance of the bubble effects in water are of prime importance to the continuing research. The simulations presented in this paper demonstrate that thin, highly flexible structures are very susceptible to seeing a large amount of interaction between the detonation and the structure. This behavior needs to be quantified and coded in a fast-running engineering level model for use with protective design and analysis software. Recently, matured coupled hydrodynamic codes, such as DYSMAS, allow for the expanded study of problems susceptible to FSI.

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