NUMERICAL MODEL FOR THE KRAKATOA HYDROVOLCANIC EXPLOSION AND TSUNAMI

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ABSTRACT

Krakatoa exploded August 27, 1883 obliterating 5 square miles of land and leaving a crater 3.5 miles across and 200-300 meters deep. Thirty three feet high tsunami waves hit Anjer and Merak demolishing the towns and killing over 10,000 people. In Merak the wave rose to 135 feet above sea level and moved 100 ton coral blocks up on the shore.

Tsunami waves swept over 300 coastal towns and villages killing 40,000 people. The sea withdrew at Bombay, India and killed one person in Sri Lanka.

The tsunami was produced by a hydrovolcanic explosion and the associated shock wave and pyroclastic flows.

A hydrovolcanic explosion is generated by the interaction of hot magma with ground water. It is called Surtseyan after the 1963 explosive eruption off Iceland. The water flashes to steam and expands explosively. Liquid water becoming water gas at constant volume generates a pressure of 30,000 atmospheres.

The Krakatoa hydrovolcanic explosion was modeled using the full Navier-Stokes AMR Eulerian compressible hydrodynamic code called SAGE which includes the high pressure physics of explosions.

The water in the hydrovolcanic explosion was described as liquid water heated by the magma to 1100 degree Kelvin or 19 kcal/mole. The high temperature water is an explosive with the hot liquid water going to a water gas. The BKW steady state detonation state has a peak pressure of 89 kilobars, a propagation velocity of 5900 meters/second and the water is compressed to 1.33 grams/cc.

The observed Krakatoa tsunami had a period of less than 5 minutes and wavelength of less than 7 kilometers and thus rapidly decayed. The far field tsunami wave was negligible. The air shock generated by the hydrovolcanic explosion propagated around the world and coupled to the ocean resulting in the explosion being recorded on tide gauges around the world.

INTRODUCTION

The Krakatoa volcanic explosion and its consequences are described in detail by George Pararas-Carayannis in reference 1 and Simon Winchester in reference 2.

Krakatoa exploded August 27, 1883 obliterating 5 square miles of land and leaving a crater 3.5 miles across and 200-300 meters deep. Thirty three feet high tsunami waves hit Anjer and Merak, demolishing the towns and killing over 10,000 people. In Merak the wave rose to 135 feet above sea level and moved 100 ton coral blocks up on the shore. Tsunami waves swept over 300 coastal towns and villages killing 40,000 people. The sea withdrew at Bombay, India and killed one person in Sri Lanka.

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NUMERICAL MODELING

The compressible Navier-Stokes equations are described in reference 3 and 4 and examples of many numerical solutions of complicated physical problems are described. The compressible Navier-Stokes equations are solved by a high-resolution Godunov differencing scheme using an adaptive grid technique described in reference 5.

The solution technique uses Continuous Adaptive Mesh Refinement (CAMR). The decision to refine the grid is made cell-by-cell continuously throughout the calculation. The computing is concentrated on the regions of the problem which require high resolution.

Refinement occurs when gradients in physical properties (density, pressure, temperature, material constitution) exceed defined limits, down to a specified minimum cell size for each material. The mesh refinement is described in detail in reference 3.

Much larger computational volumes, times and differences in scale can be simulated than possible using previous Eulerian techniques such as those described in reference 4.

The original code was called SAGE. A later version with radiation is called RAGE. A recent version with the techniques for modeling reactive flow described in reference 3 is called NOBEL. It was used for the modeling of hydrovolcanic explosions described in this paper.

Some of the remarkable advances in fluid physics using the SAGE code have been the modeling of Richtmyer-Meshkov and shock induced instabilities described in references

6 and 7. It was used for modeling the Lituya Bay impact landslide generated tsunami and water cavity generation described in references 8 and 9. NOBEL/SAGE/RAGE were used to model the generation of water cavities by projectiles and explosions and the resulting water waves in reference 10. The codes were used to model asteroid impacts with the ocean and the resulting tsunami waves in references 11 and 12.

The codes can describe one-dimensional slab or spherical geometry, two-dimensional slab or cylindrical geometry, and three-dimensional Cartesian geometry.

Because modern supercomputing is currently done on clusters of machines containing many identical processors, the parallel implementation of the code is very important. For portability and scalability, the codes use the Message Passing Interface (MPI). Load leveling is accomplished through the use of an adaptive cell pointer list, in which newly created daughter cells are placed immediately after the mother cells. Cells are redistributed among processors at every time step, while keeping mothers and daughters together. If there are a total of M cells and N processors, this technique gives nearly (M / N) cells per processor. As neighbor cell variables are needed, the MPI gather/scatter routines copy those neighbor variables into local scratch memory.

The calculations described in this paper were performed on IBM NetVista and ThinkPad computers and did not require massive parallel computers.

The codes incorporate multiple material equations of state (analytical or SESAME tabular). Every cell can in principle contain a mixture of all the materials in a problem assuming that they are in pressure and temperature equilibrium.

As described in reference 4, pressure and temperature equilibrium is appropriate only for materials mixed molecularly. The assumption of temperature equilibrium is inappropriate for mixed cells with interfaces between different materials. The errors increase with increasing density differences. While the mixture equations of state described in reference 4 would be more realistic, the problem is minimized by using fine numerical resolution at interfaces. The amount of mass in mixed cells is kept small resulting in small errors being introduced by the temperature equilibrium assumption.

Very important for hydrovolcanic explosions, water cavity collapse and the resulting water wave history is the capability to initialize gravity properly, which is included in the code. This results in the initial density and initial pressure changing going from the atmosphere at 2 kilometers altitude down to the ocean surface. Likewise the water density and pressure changes correctly with ocean depth.

HYDROVOLCANIC MODEL

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THE KRAKATOA MODEL

The island of Krakatoa today and before 1883 are shown in Figure 1.

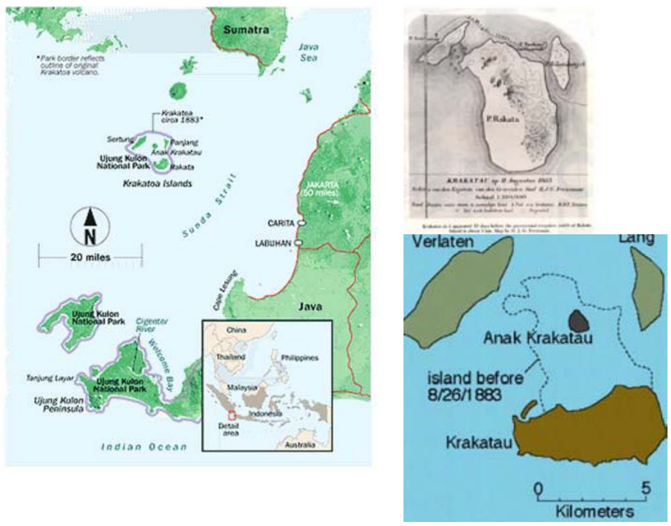

Figure 1. Maps of Krakatoa today and before 1883.

It was modeled in two-dimensions as a spherical island 200 meters high above the ocean level and 3 kilometers in radius tapering down to ocean level by 4 kilometers as shown in Figure 2. The ocean was 100 meters deep and extended in the rock under the island. The lava was initially assumed to interact with the water in the center of the island in a 500 meter radius hot spot region. The propagating hydrovolcanic explosion propagated outward at about 5900 meters per second and at a constant volume pressue of about 30,000 atmospheres as shown in Figure 3.

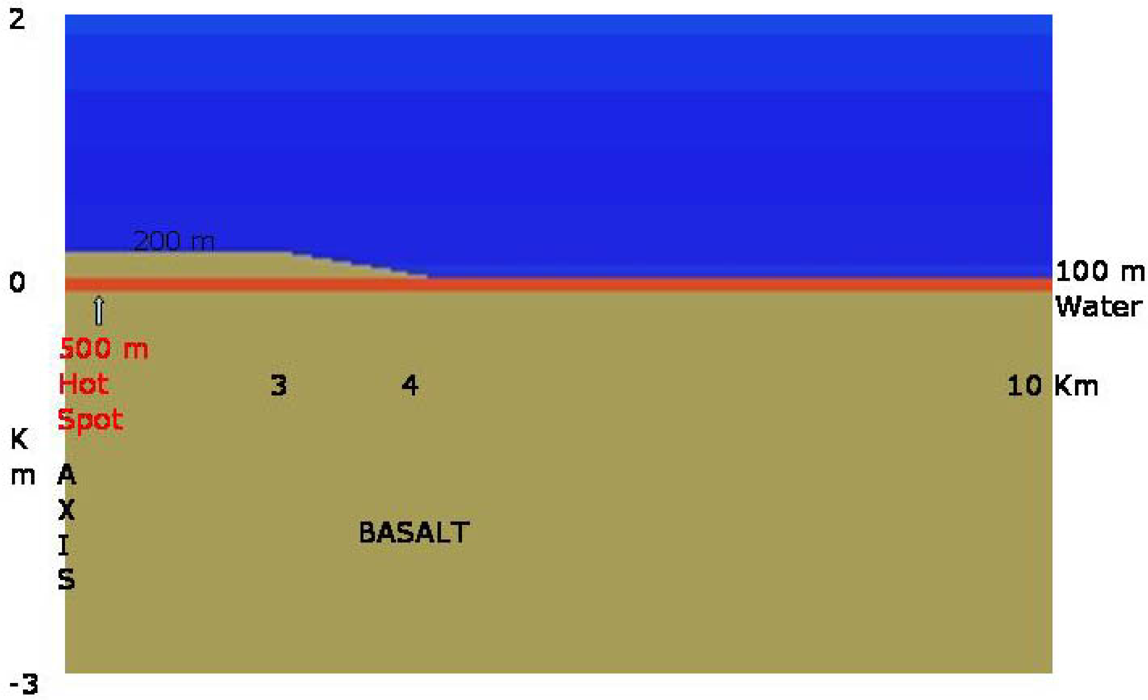

Figure 2. The spherical model for the Krakatoa hydrovolcanic explosion.

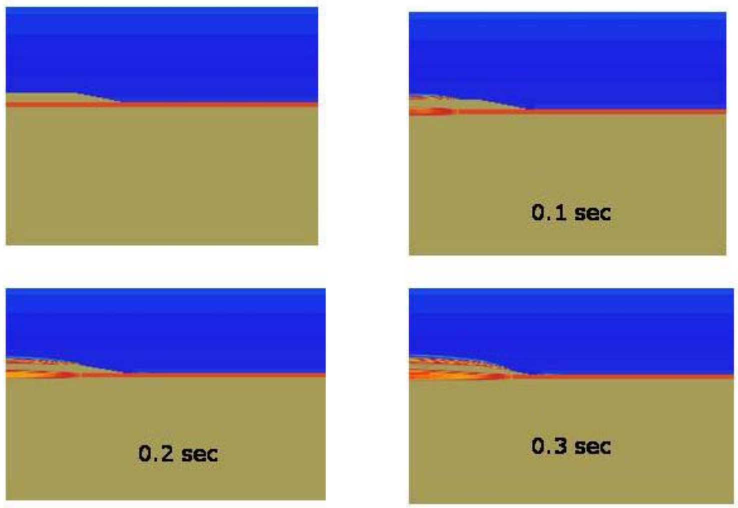

Figure 3. The propagating hydrovolcanic explosion.

The expansion of the hydrovolcanic explosion is shown in Figures 4 and 5 at various times up to 10 seconds as density picture plots.

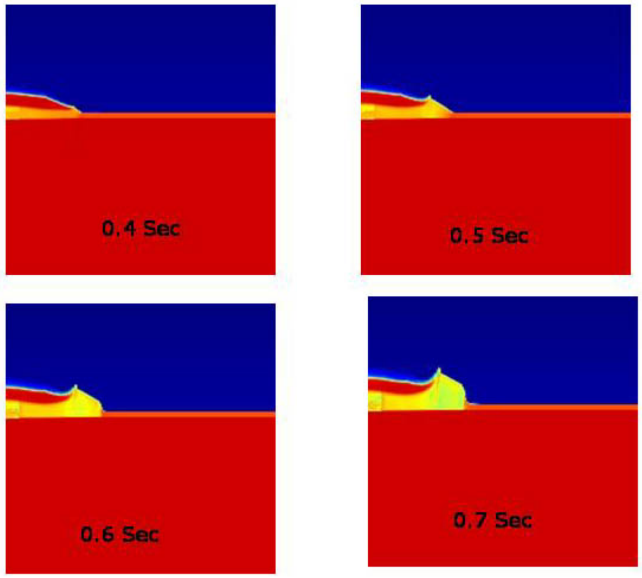

Figure 4. The density profile at various times for the hydrovolcanic explosion of Krakatoa.

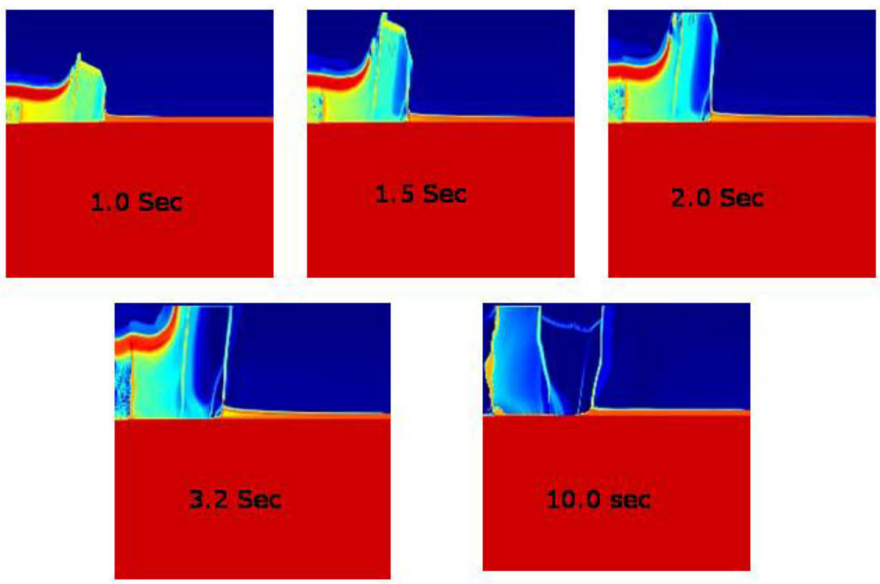

Figure 5. The density profile at later times for the hydrovolcanic explosion of Krakatoa.

The velocity contour picture plots in the X-direction are shown in Figure 6. The propagation of the shock wave in the basalt below the island, the basalt above sea level, the water and in the air is shown.

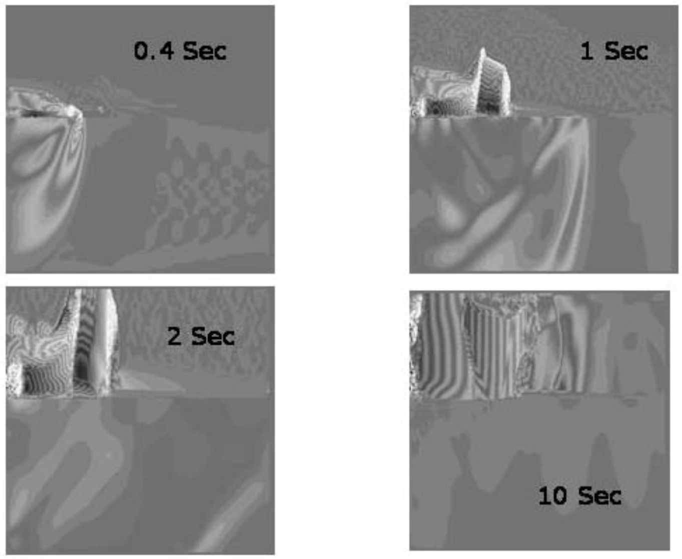

Figure 6. The velocity profiles in the horizontal or X-Direction at various times.

The water wave profiles at 4, 5, and 8 kilometers are shown in Figure 7. The wave outside the hydrovolcanic explosion at 4 km is 130 meters high and decays to 48 meters by 5 kilometers and to 7.5 meters at 8 kilometers.

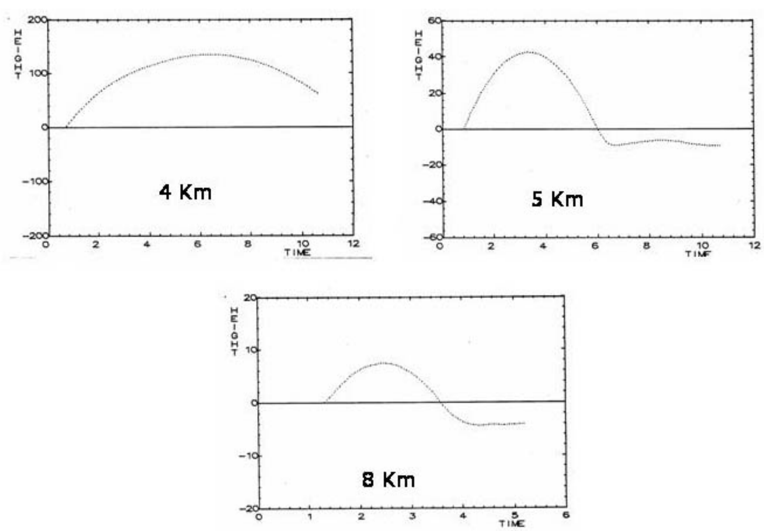

Figure 7. The water wave profiles as a function of time at 4, 5 and 8 km.

The states of the water at 1.5 kilometers in the middle of the hydrovolcanic explosion of the water reached pressures greater than 25,000 bars and expanded to altitudes greater than 2 kilometers and drove the Krakatoa island basalt to altitudes greater than 2 kilometers. Perhaps the hydrovolcanic explosion looked something like 1946 Bikini nuclear explosion shown in Figure 8 without the warships. The Baker shot was a 21 kiloton device fired at 27 meter depth in the ocean. The Krakatoa event released 150-200 megatons.

Figure 8. The 1946 Bikini Atomic Explosion.

CONCLUSIONS

A fully-compressible reactive hydrodynamic model for the process of hydrovolcanic explosion of liquid water to steam at constant volume and pressures of 30,000 atmospheres has been applied to the explosion of Krakatoa in 1883. The idealized spherical geometry exhibits the general characteristics observed including the destruction of the island and the projection of the island into high velocity projectiles that travel into the high upper atmosphere above 2 kilometers. A high wall of water is formed that is initially higher than 100 meters driven by the shocked water, basalt and air. The initial wave period of about 30 seconds and the rapid decay of the water wave suggests that the hydrovolcanic explosion in the calculation was less than in the Krakatoa explosion. The idealized 2-D geometry needs to be replaced with a realistic 3-D one. The hydrovolcanic process needs to involve a more accurate description of the water filled porous basalt layer where the hydrovolcanic explosion occurs.

The contributions of Dr. George Pararas-Carayannis are gratefully acknowledged.

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