LA-UR -85-2412

AUG 0 7 1985

CONF-8508112--1

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LA-UR--85-2412

DE85 015724

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SUBMITTED TO Proceedings of the 1985 International Tsunami Symposium
Victoria, Canada
August 6-9, 1985

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THREE-DIMENSIONAL MODELING OF TSUNAMI WAVES

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ABSTRACT

Two- and three-dimensional, time-dependent, nonlinear, incompressible, viscous flow calculations of realistic models of tsunami wave formation and run up have been performed using the Los Alamos-developed SOLA-3D code.

The results of the SOLA calculations are compared with shallow-water, long-wave calculations for the same problems using the SWAN code.

Tsunami wave formation by a continental slope subsidence has been examined using the two numerical models. The SOLA waves were slower than the SWAN waves and the interaction with the shoreline was more complicated for the SOLA waves.

In the SOLA calculation, the first wave was generated by the cavity being filled along the shoreline close to the source of motion. The second wave was generated by the cavity being filled from the deep water end. The two waves interacted along the shoreline resulting in the second wave being the largest wave with a velocity greater than the first wave. The second wave overtook the first wave at later times and greater distances from the source. In the SWAN calculation, the second wave was smaller than the first wave.

I. INTRODUCTION

Tsunami waves are usually numerically modeled using the shallow-water, long-wave equations. A few calculations of Tsunami waves have been performed using the two- and three-dimensional, time-dependent, nonlinear, incompressible, viscous flow equations.

Tsunami wave formation by a continental slope subsidence has been examined using the two models. The collapse of an explosively generated cavity has also been examined.

II. SHALLOW-WATER, LONG-WAVE MODEL

The long-wave theory applies when the depth relative to the wavelength is small, and when the vertical component of the motion does not influence the pressure distribution, which is assumed to be hydrostatic. It is appropriate for Tsunami wave formation, propagation, and early shoaling behavior as described in Ref. 1. The SWAN code solves the long-wave equations using an improved numerical difference technique described in Refs. 2 and 3.

The long-wave equations solved by the SWAN code are:

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} + g\frac{\partial H}{\partial X} = FV + F^{(x)} - g\frac{U(U^2+V^2)^{1/2}}{C^2(D+H)}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} + g\frac{\partial H}{\partial Y} = FU + F^{(y)} - g\frac{U(U^2+V^2)^{1/2}}{C^2(D+H)}$$

$$\frac{\partial H}{\partial t} + \frac{\partial(D+H-R)U}{\partial X} + \frac{\partial(D+H-R)V}{\partial Y} - \frac{\partial R}{\partial t} = 0$$

where U = velocity in X direction
V = velocity in Y direction
g = gravitational acceleration
t = time
H = wave height above mean water level
R = bottom motion
F = Coriolis force parameter

C = coefficient of DeChezy for bottom stress

$F^{(x)}$, $F^{(y)}$ = forcing functions of wind stress and barometric pressure in X and Y direction

D = depth .

III. INCOMPRESSIBLE NAVIER-STOKES MODEL

Three-dimensional, time-dependent, nonlinear, incompressible viscous flow was calculated using the SOLA-3D code.

The SOLA-3D code is a three-dimensional version of the two-dimensional SOLA code described in Ref. 4. The program has evolved from the marker-and-cell (MAC) finite difference technique which uses pressure and velocity as primary dependent variables. A variable mesh capability has been included to improve the numerical resolution. The surface height of the center of each cell is computed each cycle according to the kinematic equation

$$\frac{\partial H}{\partial t} + U\frac{\partial H}{\partial x} + V\frac{\partial H}{\partial y} = W \quad ,$$

similar to that described in Ref. 4 for the SOLA-SURF version of the SOLA code. The Navier-Stokes equations for incompressible viscous fluid flow are

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0$$

$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y} + W\frac{\partial U}{\partial z} = -\frac{\partial P}{\partial x} + g_x + \nu\left(\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2} + \frac{\partial^2 U}{\partial z^2}\right)$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + W\frac{\partial V}{\partial z} = -\frac{\partial P}{\partial y} + g_y + \nu\left(\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2} + \frac{\partial^2 V}{\partial z^2}\right)$$

$$\frac{\partial W}{\partial t} + U\frac{\partial W}{\partial x} + V\frac{\partial W}{\partial y} + W\frac{\partial W}{\partial z} = -\frac{\partial P}{\partial z} + g_z + \nu\left(\frac{\partial^2 W}{\partial x^2} + \frac{\partial^2 W}{\partial y^2} + \frac{\partial^2 W}{\partial z^2}\right)$$

where U,V,W are velocity components in the x,y,z directions,

t is time,

P is pressure,

g_x, g_y, g_z are x,y,z components of gravity, and
ν is the kinematic viscosity coefficient .

The equations are solved using the finite difference technique described in Ref. 4.

IV. MODELING OF TSUNAMI WAVE FORMATION

The Hawaii tsunami of November 29, 1975, was generated by an earthquake near the Hawaii Volcanoes National Park with a magnitude of 7.2 on the Richter scale. Near the source, the first wave was smaller than the second Coincident with the earthquake was considerable subsidence (up to 3 meters) of the shoreline.

In Ref. 5 we investigated an undersea landslide source for the Hawaii tsunami. The observed tsunami wave profile of the 1975 Hawaii tsunami near the source of the second wave larger than the first was not reproduced by a landslide source in an incompressible three-dimensional Navier-Stokes calculation in contrast with results obtained using the shallow-water model.

In Ref. 6 we investigated the waves formed by the sea floor dropping 3 meters. The observed tsunami wave profile near the source could not be reproduced using the shallow-water model without introducing a source displacement change with time. The observed tsunami wave profile was reproduced by the incompressible Navier-Stokes calculation.

The Navier-Stokes waves were slower than the shallow-water waves and the interaction with the shoreline was more complicated for the Navier-Stokes waves.

In the Navier-Stokes calculation the first wave was generated by the cavity being filled along the shoreline close to the source of motion. The second wave was generated by the cavity being filled from the deep water end.

The two waves interacted along the shoreline resulting in the second wave being the largest wave with a velocity greater than the first wave. The second wave overtook the first wave at later times and greater distances from the source. In the shallow water calculation the second wave was smaller than the first wave.

CONCLUSION

The difference between the shallow-water and full Navier-Stokes calculations are that the water waves formed in the full Navier-Stokes calculations are deep-water waves, which move slower than the shallow-water waves formed in the shallow-water calculations. The nature of the surface collapse is also different with the collapse occurring throughout the source region in the Navier-Stokes calculations and mostly at the sides in the shallow-water calculations.

Similar results were reported in Ref. 2 for waves formed by explosions near the water surface. A 0.5-meter radius hole collapsed from the sides in less than 0.1 second in the shallow-water calculation while the Navier-Stokes cavity calculation collapsed from the bottom in about 0.5 second. The experimentally observed bubble collapsed approximately symmetrically from the bottom in about 0.3 second.

The experimentally observed waves from the cavities formed by explosions near the water surface are better reproduced by models solving the incompressible Navier-Stokes equations than by models solving the shallow-water, long-wave equations. The experimentally observed waves are deep-water waves and not the shallow-water waves required for Tsunamis.

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