Title
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DISCLAIMER

SLOSHING OF WATER IN ANNULAR CIRCULAR TANKS UNDER EARTHQUAKE GROUND MOTIONS*

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Introduction

Sloshing response of water in annular circular tanks under arbitrary horizontal ground motions is predicted and the results are verified by tests. A linearized theory has been developed to derive the velocity potential for irrotational flow from which the water surface displacements, pressures, and velocities can be determined anywhere in the fluid. Comparisons with test results have shown that the linear solution has a sufficient range for practical problems such as encountered in annular tanks with outer and inner diameters of 120 ft. and 80 ft., respectively, and a depth of water of 20 feet. These structures are essentially rigid for this analysis.

Mathematical Model

Assumptions:

(1) Tank walls are rigid.
(2) Fluid displacements are small.
(3) Fluid is incompressible and non-viscous.
(4) Flow is irrotational.

Since the flow is irrotational, the velocity potential ϕ must satisfy the Laplace equation. Laplace's equation for ϕ was solved with appropriate boundary conditions, noting that the boundary conditions are time-dependent. A computer program was written to obtain numerical solutions for arbitrary ground motions applied to the tank.

Once the velocity potential is known, the displacement of the fluid, the pressure, and the velocity at any point in the fluid can be derived from the velocity potential. The computer program determines the sloshing frequencies, mode shapes, and water surface profile. Distribution of the pressure variation with depth along the inner and outer boundaries is also determined.

Comparison with Test Results

Tests to determine sloshing frequencies and water surface displacements were made on a small scale model (outer radius = 9 in., inner radius = 6 in., height of water = 3 in.). These tests were carried out under harmonic motions. The agreement between analytical and test results was within 10 percent for water surface displacement as high as 12 percent of the water depth, indicating a good range of the linear solution.

Test data for a 12-foot-diameter simple circular tank under actual earthquake ground accelerations were made available to us by Douglas Clough from his doctoral research project. Figure 1 shows the comparison between our theory and these test data for the El Centro (1940) earthquake. The analysis was carried out by letting the inner radius approach zero. The depth of water in the tank was 5 feet, and the maximum vertical displacement of the water surface was about 12.7 inches. It should be noted that for surface water displacements as high as 21 percent of the water depth, the agreement between the test and analytical results was remarkably good and the differences were within 10 percent. It should also be noted that the analytical model is good not only for the annular tanks, but also for the simple circular tanks.

The accuracy of dynamic pressure was checked against a known analytical solution for a simple circular tank and was found to agree within one percent.

Conclusions

The computer program based upon the irrotational flow theory can accurately predict the sloshing response of water in annular circular tanks (and also simple circular tanks) under arbitrary horizontal ground motions. The range of the linearized theory gives satisfactory results for water surface displacements of up to 20 percent of water depth.

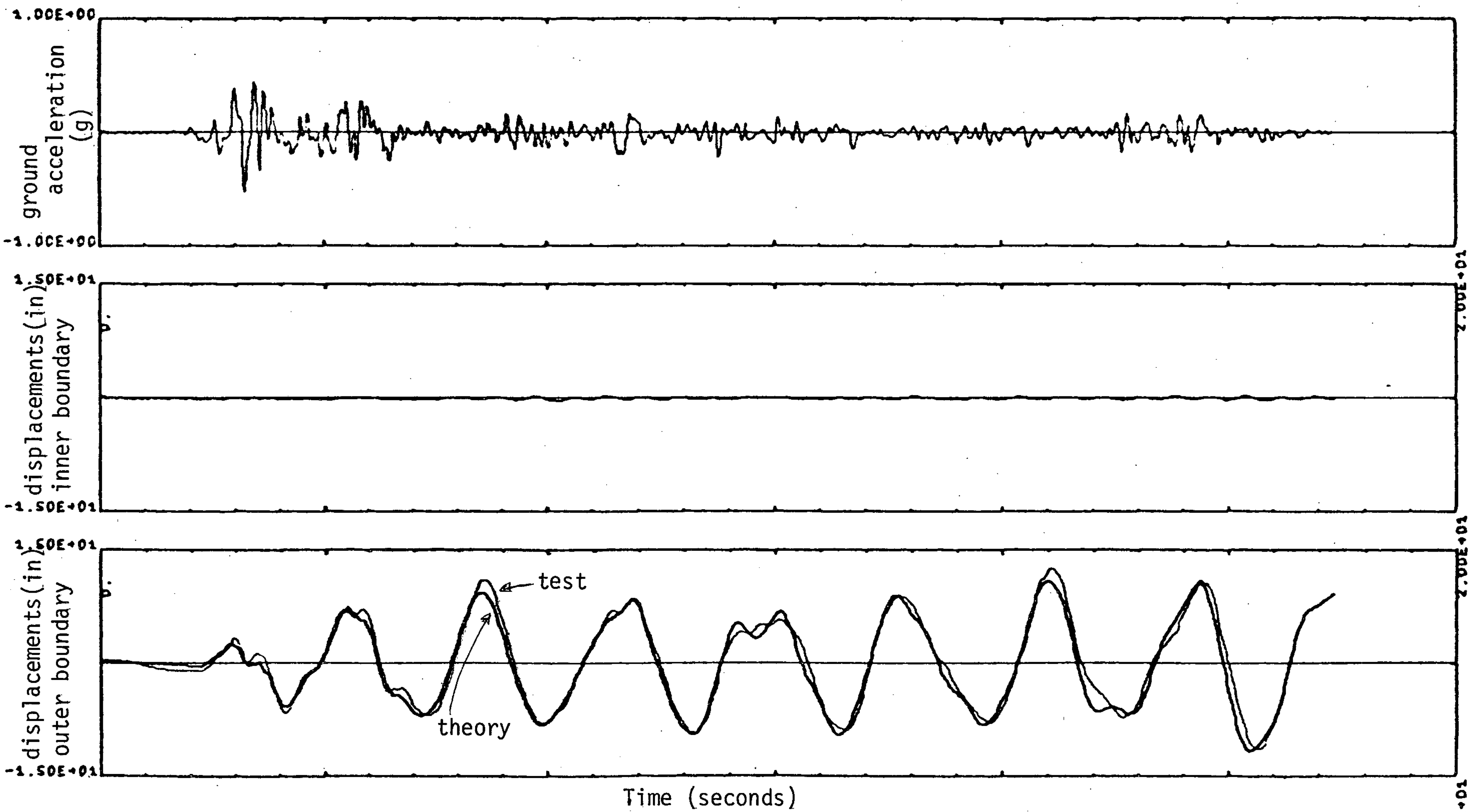

Fig. 1 SLOSHING RESPONSE OF WATER IN ANNULAR TANK (INNER RADIUS =0.1 IN, OUTER RAD=72.0IN, DEPTH OF WATER=60.0IN) UNDER ELCENTRO EARTHQUAKE (1940) TIME SCALE=1.73, MAX.ACCEL.=0.5G

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