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HYDRODYNAMIC RESPONSE OF VISCOUS FLUIDS UNDER SEISMIC EXCITATION*

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1 INTRODUCTION

Hydrodynamic response of liquid-tank systems, such as reactor vessels, spent-fuel pools and liquid storage tanks have been studied extensively in the last decade (Chang et al. 1988; Ma et al. 1991). However, most of the studies are conducted with the assumption of an inviscid fluid. In recent years, the hydrodynamic response of viscous fluids has received increasing attention in high level waste storage tanks containing viscous waste material.

This paper presents a numerical study on the hydrodynamic response of viscous fluids in a large 2-D fluid-tank system under seismic excitation. Hydrodynamic responses (i.e. sloshing wave height, fluid pressures, shear stress, etc.) are calculated for a fluid with various viscosities. Four fluid viscosities are considered. They are 1 cp, 120 cp, 1000 cp and 12,000 cp (1 cp = 1.45×10^{-7} lb-sec/in^2). Note that the liquid sodium of the Liquid-Metal Reactor (LMR) reactor has a viscosity of 1.38×10^{-5} lb-sec/in^2 (about 95 cp) at an operational temperature of 900°F.

Section 2 describes the pertinent features of the mathematical model. In Section 3, the fundamental sloshing phenomena of viscous fluid are examined. Sloshing wave height and shear stress for fluid with different viscosities are compared. The conclusions are given in Section 4.

2 DESCRIPTION OF THE FLUID-TANK SYSTEM

In the following numerical example the seismic-induced hydrodynamic response of viscous fluids in a two-dimensional fluid-tank model shown in Fig. 1 is presented. The physical dimensions of the fluid-tank system are 48 ft. for tank width and 72 ft. for tank height. The fluid depth is 60 ft.

The FLUSTR-ANL (Fluid-Structure interaction code - augmented at Argonne National Laboratory) finite element computer code is used in the calculation. The code has been used extensively in the seismic fluid-structure interaction analysis of liquid metal reactors (Chang et al. 1988; Ma et al. 1991). The code can perform nonlinear sloshing analysis of viscous, compressible fluids based on mixed Lagrangian-Eulerian formulation. In the present study, only

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the linear sloshing response is considered. The free surface wave effects are treated by a perturbation term of fluid body forces which is mainly a function of gravitational forces and free surface displacements. The detailed mathematical formulation and solution algorithm of the code can be found in the reference paper (Chang et al. 1988).

The model shown in Fig. 1 consists of 48 regular fluid elements and 16 thin fluid elements. The tank wall is assumed to be rigid. The fluid mass density is 10^3 kg/m^3 (9.34 x 10^{-5} lb-sec^2/in^4), and the bulk modulus of the fluid is 10^9 Pa (1.45 x 10^5 psi). A thin layer of fluid element is placed at the fluid-tank interface to simulate the contact/sliding effects. The thin fluid element is identical to the regular fluid element, except that it has a small dimension in the direction normal to the fluid-tank interface. The dashed line in Fig. 1 shows the deformed thin fluid element.

For comparison purposes, four dynamic fluid viscosities are considered in the study: 1 cp, 120 cp, 1000 cp and 12,000 cp. Note that the dynamic viscosity of water at room temperature is about 1 cp; liquid waste material has a viscosity of about 120 cp; the castor oil has a dynamic viscosity of about 1000 cp at room temperature; and liquid sodium has a viscosity of 1.38 x 10^{-5} lb-sec/in^2 (about 95 cp) at an operational temperature of 900°F. The dynamic viscosities of various other fluids can be found in the reference book (Pao 1967).

The input base excitation is a 10 second duration U.S. Nuclear Regulatory Commission, Regulatory Guide (R.G.) 1.60 spectrum-compatible synthetic acceleration time history depicted in Fig. 2. The maximum acceleration of the input motion is scaled down to 0.5 g. The step-by-step time history analysis is carried out with Newmark parameters of $\delta = 0.25$ and $\gamma = 0.5$. The fluid dynamic response and the effects of fluid viscosity are examined.

3 HYDRODYNAMIC RESPONSE OF VISCOUS FLUIDS

Since the sloshing motion is characterized by low frequency motion, the analysis is carried out to 100 seconds. Note that the input motion is terminated at the end of 10 seconds. Figure 3 shows the calculated 100-second sloshing wave height history of node 97 at free surface (see Fig. 1) for the four cases of fluid viscosity. The maximum wave height is tabulated in Table 1. It is noted that there is hardly any change in wave height when the viscosity is increased from 1 cp to 120 cp. The maximum wave height is about 39 in. Even in the case of 1200 cp, the reduction of wave height is still insignificant. The effect is more pronounced as viscosity increases to 12,000 cp as shown in Fig. 3(D). In this case, the maximum wave height is reduced from 39.0 in. to 29.0 in. Therefore, for large fluid-tank systems, the fluid viscosity can be ignored on wave weight estimation if viscosity is less than 1000 cp. The damping effect due to viscosity can be clearly observed in Fig. 3(D). Note that the fluid viscosity has significant effects on wave height for small tanks as described in a companion paper (Tang 1993).

The sloshing wave height at node 97 and the shear stress at the fluid-tank interface (thin fluid element 8 at tank top) for 12,000 cp case are shown in Figs. 4(A) and 4(B), respectively. Note that only the first 50-seconds of the sloshing wave height history is shown in Fig. 4. It can be clearly observed that the shear stress is closely related to the sloshing motion. After the input motion is ceased at the end of 10 seconds, the shear stress has a frequency identical to the sloshing frequency (i.e. 0.22 Hz). However, it has a 90° phase-shift with the sloshing wave. The maximum shear stress (or maximum velocity gradient) occurs when the wave height is zero. Further examinations indicated that, similar to the sloshing convective pressure, the shear stress has the maximum value at the tank top and decreases with the fluid depth. Table 2 shows the distribution of the shear stress and fluid pressure at the fluid-tank interface along the height of the tank. The maximum shear stress is 0.056 psi and occurs at the tank top. Table 3 shows the comparison of the fluid pressure at the tank top, tank midheight and tank bottom for fluid viscosities of 120 cp and 12,000 cp. As can be seen, the increase of fluid viscosity slightly reduces the fluid pressure, and the effects are more pronounced at the upper part of the tank.

4 CONCLUSIONS

The hydrodynamic phenomena of viscous fluids under seismic excitation are examined. The study is limited to a rigid tank assumption and linear sloshing response. Four fluid viscosities, 1 cp, 120 cp, 1000 cp and 12,000 cp are used. They represent a wide range of fluid viscosity. The following conclusions can be drawn from this study:

1. The effects of viscosity on sloshing wave height under seismic excitation can be generally ignored for large fluid-tank systems if fluid viscosity is less than 1000 cp.
2. The shear stress, caused by viscosity, at the fluid-tank interface is closely related to sloshing motion due to the large velocity gradient in the free surface. Similar to the sloshing convective pressure, the shear stress has the maximum value at tank top and decreases with the fluid depth. The fluid pressure is reduced when the viscosity is increased. For the case of fluid with viscosity of 12,000 cp, the total fluid dynamic pressure at tank top is reduced by 3% compared to that of the fluid with viscosity of 1 cp.
3. The present study is limited to a rigid tank assumption and linear sloshing response. Since shear stress is closely related to sloshing motion, it is characterized by low frequency motion. Future studies will consider the interaction between the tank flexibility and fluid viscosity.

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Table 1. Free surface wave height versus viscosity

Viscosity (cp)	1 cp	120 cp	1200 cp	12,000 cp
Maximum Wave Height (inch)	39.0"	38.6"	34.7"	29.0"

Table 2. Shear stress and fluid pressure of the case of 12,000 cp

Thin Fluid Element	Shear Stress (psi)	Pressure (psi)
8 (tank top)	0.0560	2.16
7	0.0340	3.15
6	0.0190	3.80
5	0.0116	4.37
4	0.0068	4.70
3	0.0039	4.90
2	0.0020	5.00
1 (tank bottom)	0.0006	5.05

Table 3. Fluid pressure of the cases of 120 cp and 12,000 cp

		Viscosity = 120 cp	Viscosity = 12,000 cp	Difference
Total Pressure (psi)	Tank top, thin fluid element 8	2.225	2.165	-3.8%
	Tank mid-height, thin fluid element 4	4.712	4.700	-0.25%
	Tank bottom, thin fluid element 1	5.05	5.05	0%

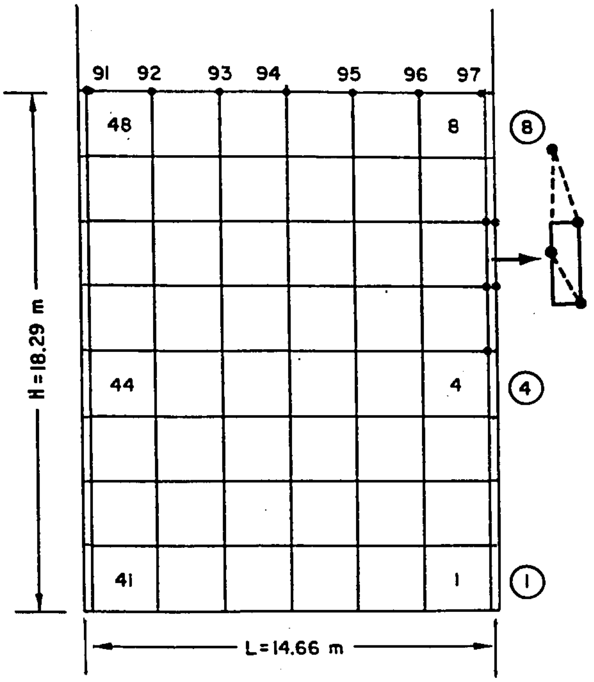

Fig. 1 2-D Fluid-Tank System

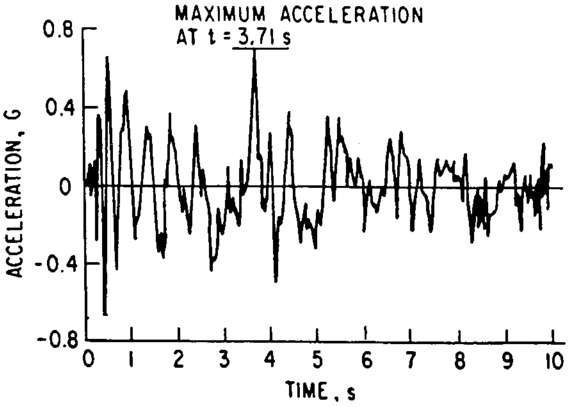

Fig. 2 Input Motion

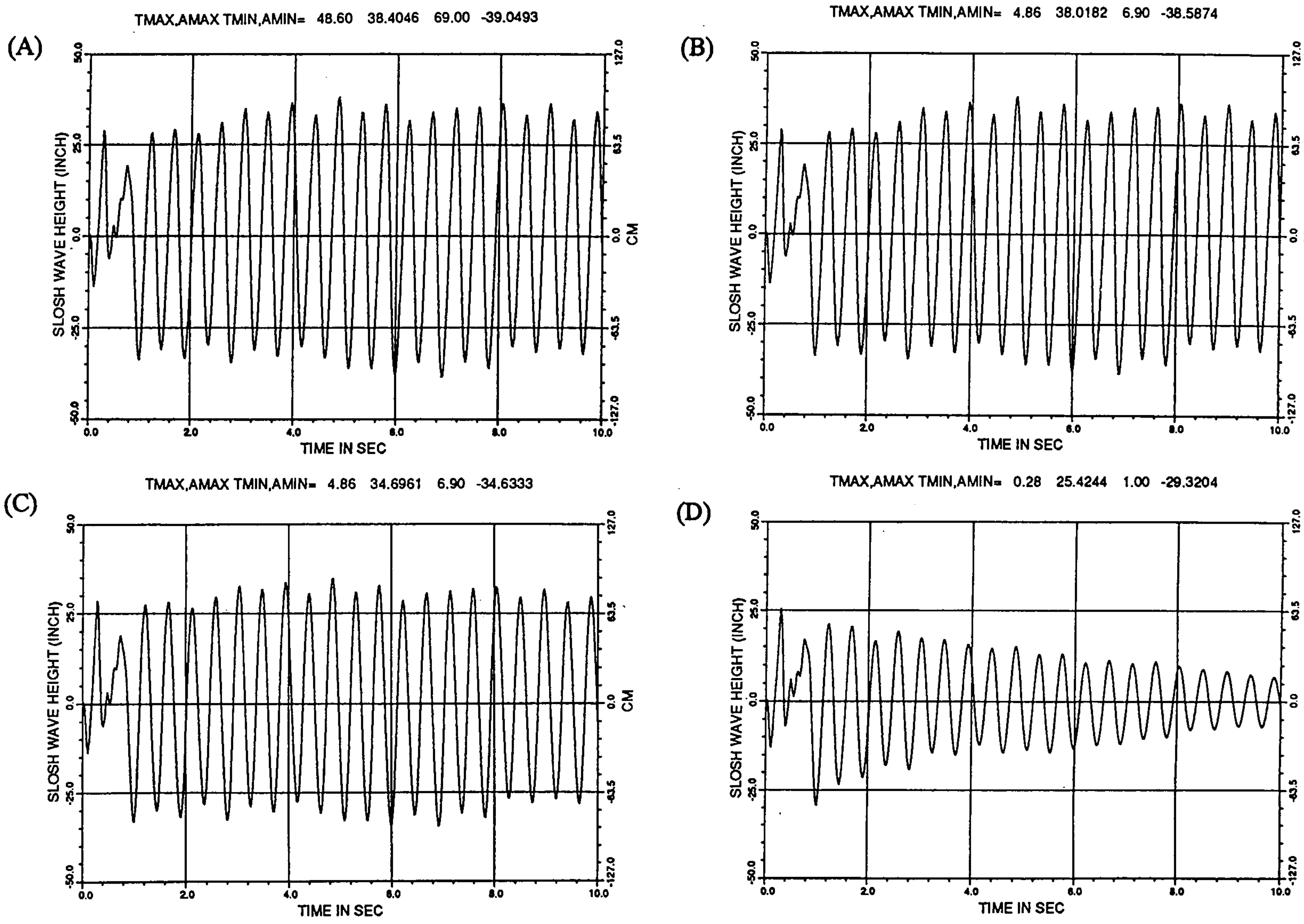

Fig. 3 Wave Height History at Node 91, (A) 1 cp, (B) 120 cp, (C) 1,000 cp and (D) 12,000 cp

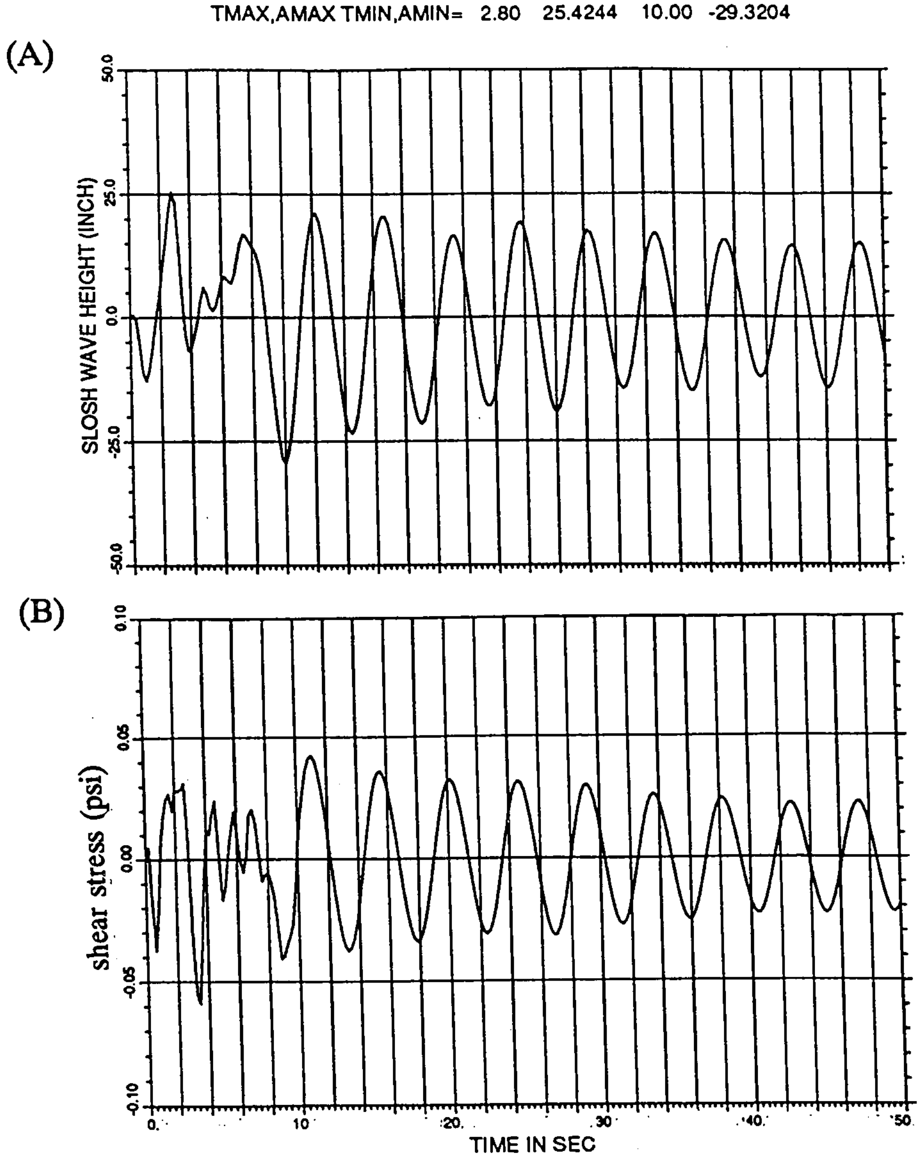

Fig. 4 (A) Wave Height History at Node 97 and (B) Shear Stress History at Thin Fluid Element 8 for 12,000 cp Case