



Nonlinear seismic response of a partially-filled rectangular liquid tank with a submerged block



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ABSTRACT

The seismic response of partially-filled two-dimensional rigid rectangular liquid tanks with a bottom-mounted submerged block is numerically simulated. The Galerkin-weighted-residual based finite element method (FEM) is used for solving the governing Laplace equation with fully nonlinear free surface boundary conditions and also for velocity recovery. Based on the mixed Eulerian–Lagrangian (MEL) method, a fourth order explicit Runge–Kutta scheme is used for the time-stepping integration of free surface boundary conditions. A cubic-spline fitted regridding technique is used at every time step to eliminate possible numerical instabilities on account of Lagrangian node induced mesh distortion. An artificial surface damping term is used to mimic the viscosity induced damping. Three different earthquake motions characterized on the basis of low, intermediate and high frequency contents are used to study the effect of frequency content on the nonlinear dynamic response of this tank-liquid-submerged block system. The effect of the submerged block on the impulsive and convective response components of the hydrodynamic forces manifested in terms of base shear, overturning base moment and pressure distribution along the tank wall as well as the block wall has been quantified vis-a-vis frequency content of ground motions. It is observed that the convective response of this tank-liquid system is highly sensitive to the frequency content of the ground motion.

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1. Introduction

Sloshing is essentially a nonlinear physical phenomenon, beyond the ambit of linear theory, characterized by low frequency free surface motion of liquid in a partially-filled moving container. Across the board, liquid containers constitute a major proportion of critical lifeline structures and are widely used in water supply facilities, oil and gas industries, and nuclear power plants for storage of a variety of liquids such as water, fuel, oil products, liquefied natural gas, chemical fluids and industrial wastes of different forms. Safe up-keeping and uninterrupted supplies of such products are of principal importance to industry. In this perspective, the threat to the structural safety and stability of their containers, in the event of seismic mishap, is a matter of great concern to a wide range of industrial facilities, civic bodies and environmental agencies, etc. Precise calculation of the maximum sloshing force due to an earthquake constitutes a fundamental issue for the structural integrity of these containers. This has been a major challenge before the scientific community, constantly working to understand the complex mechanism of sloshing in order to counter the threat.

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Sloshing is regarded as a classic linear eigenvalue problem in terms of the fluid velocity potential function, representing the small amplitude free vibrations of the surface of an ideal liquid inside a stationary container. Under a particular external excitation, sloshing represents the motion of fluid in a moving container and is treated as a transient problem. In many engineering applications, besides sloshing frequencies, sloshing induced hydrodynamic pressures and forces need to be calculated. Especially earthquake-induced sloshing has been identified as a crucial issue toward protecting the structural safety and integrity of liquid containers. Over decades, since the pioneering works of Housner [1,2], sloshing has been the matter of several analytical, numerical and experimental works, and those form a vast body of the available literature. Sloshing characteristics depend on such diverse parameters of the liquid-tank system as tank geometry, liquid fill-depths, aspect ratio of the tank, compressibility and viscosity of liquid, amplitude and frequency of external excitation, orientation and type of excitation, properties of tank material, submerged components if any, and restraint conditions of support structure etc. The dynamics of liquid storage tanks subjected to seismic loading depends on the inertia of the liquid and the interaction effects if any, depending on if the tank is rigid or flexible, between the liquid and the tank shell. Records of past earthquakes in various parts of the world bears the testimony to the extensive damage inflicted on various kinds of liquid storage tanks leading to loss of valuable contents, environmental hazards, fire-breaks and temporary loss of essential services [3–10]. While the complicated deformed configurations of liquid storage tanks and the interaction between the fluid and the structure result in a wide variety of possible failure mechanisms, field reports from past earthquakes imply that damage to the liquid-filled tanks are mainly ascribed to: (1) two nonlinear buckling mechanisms characterized as “elephant-foot buckles and diamond shape buckles” and (2) sloshing of a contained liquid with inadequate freeboard between the quiescent liquid surface and the tank-roof. The dynamic response of a fluid-structure system is very responsive to the characteristics of ground motion and configuration of the system [2,3,11–13]. Strikingly diverse failure patterns have been reported in cases of anchored and unanchored tanks [14–17].

A good number of analytical [18,19], numerical [20–27] and experimental [28–32] works involving liquid tanks with baffles of various configurations such as passive slosh damping elements have been carried out though, most of these works are either related to free vibration characteristics of liquid or have employed harmonic motion as external excitations to study the effect of baffles on the dynamic behaviour of the tank.

The presence of submerged equipment or components like those in a nuclear spent fuel storage pool, a structure of seismic category I, the dynamic behaviour of fluid-structure systems may be radically changed. Compared to the vast body of literature concerning liquid tanks of different geometries, only a few works on tanks with submerged internal components have been published (Mitra and Sinhamohapatra [33], Choun and Yun [34]). However, their studies are limited to linear analysis. Nevertheless, “impulsive-convective” pressure concept which lay the basis of almost all recent design codes and guidelines, e.g., API Standard 650 [35], Eurocode 8 [36], and ASCE [37], has been overlooked in the above studies. Faltinsen [39] has presented a numerical nonlinear method for analysis of sloshing motion in tanks with two-dimensional flow. Wu et al. [44] have analysed the sloshing waves in a three dimensional tank undergoing harmonic motion. The analysis is carried out using a finite element method based on the fully nonlinear wave potential theory. Frandsen [45] has used a fully nonlinear finite difference model to analyse the sloshing wave motion in a 2-D tank subjected to harmonic base excitations. Wang and Khoo [46] have analysed a two-dimensional nonlinear random sloshing problem by the fully nonlinear wave velocity potential theory based on the finite element method. Sriram et al. [47] have studied the motion of sloshing waves in a tank due to horizontal and vertical random excitation. The fully nonlinear wave is simulated using the finite element method with the cubic spline and finite difference approximations. Nayak and Biswal [48] have studied the nonlinear sloshing response in a partially filled liquid container without any submerged objects.

The objective of the present paper is to methodically investigate the effect of the submerged block on the nonlinear sloshing, base shear, overturning base moment and dynamic pressure distribution on the walls of the tank and block. The effect of submerged block on impulsive and convective response of dynamic behaviour of liquid in a tank is quantified. The ratio of peak ground acceleration (PGA) to peak ground velocity (PGV) is a commonly accepted measure of frequency contents of ground motion records, where PGA is in g, and PGV in m/s. On the basis of the PGA/PGV ratio, the earthquake

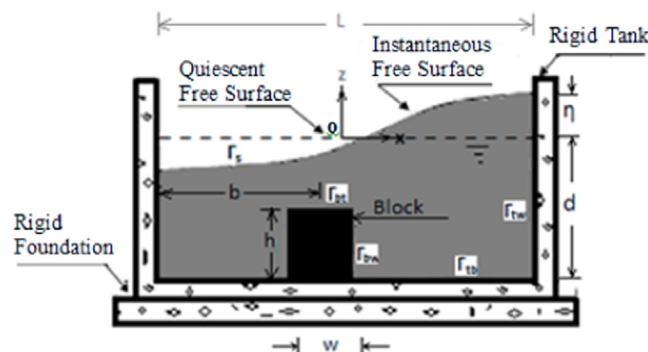


Fig. 1. Schematic diagram of tank-liquid-submerged block system.

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