Journal of Fluids and Structures 81 (2018) 97–115

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Shake table testing of an open rectangular water tank with water sloshing

Jure Radnić *, Nikola Grgić, Marina Sunara Kusić, Alen Harapin

University of Split, Faculty of Civil Engineering, Architecture and Geodesy, Croatia

ARTICLE INFO

Article history:
Received 23 November 2017
Received in revised form 5 February 2018
Accepted 24 April 2018

Keywords:
Open rectangular tank
Water sloshing
Shake table
Pressure
Displacement
Strain

ABSTRACT

Liquid storage tanks are widely used structures in industry. Their safety during an earthquake is important because damage to or the collapse of these structures can cause substantial material damage and human losses. In this paper, the behaviour of small-scale open rectangular water tanks with water sloshing during dynamic excitation was experimentally investigated. The effects of several parameters were studied using a shake table (tank wall stiffness; tank water level; dynamic excitation type; and period, amplitude and duration of the harmonic ground excitation). The most important conclusions of the investigated effects are presented. It is expected that the experimental database can be useful for the verification and calibration of numerical models used to simulation liquid–structure coupled problems.

1. Introduction

Liquid storage tanks are widely used, e.g., in water supply facilities, the oil and gas industry and nuclear power plants. The behaviour of such constructions during an earthquake remains unclear due to the complex motion of the liquid with respect to the tank and the sloshing of the liquid as well as the dynamic interaction of the liquid–tank–soil coupled nonlinear system. The safety of liquid storage tanks during an earthquake is important because of the potentially catastrophic consequences of their collapse. Therefore, experimental investigations on the behaviour of such structures are needed.

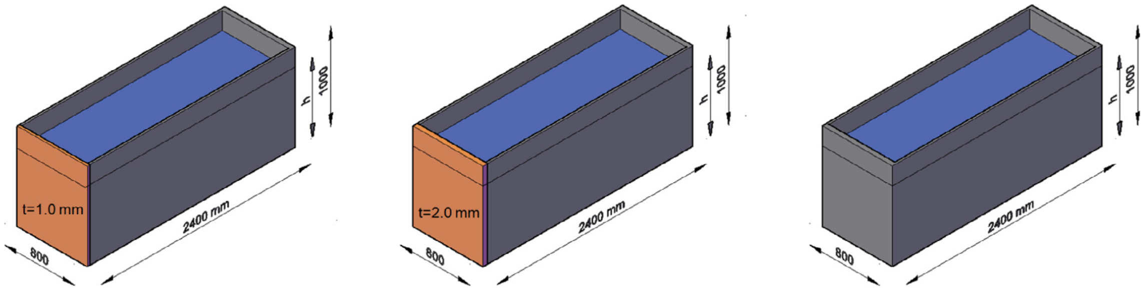
While theoretical and numerical studies related to the behaviour and safety of liquid storage tanks have been fairly frequently presented, experimental investigations of tank behaviour during dynamic excitation are rare and mostly concern tanks with rigid walls. The following paragraph briefly presents the results of several experimental investigations of liquid storage deformable tank behaviour during dynamic excitation.

Cho and Cho (2007) investigated the behaviour of a deformable steel tank during an earthquake. Chiba (1992) investigated the impact of an elastic tank bottom on the nonlinear hydroelastic vibration of a cylindrical tank that contained liquid. De Angelis et al. (2009) investigated the impact of tank base isolation on the behaviour of a steel liquid storage tank equipped with floating roof using a shaking table. Burkacki and Jankowski (2014) investigated the behaviour of a scaled model of a Polish steel tank, also using a shake table. Park et al. (2016) investigated the dynamic characteristics of cylindrical liquid storage tank subjected to seismic excitation.

Liquid storage tanks generally exhibit a long initial period of free oscillations, which is primarily determined by the characteristics of the contained liquid. Therefore, long-period and long-duration ground motions are the most unfavourable

* Corresponding author.
E-mail addresses: jure.radnic@gradst.hr (J. Radnić), nikola.grgic@gradst.hr (N. Grgić), marina.sunara@gradst.hr (M. Sunara Kusić), alen.harapin@gradst.hr (A. Harapin).

https://doi.org/10.1016/j.jfluidstructs.2018.04.020
0889-9746/



(a) Tank R1. (b) Tank R2. (c) Tank R3.

Fig. 1. Tested tanks.

for them. Even at a low magnitude of acceleration, earthquakes can cause waves in the tank and significant changes in the free surface of the liquid. That is, they can result in high liquid pressure on tank walls, which can cause structural collapse.

In this paper, the results of experimental testing of the behaviour of an open rectangular water tank during an earthquake using a shake table are presented. The effects of several parameters were investigated: tank wall stiffness; tank water level; dynamic excitation type; and the period, amplitude and duration of the harmonic ground excitation. A total of 54 different tests were performed. During each test, the pressure distribution on the front tank wall and the displacements and strains of the front tank wall were measured. In addition, the motion of the water in the tank was recorded. A number of the research results are graphically presented and briefly discussed. Finally, the most important conclusions of the research are described.

The primary aim of this experimental research was to contribute to the knowledge of the behaviour of an open rectangular tank during earthquakes that cause significant water motion in the tank, i.e., sloshing. Another objective was to create an experimental database that can be used to verify and calibrate numerical models of liquid–structure coupled problems under dynamic excitation with a large displacement of the liquid. Namely, the motive for this paper was the need to verification of numerical model, developed by authors, for simulation of fluid–structure dynamic interaction with large fluid displacements using the results of suitable and well-documented experimental tests that were not available. Because the presentation of this numerical model together with the presentation of even small part of the obtained experimental results would be too large for one article, it was decided that only the results of the experimental research are presented first. As the experimental research was performed on small-scale tanks, applicability of obtained tests results on full-scale tanks are shortly discussed in Section 4.

2. Experimental setup

2.1. Tested tanks

Three small-scale (approx. 1:10) open rectangular tanks with different wall stiffnesses were tested (Fig. 1). Tanks R1 and R2 had front walls of steel sheet, while the other walls were rigid. Tank R3 had all the walls rigid. The steel sheet thickness of the front wall (t) was 1 mm for tank R1 and 2 mm for tank R2. Thus, the longitudinal stiffness ratio of these tank walls was 1:2, and bending stiffness ratio was 1:8. The rigid tank walls were 100 mm thick. They were constructed of high-strength concrete and highly reinforced (HRN, 2006). The inside dimensions of all tanks were the same: length: 2400 mm, width: 800 mm and height: 1000 mm. Tank R3 was symmetrical, while tanks R1 and R2 were longitudinally non-symmetrical.

The tanks were filled with water to height h and exposed to ground motion in the longitudinal direction. To investigate the effect of water interaction with deformable construction, different stiffnesses of the front tank wall were adopted. The steel wall was firmly clamped into the concrete tank walls. The inner parts of the tank walls were flat and smooth. The bottom of the tank was fixed to the top of the shake table.

The tested uniaxial tensile strength of the steel sheet was 365 MPa, the yield strength was 245 MPa and the elastic modulus was 205 GPa. During all the tests, the steel sheet strains were in the elastic deformation region. Water from the waterworks was used, and its temperature during the tests was approximately 22 °C. Tank R2 prepared for testing is shown in Fig. 2.

2.2. Measured values

For each test, water pressure p (hydrostatic and hydrodynamic) was measured at ten points along the vertical dimension of the tank (Fig. 3a), the horizontal displacement of the steel sheet was measured at two points on the vertical dimension of the front wall (Fig. 3b), and the transverse horizontal strain of the steel sheet was measured at two points on the vertical dimension of the front wall (Fig. 3c). The motion of the water–tank system during each test was recorded with two digital cameras. That is, the change in the water level in the tank was monitored (Fig. 3d).