Nonlinear Earthquake Behavior of a Rectangular Liquid Storage Tank to Three-Directional Ground Motion

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1. Introduction

Liquid storage tanks including a spent fuel storage are essential infrastructure for modern society and industry because they contain various fluid such as water, oil, LNG, etc. If they are damaged due to earthquake, they can have negative effects on environments and bring serious losses. The damage can result in a loss of lives in the worst case. Therefore, their seismic safety is very important for society and industry. However, it was observed from the Alaska earthquake in 1964, the San Fernando earthquake in 1971, the Kobe earthquake in 1995, and the Chi-Chi earthquake in 1999 that liquid storage tanks were damaged heavily by earthquake ground motions. Based on the observations, many studies have been performed to investigate the fluid-structure interaction effects on the seismic performance of liquid storage tanks. However, the effects of fluid-structure interaction with a material nonlinearity have not been widely considered on the assessment of the seismic performance while determination of the maximum hydrodynamic pressures induced by horizontal and vertical excitation requires, in principle, use of nonlinear dynamic (time-history) analysis in Eurocode 8 [1].

In this study, earthquake responses of rectangular liquid storage tanks are investigated with material nonlinearity taken into consideration. Specifically, this study is focused on concrete structures. The material nonlinearity in concrete will be considered using the concrete damage plasticity (CDP) model. In order to examine the effects of material nonlinearity, the nonlinear responses will be compared with those from linear dynamic analysis.

It should be noted that the earthquake responses depend on the incident angles of a bi/three-directional earthquake ground motion because the rectangular structure has geometric asymmetry. The directional effects will be examined in this study. The nonlinear earthquake responses will be calculated for a three-directional earthquake ground motion with various incident angles.

2. Finite-element formulation

Finite elements are employed for the system. Its governing equation can be obtained as follows:

$$\mathbf{M}\ddot{\mathbf{U}} + \mathbf{C}\dot{\mathbf{U}} + \mathbf{f}_{\text{int}}\left(\boldsymbol{\varepsilon},\dot{\boldsymbol{\varepsilon}}\right) = \mathbf{F}_{fluid} + \mathbf{F}_{eq} \tag{1}$$

$$\mathbf{f}_{\text{int}}\left(\boldsymbol{\varepsilon},\dot{\boldsymbol{\varepsilon}}\right) = \int \mathbf{B}^T \boldsymbol{\sigma}\left(\boldsymbol{\varepsilon},\dot{\boldsymbol{\varepsilon}}\right) dV \tag{2}$$

$$\mathbf{F}_{fluid} = \int \mathbf{N}_S^T \mathbf{v}^T \mathbf{N} dS\, \mathbf{P} = \mathbf{S}^T \mathbf{P} \tag{3}$$

$$\mathbf{F}_{eq} = -\mathbf{M}\ddot{\mathbf{U}}_g \tag{4}$$

where $\mathbf{M}$ and $\mathbf{C}$ are mass and damping matrices for the structure, respectively. $\mathbf{f}_{\text{int}}\left(\mathbf{U},\dot{\mathbf{U}}\right)$ is an elastic/inelastic internal force vector of the structure, $\boldsymbol{\varepsilon}(x,y,z,t)$ and $\boldsymbol{\sigma}\left(\boldsymbol{\varepsilon},\dot{\boldsymbol{\varepsilon}}\right)$ are strain and stress in the structure, respectively, and $\mathbf{B}(x,y,z)$ is the matrix which relates displacement in the structure to its strain, i.e., $\boldsymbol{\varepsilon} = \mathbf{B}\mathbf{U}$ where $\mathbf{U}(t)$ represents a relative displacement vector of the structure with respect to the ground motion $\ddot{\mathbf{U}}_g(t)$. $\mathbf{P}(t)$ and $\mathbf{F}_{fluid}(t)$ are the hydrodynamic pressure and force, respectively. $\mathbf{F}_{eq}(t)$ is the effective earthquake force.

Hydrodynamic pressure in Eq. (3) is evaluated using the finite-element approach with acoustic elements.

$$\left(\mathbf{G} + \mathbf{G}_{fs}\right)\ddot{\mathbf{P}} + \mathbf{H}\mathbf{P} = \mathbf{Q} \tag{5}$$

$$\mathbf{G} = \frac{1}{C^2}\int \mathbf{N}^T \mathbf{N} dV \tag{6}$$

$$\mathbf{G}_{fs} = \frac{1}{g}\int \mathbf{N}^T \mathbf{N} dS \tag{7}$$

$$\mathbf{H} = \int \mathbf{B}^T \mathbf{B} dV \tag{8}$$

$$\mathbf{B} = \left[\frac{\partial \mathbf{N}}{\partial x} \quad \frac{\partial \mathbf{N}}{\partial y} \quad \frac{\partial \mathbf{N}}{\partial z}\right]^T \tag{9}$$

$$\mathbf{Q} = -\rho \mathbf{S}\ddot{\mathbf{U}}^t = -\rho \mathbf{S}\ddot{\mathbf{U}} - \rho \mathbf{S}\ddot{\mathbf{U}}_g \tag{10}$$

$$\mathbf{S} = \int \mathbf{N}^T \mathbf{v} \mathbf{N}_S dS \tag{11}$$

where C is the pressure-wave velocity of fluid, $\mathbf{N}$ is a shape function for hydrodynamic pressure, $\mathbf{N}_S$ is a shape function for structural displacements, and $\mathbf{v}$ is an outward unit normal vector.

3. Application

Earthquake responses of a rectangular liquid storage tank, shown in Fig. 1, subjected to three-directional earthquake ground motion in Fig. 2 are obtained.

The profiles of the hydrodynamic pressure on the mid-line of the long sided-walls are provided in Fig. 3 when the peak values of hydrodynamic pressure are attained. It can be observed that the distributions are influenced significantly by the incident angles of the input ground motion. The base shear and overturning moment due to the hydrodynamic pressure per unit width are also influenced. Because the base shear is affected by the material nonlinearity and the incident angle of the input ground motion, the resulting impulsive mass is also influenced in the same way. The affected base shear and overturning moment cause a change of the impulsive-mass height.

The evolution of tensile damage is shown in Fig. 4. The tensile damage in the lower part of the long-sided walls has occurred by this time, as shown in Fig. 4(a). Subsequent damage occurs up to 1.91 sec, as shown in Fig. 4(b). The damaged region is extended over the lower part of the long-sided walls and inclined damage is observed on the walls. Fig. 4(c) shows that the tensile damage spreads over the long-sided walls. Inclined cracks are observed on the long-sided walls, as shown in Fig. 4(d). The tensile damage does not substantially change after this time. This kind of damage is typical for concrete structures such as slabs and plates. Reinforcing bars should be optimally placed in the areas by considering the inclined cracks.

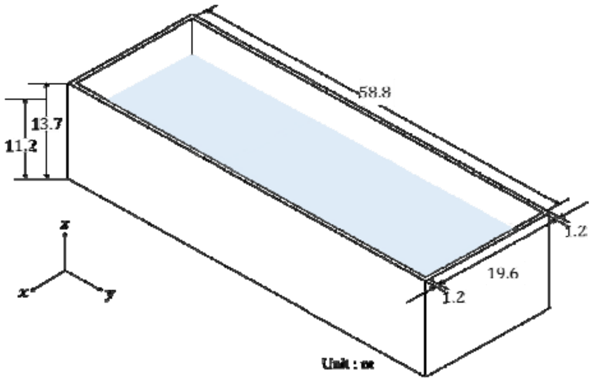


Fig. 1. Rectangular liquid storage tank

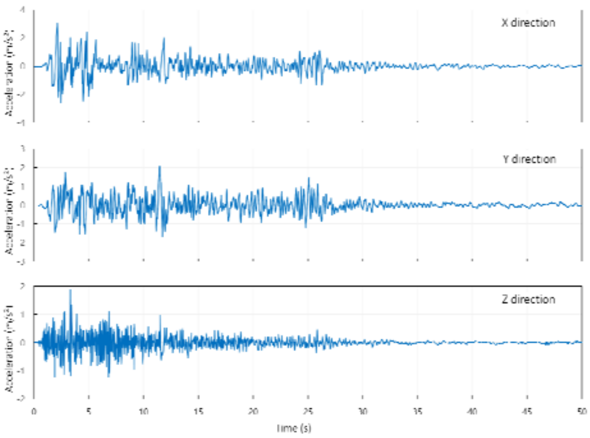


Fig. 2. Three-directional input ground motion

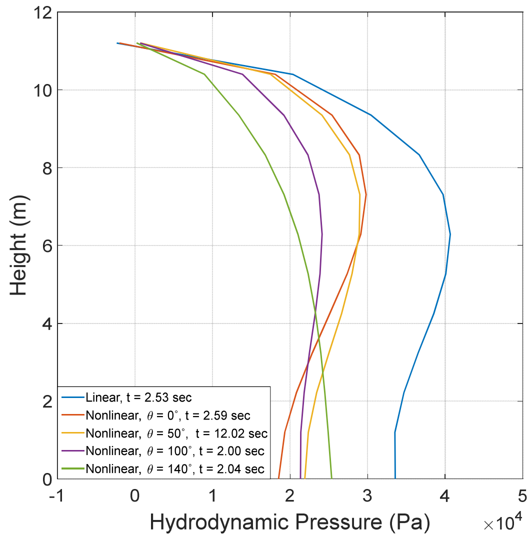


Fig. 3. Hydrodynamic pressure distribution

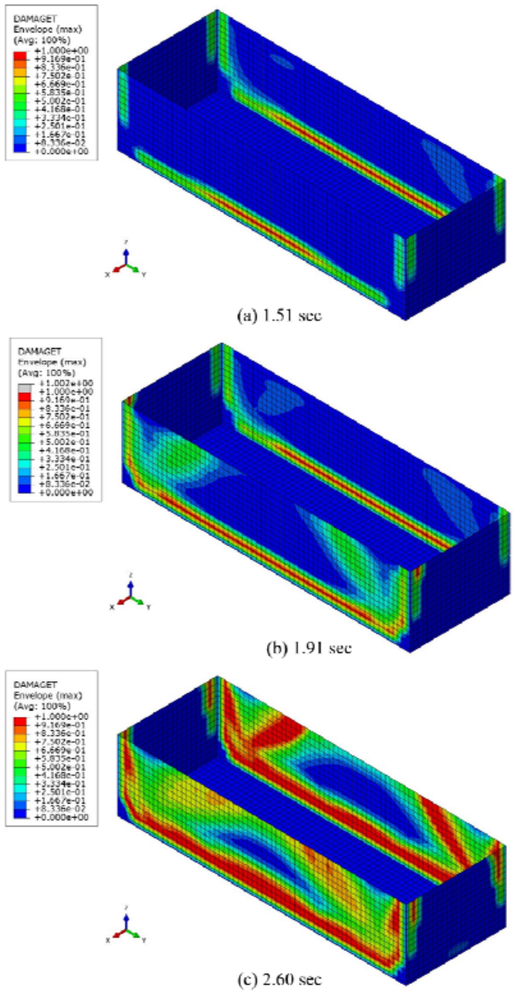
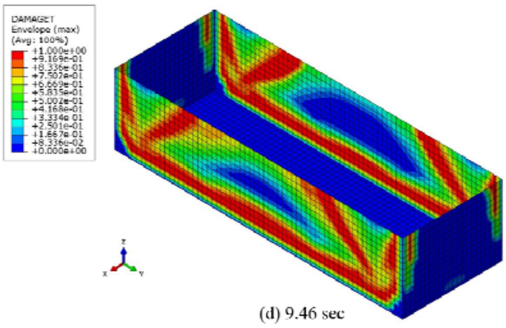


Fig. 4. Tensile damage variable d_t



(d) 9.46 sec

Fig. 4. Tensile damage variable d_t (continued)

4. Conclusions

In this study, the earthquake responses of a rectangular liquid storage tank made of concrete were investigated with material nonlinearity taken into consideration. The material nonlinearity in concrete was considered using the concrete damage plasticity model. Because the rectangular structure has geometric asymmetry and given that the corresponding earthquake responses depend on the incident angle of three-directional earthquake ground motion, directional effects were examined in this study. It can be concluded from the dynamic analyses of a rectangular liquid storage tank subjected to three-directional earthquake ground motion that the effects of material nonlinearity are significant and the earthquake responses of a rectangular liquid storage tank are affected significantly by the incident angle of the earthquake ground motion.

Acknowledgements

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