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Nonstationary seismic response of a tank on a bilinear hysteretic soil using wavelet transform

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Abstract

A wavelet based nonlinear random vibration theory has been proposed in the present study to obtain responses of liquid storage tanks in form of instantaneous root mean square displacements of impulsive modes of the tank-liquid system supported on bilinear hysteretic (elasto-perfectly plastic) soil medium. The superstructure has been modeled by a combination of mass-spring-damper system. In order to evaluate the instantaneous root mean square values of the displacement responses of the tanks, zeroth moments of instantaneous power spectral density function (PSDF) have been evaluated. The hysteretic displacement is assumed to follow a truncated mixed Gaussian distribution. The evaluation of this zeroth moment depends on the post-yield or the pre-yield state of the hysteretic spring. The instantaneous root-mean-square (r.m.s) impulsive displacement response of the tank has been validated by simulation. A parametric study has been carried out to see the effects of the soil nonlinearity, the shear wave velocity in the soil and the height of the tank on tank responses.

Keywords: Nonlinear soil medium; Elasto-perfectly plastic hysteresis; Nonstationary; Seismic; Tank; Wavelet

1. Introduction

The responses of fluid storage tanks subjected to seismic ground motions have been studied by numerous researchers in the last few decades. Many of the earlier studies have been carried out considering fixed base tanks [1–8,46,47]. Several researchers have studied the soil-structure interaction (SSI) effects to obtain the responses of fluid storage tanks both theoretically and experimentally [9,10].

In all the studies mentioned earlier the loadings were either considered to be harmonic or represented by deterministic time histories. However, earthquake ground motions are known to be stochastic and highly nonstationary due to the generation of body waves and several modes of surface waves [11]. Due to random nature of seismic excitations, the induced vibrational responses in the structure are also nonstationary in nature. Different techniques have been adopted by the researchers to account for the amplitude nonstationarity of the ground motions. [12–15] and many others used various types of amplitude modulating functions viz. step function, staircase function, exponentially decaying function etc. to model the input as uniformly modulated stationary process. Besides the amplitude nonstationarity of earthquake ground motions, frequency nonstationarity is also an important characteristic feature of such excitations. Wavelet transform enables one to obtain the frequency content of a nonstationary process locally in time. Considerable research has been carried out to develop several wavelet functions with specific characteristics to suit different purposes [16–21]. Wavelet analysis can be used to provide an enhanced time-frequency resolution desirable for several applications and can be effectively used to generate random processes and fields [22,23], simulate earthquake ground motions [24] and model stochastic dynamic systems [25]. Wavelet based system identification techniques for linear and nonlinear systems and solution of time-varying differential equations have been developed by [26,27], Ghanem and Romeo [48] and Ghanem and Romeo [45]. The nonstationary seismic responses of linear structures have been analyzed by [21,28,29]. [30] developed a generalized approach to

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obtain the stochastic response of a multi-degree-of-freedom (MDOF) system by Harmonic wavelets and a rigorous approach to obtain the evolutionary spectral estimates for both orthogonal and non-orthogonal wavelet bases was developed by [31], generalizing the earlier formulations by [21,28,29]. Studies have also shown [21,28,32,33,41,44] that the structural responses are considerably affected by the nonstationarity of ground motions, particularly in case of nonlinear systems.

The tank responses may also be significantly affected by nonlinear behaviour of soil under the action of moderate to severe seismic forces. Several researches have been reported in the past on the material nonlinearity of the soil and also its influence on the responses of structures, e.g. the study of nonlinear stress–strain relationship [34,35], the nonlinear load-displacement relationship [36], the effective shear wave velocities in the nonlinear soil by using transfer function analyses [37] etc. In an attempt to model the nonlinearity in the force-displacement characteristic of systems by a hysteretic curve, the area enclosed by the hysteresis loop may become quite appreciable when a large deformation of a system occurs and this may have to be modeled by a ‘fat’ hysteresis loop instead of ‘slim’ ones [38]. In such cases, it is preferable to model the effect of the hysteresis loop instead of representing it by a stiffness nonlinearity reflecting a backbone curve and an equivalent viscous damping representing the energy dissipation.

In the previous researches on the non-stationary seismic response of tank-foundation systems [39,40] the non-linearity of the soil-foundation system was not considered, though rocking of the foundation and the impulsive and the convective liquid motions were considered in the stochastic responses. In the present study, a methodology for obtaining the nonstationary seismic responses of liquid storage tanks supported on hysteretic elasto-perfectly plastic soil medium has been proposed on the basis of wavelet analysis technique. In the earlier works by [41,44] the non-linearity in the system was accounted for by an extension of the equivalent linearization technique [38]. In this paper, since the non-linearity has a bilinear form, the formulation of [21,28] is further extended to adapt for the present case as the linear theory is valid for each of the piecewise linear (pre-yield and post-yield) phases. Subsequently, certain probabilistic compatibility conditions are used to evaluate the spectral estimates. The computed estimates are validated by simulation results from a generated ensemble. Parametric variations have been carried out to observe the effects of the shear wave velocity, the yield displacement of the underlying soil medium and the height of the tank.

2. Modeling of the system

The tank-fluid superstructure system consists of a right circular cylindrical, rigid thin-walled tank of radius R, filled with an incompressible liquid to a height, H. The tank wall is assumed to be of uniform thickness, h. The Young’s modulus of elasticity, the density of the tank material and the thickness of the tank wall are denoted by E, ρ and h, respectively. This tank-liquid system has a fixed-base natural frequency of vibration, ω_n and a damping ratio, ζ_i. The liquid in the tank is assumed to be vibrating in unison with the tank (i.e. in impulsive mode). So, the frequency of vibration of the liquid, ω_i may be assumed to be equal to ω_n. The tank is rigidly clamped to a thick, rigid, circular base mat, which is of same radius as that of the tank. The tank with the mat is resting on the surface of a laterally flexible nonlinear soil medium. The shear modulus of elasticity, the Poisson’s ratio and the velocity of shear wave propagation of the supporting medium are denoted by G_s, ν_s and V_s, respectively. The tank-liquid system is represented by a mass-spring-dashpot model as shown in Fig. 1. The impulsive mass of the liquid, m_i, is attached to the foundation mass, m_f through a linear spring with stiffness, K_i and a linear viscous damper with coefficient, C_{di}. The nonlinearity of the supporting soil medium is represented by a single elasto-perfectly-plastic (EPP) hysteretic spring, so the ratio of the post-yield stiffness to the pre-yield stiffness of this spring is zero. The foundation of the tank has been assumed to be attached to the inelastic soil medium through this hysteretic spring with static stiffness coefficient, K^c and a linear viscous damper having coefficient, C_0. The motion of the tank foundation induces a displacement in the spring till the yield level is reached beyond which the associated friction element slips. Further, when the hysteretic loop unwinds the change in the foundation displacement induces a displacement in the spring in the opposite direction. Thus, the soil model considered represents a nonlinear (bilinear hysteretic) system. The expressions for K^c and C_0 for circular

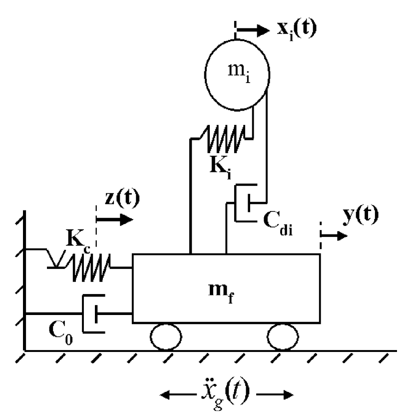

Fig. 1. Tank-liquid-foundation system on nonlinear soil (2-DOF Model) subjected to seismic ground motions.