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Buckling behavior of the anchored steel tanks under horizontal and vertical ground motions using static pushover and incremental dynamic analyses

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ABSTRACT

This paper investigates the static and dynamic buckling of an anchored cylindrical steel tank subjected to horizontal and vertical ground acceleration. The buckling capacity of the tank is estimated using static pushover (SPO) and incremental dynamic analyses (IDA). Appropriate load patterns due to the horizontal and vertical components of ground excitations are utilized for SPO analyses. The buckling capacity curves and critical buckling loads computed using SPO analyses are compared to those obtained from IDA. A proper vertical to horizontal acceleration ratio (a_v/a_h) for SPO analysis is proposed that leads to good agreement between SPO and IDA results.

1. Introduction

Aboveground flexible cylindrical steel tanks are among the lifeline structures widely used in various places such as water supply facilities, oil and gas refineries, etc. Different modes of failure and extensive damages were observed in steel tanks during past major earthquakes. One of the common yet most damaging failure modes of steel tanks under earthquake loading is shell dynamic buckling mode [1]. Dynamic buckling of tank shell usually occurs in the forms of elephant foot buckling and diamond shaped buckling modes. The elephant foot buckling mode that is considered as an elasto-plastic type of instability, is described by an outward bulge of the tank shell near to its base. This type of buckling of steel tank wall is caused by the interaction of both circumferential tensile stress close to yield strength and axial compressive stress exceeding the critical stress. Due to cyclic nature of seismic loading, elephant foot buckling often extends around the circumference of the tank wall. On the other hand, the diamond buckling is a type of elastic instability that is caused by severe axial compressive stresses [2,3].

In early 1960s, Housner conducted a research on the dynamic behavior of the tank-liquid system [4]. He separated the hydrodynamic response of a rigid tank- liquid system into the liquid impulsive and convective (sloshing) parts. The part of liquid which vibrates with the tank wall is known as the impulsive liquid, while the rest of the tank content that vibrates independently is considered as the convective liquid. Impulsive and convective responses of the tank-liquid system are identified with a short and long natural period of vibration, respectively. Impulsive and convective modes may be considered uncoupled as their corresponding modal frequencies are well separated [5].

Early experimental investigation on seismic behavior of steel tanks conducted by Clough [6], Manos and Clough [7]. Experimental study on the buckling behavior of a small tank model made of polyester resin is reported by Shih and Babcock [8]. The tank model was subjected to one horizontal harmonic or simulated seismic base excitation. They observed the occurrence of elasto-plastic buckling near the tank base and the elastic buckling at the top of the tank wall.

Rotter [9] investigated the elastic-plastic buckling and collapse of thin cylindrical shells subjected to axial compression load and internal pressure. He described the results and compared those with the existing design recommendations. Finally, based on a semi empirical work, he proposed a simple and practical equation for seismic tank design which adopted by the European Standards ENV1998-4 [10]. Virella et al. [11] numerically investigated the dynamic buckling of ground supported, cylindrical, anchored steel tanks subjected to horizontal ground motion. They estimated the horizontal peak ground acceleration that induces dynamic elastic buckling and material plasticity of tank wall. Kianoush and Chen [12] evaluated the importance of the vertical component of base excitation on the overall seismic response of rectangular concrete tanks. They proved that the response of the tank wall due to vertical base excitation should be considered in tank design. Virella et al. [13] studied the elastic buckling behavior of steel tanks under horizontal component of ground motions using nonlinear static method. The analysis procedure was based on a capacity spectrum method that is similar to the proposed method in ATC [14]. In this way, the minimum

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peak horizontal acceleration that causes the elastic buckling at the top of the tank shell is calculated. The critical PGAs for three tank models, estimated by nonlinear static method in comparison to those obtained from dynamic analysis are slightly smaller.

Amiri and Sabbagh-Yazdi [15] examined the effect of tank roof on natural frequencies and mode shapes of three tall steel tanks using FEA and ambient vibration test results. The results of this research showed that the influence of roof on the natural frequencies of the axial and vertical vibrational modes is insignificant, but it has remarkable effect on natural frequencies of circumferential modes. Recently, an excellent literature survey is provided by Godoy [16] in the field of static buckling of steel tanks under static and quasi-static loads including uniform pressure, wind, foundation settlement and fire.

In previous studies such as Virella et al. [11], Buratti and Tavano [17], Maheri and Abdollahi [18] and Djermane et al. [19], the dynamic buckling of steel tanks under only horizontal component of ground acceleration was investigated. Also, the dynamic analyses of steel tank were carried out for only one or two earthquake records.

This study presents the static and dynamic buckling analyses of anchored shallow steel tanks under horizontal and vertical ground motions using nonlinear static pushover (SPO) and incremental dynamic analyses (IDA). On that regard, the elasto-plastic buckling of a widely used tank model in the petrochemical industry with a height to diameter ratio (H/D) of 0.40 is considered. Also, the influence of vertical component of ground acceleration on buckling behavior of steel tanks is investigated. The material and geometric nonlinearities are included in the static and dynamic analyses that are carried out using the finite element package ABAQUS [20] under horizontal component (uni-directional) and both horizontal and vertical components (bi-directional) of ground motions. The buckling criterion is used to evaluate the critical PGA and load pattern for elasto-plastic buckling of the tank shell. The buckling capacity curves and critical loads for the steel tank obtained from the SPO analyses are compared to those obtained from the IDA and the necessary conclusions are made.

2. The considered steel tank

The geometry of the tank model considered in this study is similar to the shallow tank (model A) used by Virella et al. [11,13]. The height and diameter of the steel tank are 12 and 30 m, respectively. The height to diameter ratio (H/D) of the tank is 0.40. Since the majority of reports of earthquake damage to cylindrical steel tanks indicate that the tanks completely filled with liquid have suffered more damage, thus the filling level of 90% is assumed in this work [11]. In this study, the thickness of the tank shell is determined based on the seismic design requirements of the standard API 650 [21]. The seismic design of tank is carried out assuming PGA = 0.35 g. The height of each shell course is 2 m with the thickness of first course equal to 10 mm and a thickness of 8 mm for the rest of the shell courses. The minimum shell thickness according to API 650 [21] is equal to 6 mm but due to design consideration, a minimum thickness of 8 mm is considered in this study. Since this study focuses on the buckling of the cylinder tank wall, the tank is modeled without a roof. However, the effect of roof's in plane stiffness on the overall tank response is taken into account by a rigid body constraint at the upper edge of tank shell. This rigid body is a collection of top wall nodes whose motion is governed by the motion of a single node, called the rigid body reference node [20]. The geometric configurations of the designed steel tank are shown in Fig. 1. The designed tank model is called as "TK040" to specify the tank height to diameter ratio.

3. Finite element model of the tank-liquid system

The nonlinear static and dynamic analyses of the tank-liquid system were carried out using the finite element analysis package ABAQUS [20]. The finite element meshes of steel tank consisted of four-node, doubly curved quadrilateral shell elements (S4R). Each node of shell element has three translational and three rotational degrees of freedom. The liquid is modeled using eight-node brick acoustic elements (AC3D8). The acoustic finite element model is based on the linear wave theory and considers the dilatational motion of the liquid. The acoustic element has only one pressure unknown as degree of freedom at each node.

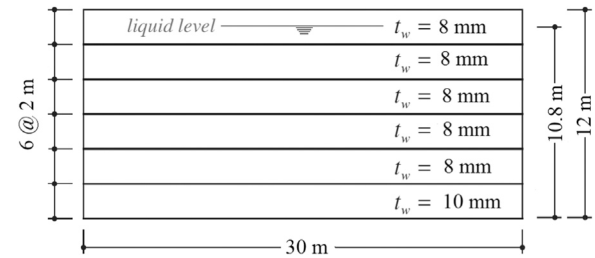

Fig. 1. Geometric characteristics of the designed steel tank (model TK040).

The tank-liquid interaction was considered using the definition "Surface tied normal contact constraint" between the interfaces of liquid and tank. This constraint is formulated based on a master-slave contact method, in which normal force is transmitted using tied normal contact between both surfaces through the simulation. The sloshing waves are considered in the liquid model. Assuming the small-amplitude gravity waves on the free surface of the liquid, the boundary condition specified at free liquid surface can be presented as [22]:

$$\frac{\partial^2 P}{\partial t^2}+g\frac{\partial P}{\partial z}=0 \tag{1}$$

in which P is the hydrodynamic pressure at the free liquid surface. The considered anchored tank model has a fixed connection to the ground at its base level. The boundary conditions specified for the liquid-tank finite element model are shown in Fig. 2.

Both geometric and material nonlinearities are considered in the static and dynamic finite element analyses. Considering the von Mises yield criterion for the plastic behavior of the shell elements, a yield stress of 248 MPa and elastic modulus of $E = 200$ GPa is assumed for the steel material. The water density is considered to be 1000 kg/m^3, and the Rayleigh mass proportional damping was employed for the tank model assuming a damping ratio of 2.0%, for the fundamental vibration mode of the tank-liquid system [11].

Due to the structural symmetry and to reduce the computational cost, only half of the tank-liquid system is modeled and symmetry plane boundary conditions were employed. Various sensitivity analyses resulted in selection of finite element mesh sizes of the tank and its content in longitudinal and circumferential directions as 0.20 m and 0.50 m, respectively, to achieve acceptable accuracy. The 3-D finite element mesh of TK040 model is illustrated in Fig. 3.

4. Finite element model verification

To verify the tank-liquid finite element model used in this study, the

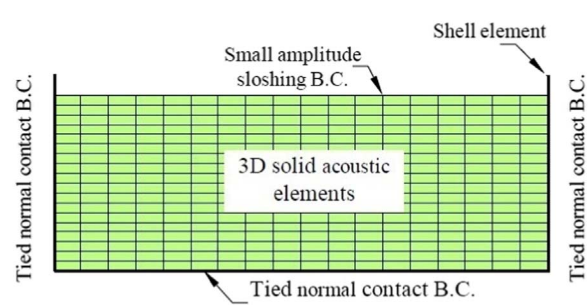

Fig. 2. Boundary conditions of the 3-D tank-liquid finite element model.