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General considerations in the seismic analysis of steel storage tanks

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Abstract: One of the important and functional types of structures widely used in petroleum complex due to the ease of design, including oil depots are cylindrical steel tanks. Oil tanks damaging causes wild fire sand leakage of toxins and pollute the environment. This issue reveals the importance of studying vulnerability and retrofit of the structures. In this article, in order to collect data, mainly the field study is used based on documents and available plans. In order to write the literature of article, Persian and Latin resources available in libraries, documentation, and scientific centers have been used. In this paper, first comprehensive explanations about earthquake force and Seismic behavior of tank are given. Then the common types of damages of the tanks such as shell buckling, overturning, and uplifting the bottom of tank, bed asymmetric subsidence, and tank slip are investigated. Next, the impact of the anchor of tank parameters, the liquid level in the tank, shell and bottom thickness, and the ratio of height to diameter are examined. In addition, the interaction between tank structure and the fluid and soils discussed. The results show that unanchored cylindrical steel tanks involve relative complex dynamic and nonlinear behavior based on the interaction between structure, fluid, and soil.

Key words: Cylindrical steel tanks; Uplift; Overturning; Shell buckling; Interaction Structure fluid and soil

1. Introduction

Complex and unpredictable behavior of earthquake has caused to obtain new facts after occurrence of each earthquake. Principles of structure designing against earthquake require understanding of two parameters. These parameters are characteristics of the earthquake force and the dynamic characteristics of the structure. In general, any structure relying on the ground, during the earthquake, it is affected by ground motion components which consists two lateral components, a vertical component, and three tensional components which are around the Structures coordinate axes. The horizontal components of ground acceleration cause hydrodynamic pressuring on the tank wall which are shown as: A) Impact pressure which is occurred by tank wall vibration and its period is equal to the period of tank vibration; B) the fluctuation pressure which is created from impact vibration transmission to fluid, and appears in the form of surface waves in the fluid. Also, the created hydrodynamic pressure by the earthquake excitations causes to create shear forces and bending moments which also causes to create annular compressive, elasticity, and shear tensions in the tank shell. If there is no a good estimate of them in the design of tank, it can result in irreparable events. Steel tank is made of three parts: tank fuselage, which is a cylindrical shell of steel plate, foam of the tank, which is flat plate and relies on a widespread foundation or dense bed, and its roof, depending on type of fluid is fixed or movable. These tanks are mainly classified in two completely anchored and unanchored where their foam connected to the ground. Of course, great numbers of available tanks in oil installations are of the UN anchored in those in the past earthquakes have been more vulnerable. Anchored tanks at their base are fastened to foundation by anchored bolts. When the earthquake happens, anchored system existing in these tanks prevents moving upward and sliding. Because of the connection between this type of tanks and their foundations, overturning moment of the earthquake impacts on the foundation directly, and can cause it to be uplifted. For this reason, it is possible to use stanchion for foundation of the tanks. If anchored bolts are not enough strength against the earthquake force, they may break during the earthquake, and tank acts as an unanchored one. Anchored bolts should transfer vertical pressures caused by the earthquake on the tank wall to the foundation (American Petroleum Institute, 1998; ASCE, 1997).

2. The common damages of steel tanks

Studies on tanks performance, during past earthquakes, show that such systems are susceptible to widespread damages such as uplifting the bottom of tank; shell buckling, the roof and the upper section of shell damaging due to fluid swing sliding,

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overturning. A summary of the main damages in aboveground steel tanks will be as follows:

Fig. 1: Steel storage tanks and tanks damaged by the earthquake

2.1. Bottom of tank up lifting

When an unanchored tank is exposed to strong ground shaking, the overturning moments occurred by made hydrodynamic pressure, and its one side is up lifted unless the weight of the tank can be balanced and prevents uplifting during the overturning moment. The main difference between anchored and unanchored tanks behavior and occurring uplifting phenomenon causes unanchored tanks behavior to enter to the nonlinear stage. The effects of several parameters such as axial force existing on the tank bottom plate, the large deformations of the tanks wall, tank-soil-fluid interaction, large deformations of the tank wall caused by surface waves, membrane pressures In and bottom of the tank, shell geometric imperfections, and flexible foundation in the analysis of steel tank are considered to the process of complex uplifting phenomenon and its completed description. This phenomenon is resulted in several different factors. The high ratio of height to diameter, low thickness of wall of the tank bottom and shell thickness are effective factors in the damaging mechanism. The allowable uplifting amount in the unanchored tanks based on existing instructions has been limited to 30 cm. If the allowable amount exceeds, it will cause to rupture the tank wall, break input-output pipes, and centralize the wall tension in the local connection or subside the asymmetric of foundation (ASCE, 1997).

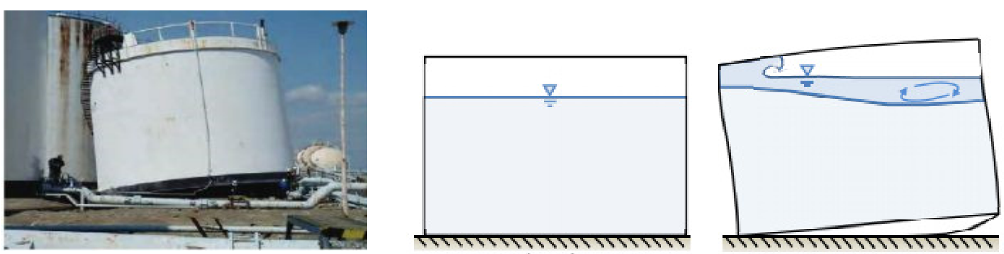

Fig. 2: The uplifting phenomenon of bottom of the tank

2.2. Shell buckling

Buckling Shell includes:

A) Elastic buckling (diamond wall) that caused by the compressive pressures made in the tank wall and in the middle part of the high altitude tanks.

B) Elastoplasts buckling (Pafili)that caused by the tensions resultant resulting from the tank overturning and uplifting power and annular tension caused by the hydrostatic pressure of the fluid at the height of 1.5m to 2.5mfrom the bottom of the tank.

To prevent elastic and Elastoplasts buckling damaging, increasing the compressive pressure created in the tank wall, and the excessive increasing of annular tension in the tank wall should be prevented, respectively. Therefore, this controls done by comparing these tensions with the amount of wall allowable pressures stated according to bylaws codes API650 With 0.9RnwhereRn is the flow resistance (American Petroleum Institute, 1998).

Fig. 3: Types of tank shell buckling

2.3. Tank asymmetric subsidence and slip

Collision between the bottom of the tank and foundation during earthquake causing doubled dynamic force makes subsidence the tank in consecutive swings. Based on existing instructions, the amount of allowable subsidence is limited to 5 cm. The shear force caused by the earthquake at the bottom level of the tank may overcome on the friction force between the tank bottoms and the foundation and cause to slip the tank. In order to control the tank against slip, foundation cutting is considered as a driving force and tank bottom friction force against the bed is considered as a counterpoise. According to the proposal of ASCE instructions, the minimum safety factor which is needed against the slipequals1.5. To calculate the counterpoise against the slip, the friction coefficient between the tank bottom and foundation is suggested equal to 0.4.This damage occurs more in tanks with diameters smaller than 9 meters (ASCE, 1997).

In many cases, the tanks are located in areas that are not suitable place to build a tank geotechnical. In the unanchored tanks or tanks have been incompletely anchored, and have solid foundation, failing in welds of the bottom of tank plates is expected. Therefore, earthquake acceleration causes that part of the tank in which the tensile force has been created to uplift. Sometimes the tank pouring out causes erosion in the tank foundation; therefore, the tank during the earthquake shows more undesirable behavior. A common failure here is the bottom of tank distortion near the tank wall, which can be occurred due to soil liquefaction, slopes instability or excessive subsidence. This damaging can be prevented by density of the soil of tank installation location and using widespread armed foundation under the tank. Tanks manufacture on flexible foundation is more suitable than their implement on a rigid foundation. Because the soft foundation causes the period of tanks vibration against the hydrodynamic forces to be prolonged (Haroun, 1983).

2.4. Damaged tanks foundation

Fig. 4: Foundation of cylindrical steel tanks

2.5. Overturning

Moment of overturning which is occurred as a result of the earthquake based on tank can cause part of the tank bottom plate to be uplifted, so seismic response of this type of tanks exits from the linear range, and enters to the non-linear phase. As shown in Table 2 and Fig. 1, with increasing height to diameter ratio of the tank, the overturn moment will be increased, so its stability will be reduced. That is due to the increase in the distance between the center of mass from the bottom. This criterion is controlled by using Appendix E from bylaws of API 650 and based on M/ D^2 (Wt+WL) ratio. In this the formula M is tank overturning moment on Newton meters, WL is the weight of the tank contents on perimeter length unit which resists against overturning, and Wt is the weight of wall plate in tank perimeter length unit on Newton meters. Thus, if the ratio is greater than 1.57, tanks will be unstable and overturned against loads (American Petroleum Institute, 1998).

2.6. Roof damaging

Vibratory force caused by the earthquake makes tank structure and the fluid in the tank vibrate; consequently, it makes waves in its fluid surface. Fluid vibration is happened when the frequency is much lower than the frequency of the wall, and vibration amplitude of fluid is affected by the frequency of earthquakes. Therefore, if these issues are not predicted, the tanks roof cover may be damaged or its contents are emptied out. If the free distance of the fluid is not enough, the structure will be damaged. In order to control the fluid volatility (sloshing) and the roof damage, fluid free height (Free board) can be increased, or the tank roof been forced. According to API 650 bylaws, the required free height is equivalent to 70% of the wave height. Sometimes because of failing the connection between the wall and the bottom of tank, or failing the pipe connected to the tank, tank fluid is depleted quickly; as a result, the rapid discharge of fluid above the fluid level makes partial vacuum which damages the roof and the upper part of the tank shell (Hasny et al., 2013).

Fig. 5: The roof and upper part of the tank shell damaging caused by sloshing phenomenon

3. Analytical study of affecting parameters in the tanks seismic behavior

3.1. Tank anchoring

Amount of the created pressures in crust is strongly influenced by anchored or unanchored. So that the numbers of the anchored tanks response against the unanchored tanks can be assumed negligible. In an anchored tank, wall relative vertical movement has been prevented at the foundation while for an unanchored tank which can be takeoff from the ground or foundation by the effect of severe shocks, a dynamic nonlinear analysis is needed to analyze it in detail. Sometimes the capacity of anchored system used in the tank is not sufficient to resist against earthquake loads; as a result, these tanks are vulnerable seismically. Large loads caused by earthquake often stretch out or break the anchored bolts. Damages of tank anchored system are in two forms: a) failure of the anchorage bolts connecting to the tank b) failure of the foundation concrete caused by coming out the anchored bolt of the foundation (Haroun, 1983).

Fig 6: Tank anchored bolts have been cut or coming out by the earthquake

3.2. Fluid amount inside the tank

One of the parameters that have a significant impact on the amount of damages on tanks is filling tank amount (pct Full). During past earthquakes, more than 70% of tanks that their filling amount is less than 0.5have not been damaged, but those tanks with 0.9filling amount has not suitable seismic behavior, and nearly 80 percent of them have been damaged. Thus, with increasing the amount of filling possibly more damages are expected (American Petroleum Institute, 1998).

3.3. Shell and the bottom of tank thickness

Shell design is based on the hydrostatic pressure of the fluid inside the tank and the lateral earthquake. Distribution of hydrostatic pressure in the tank height is triangular and in the depth Z, the tank is defined as (γ) z. Thus shell thickness in height is a variable, and while there is not possibility in linear changes for the thickness of the tank, its changes in height is in phases, in a way that the thickness at the bottom of the tank has a maximum value, and plate stability is provided by penetrable groove welds. Tank bottom plate is usually located on the soil bed and fluid pressure upward to the bed is neutralized by vertical pressure .In order to seal, the tank bottom plates are connected together by overlapped welding Designing the tanks plate based on loads of the earthquake using manual methods is very difficult and time-consuming in the same time. Therefore, initial thickness in designing the tank plates are estimated based on static relationships and structure is modeled by finite element software, and is controlled for the lateral loads; therefore, the efficiency of the selected designs is investigated by this procedure. Increasing the thickness of the tank shell reduces the amount of bottom of the tank uplifting and the values of the compressive pressure created in the shell (American Petroleum Institute, 1998; Hasny et al., 2013).

3.4. The effect of the ratio of height to diameter (H/D)

Seismic behavior of unanchored cylinder tanks and fluid storage greatly is influenced by the height to diameter ratio, so increasing (H/D) ratio makes the amount of uplifting in the bottom of the tank and overturning increased, and reduces pressure amounts (American Petroleum Institute, 1998).

4. The effect of interaction between soils, structure, fluid on the dynamic analysis of tank structures

At dynamic analysis of structures, it is generally assumed that the soil under the foundation is rigid and its flexibility is not considered. In this case, the structure response influenced by own dynamic properties of structure, and soil flexibility does not affect the structure response. Considering the soil flexibility in foundation, it is expected the structure response to be influenced by new dynamical system Soil-foundation and structure. Based on the calculations it can be said that considering the flexibility of the soil under the foundation has affect the dynamic response of structures, and influenced by soil type and the period time of the structure. In calculations, the force of earthquake on structure the backrest usually is assumed rigid and irreversible deformation, and flexibility of the soil under the structure is not considered; but observations and past experiences reveals this fact that the factor of the deformability of the soil in addition to change the properties of free movement of the earth on surface, it may change the structure response considerably against earthquakes due to structure interaction. The routine methods to analyze the soil-structure interaction (SSI) are classified in two ways: the direct method and under structure. In the direct method, soil and structure both are models and analysis is done in the one step. The soil often is classified with finite solid elements, and the structure with finite beam elements. In the under structure method, the issue of SSI is divided into three parts separate from each other, that are combined to solve the issue completely. Thus linear behavior is necessary for the soil and structure. One of the most important problems in the analysis of soil-structure interaction phenomenon is selection of an appropriate model for the soil. Combination model of a half-space and finite elements for modeling the soil in the dynamic analysis is appropriate. The most important objective of studying the interaction of structure soil is the impact of flexible foundation on the answer of tank structure. Modeling and seismic loading of the tanks using the methods introduced in the various by laws contains many defects, because evaluating the interaction between the fluid and tank during an earthquake cannot be expressed with static relationships. Therefore, using the complete dynamic analysis becomes necessary. In this regard, tank and water are modeled in Abaqus software using SOLID and SHELL elements. After defining the interaction between fluid and tank using accelerate grams with different energy content, models are dynamically analyzed. Dynamic analysis method (calculation of moment to moment reflections in tanks affected by accelerogram of real earthquake) can be used for all the tanks. In this method, reflections of tank in any time period during the earthquake is determined using the impact of the ground motion acceleration (Accelerogram) at the level of the tank base and the dynamic calculations. (Karimian, 2011; Wolf, 1997)

5. Results and suggestions:

1- How tanks are anchored heavily influences the compressive and annular pressure. Not to anchor the tanks causes increasing in the maximum of superficial waves of the fluid in the tank. This sensitivity for the tanks with the more filling is greater.

2- Increasing in the amount of filling the fluid inside the tank causes increasing the hydrodynamic forces on the tank walls and thus creating more pressure in the wall. Reducing the height of the fluid in the tank continuously causes reducing the compressive axial pressure in shell and hydrodynamic pressure caused by the earthquake; therefore, the damage during the earthquake is decreased. Besides, increasing the height of the fluid causes the distance between the total forces from the bottom of tank and thus creating a bigger moment of overturning and more uplifting the tank bottom plate.

3- With increasing height to diameter ratio, the amount of uplifting and the bottom of tank subsidence is increased. To prevent the tank structure from damaging, the height to diameter ratio should be limited by using existing bylaws.

4- With increasing diameter of the tanks, the amplitude of fluid fluctuation inside them (sloshing) is increased. To prevent damaging the roof, free height of the fluid must be at least 13% of the total height of the tank.

5- According to the effects of soil-structure interaction, it is suggested that, like ATC conditions, a set of relationships for considering the effect of soil and structures interactions (which is based on the modification of the dynamic properties of soil – structure system.) be added to the2800bylawof Iran. Increasing the flexibility of the bed soil causes increasing annular tension and decreasing axial pressures in the tank wall. Considering the effects of soil-structure interaction precisely may cause increasing in natural frequency period and thus reducing the earthquake coefficient in the design and cost reduction as well.

6- Using the bylaws such as API650 to evaluate the vulnerability and resisting the existed tank which has been developed for designing the new tanks can cause costly resisting designs because this bylaw is conservative. Because of the primary simple assumptions used in developing the bylaw relations of API650, it is necessary to revisit. For example, the relation of Appendix E of this bylaw has been obtained by assuming the tanks wall rigidity. Also, in order to calculate the resisting moment against the overturning in the unanchored tanks, the axial force in plate of the tank bottom is not considered, and equations without axial force on the plate of tank bottom are obtained.

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