EVALUATION OF THE LIQUID STORAGE TANK FAILURES IN THE 1999 KOCAELI EARTHQUAKE

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ABSTRACT :

Significant damages to liquid storage tanks have occurred during the 1999 Kocaeli earthquake. More than 30 of the floating-roof Naphta tanks have failed due to fires at the Tupras refinary and 2 elevated liquid oxygen tanks collapsed due to the failure of their reinforced concrete pedestals at the HABAS plant. This paper begins by outlining the mechanical analogue systems to be used for calculating the overturning moment and the base shear in tank wall as well as the free surface displacements for cylindrical tanks subjected to horizontal base excitation. Seismic responses of the floating-roof Naphta tanks at the Tupras refinary were analyzed using a Matlab scipt based on the mechanical analogue systems with the acceleration time-histories records collected from the site. Results of these analyses confirmed the excessive sloshing action. It was concluded that the frequency content of the base acceleration has a significant influence on the seismic response and that site-specific time-history records should be utilized in the design of critical tanks. Furthermore, it is pointed out that there is a need to check the reliability of existing tank farms, especially those built before the 70s, with the current codes of design.

KEYWORDS: Tank Damage Sloshing Kocaeli Earthquake

1. INTRODUCTION

The moment magnitude 7.4 Kocaeli, Turkey earthquake (08.17.1999, 3:02 A.M. local time) was one of the most devastating earthquakes to strike a densely populated industrial region in the last century. The cause of the earthquake was the right-lateral strike-slip rupture of the western branch of 1500 km long North Anatolian fault. Epicenter of the earthquake was 7 km southeast of Izmit and 80 km east of Istanbul. The earthquake originated at a shallow focal depth of 15.9 km and devastated the eastern Marmara Region, especially around the Gulf of Izmit, causing over 17000 fatalities. (USGS, 2000 and Saatcioglu et al, 2001). Many of the region's industrial facilities, including the refinaries and the chemical processing plants are located in the northern coast of the Gulf of Izmit which is in close proximity to the epicenter.

The most severe damage occured at the state owned Tupras refinary, which roughly accounts for one third of Turkey's oil production. Tupras refinary, located in Tutunciftlik district of Izmit, was built in 1961 and later expanded in 1974 and 1983. There are over 100 unanchored aboveground liquid storage tanks of various sizes in the tank farm, many of which have floating roofs (Bendimerad et al, 2000). Majority of the tanks were rendered inoperable due to buckling of tank walls, poor performance of floating roof systems and fire related damages. Many of the damaged floating roof tanks were designed according to the seismic design code of California in 1961 and had metallic roof seals. Excessive sloshing of the floating roof resulted in metal to metal contact between the tank wall and the metallic seals, causing sparks to ignite the highly volatile naptha fuel. Four naptha tanks with diameters of 20-25 m and two with diameters of 10 m were burned down (Hamada, 1999). The fire later spread to crude and product oil, jet fuel and gasoline tanks, damaging 30 of the 45 floating roof tanks in the crude and product oil storage area (Johnson, 2000).

Habas gas plant, located in Kosekoy district of Izmit, is a provider of liquified gas for regional commercial plants and medical facilities. Two of three identical cylindrical elevated liquid storage tanks were damaged due to failure of their support structures. Tanks were recently built in 1995 and had a double shell structure. Inside shell had a diameter of 12.80 m and the outer shell had a diameter of 14.63 m. The space between the shells were filled with insulation material. Structural support system for these tanks consisted of 1.07 m thick reinforced concrete slab that is supported by 16 identical circular columns with a diameter of 200 mm and a height of 2.54 m. Columns were reinforced with sixteen 16 mm diameter longitudinal bars and 8 mm diameter spiral ties with a spacing of 100 mm. The two damaged tanks were %85 full with liquid oxygen whereas the third tank was filled upto %25 with liquid nitrogen (Sezen and Whittaker, 2006) (Hamada, 1999).

The damage to industrial facilities had a significant impact on the economy, as direct losses due to damage to structures and indirect losses due to business interruption resulted in over 30 billion Dollars in financial damages (Sezen and Whittaker, 2006) (Saatcioglu et al, 2001). In addition to financial losses, significant amounts of hazardous materials were released into the environment, including the air release of 200 metric tons of anhydrous ammonia to avoid tank over-pressurization; the leakage of 6500 metric tons of acrylonitrile (ACN) from the ruptured tanks; the release of 1200 metric tons of cryogenic oxygen from the two damaged tanks at Habas facility and toxic smoke from the tank farm fires in Tupras facility that took several days to extinguish (Steinberg et al.,2000).

1.1. Mechanical Analogue Systems for Liquid Storage Tanks

Liquid storage tanks are considered as critical elements of infrastructure systems. These structures are mainly used to store fuel, industrial chemicals and water. Failure of fuel or industrial storage tanks following earthquakes may result in substantial environmental and financial damages. Correspondingly, breakdown of water storage tanks may lead to disruption of firefighting efforts and delivery of potable water to earthquake-affected regions (Jaiswal et al., 2004), (Koller and Malhotra, 2004).

Many liquid storage tanks have been damaged by strong ground motions. Observed performance of cylindrical liquid storage tanks indicate that tanks undergo several types of damages. The most characteristic type of damage is the circumferential protrusion near the base, commonly referred to as "elephant's foot" that can form due to large axial compressive stresses caused by beam-like bending of the tank wall (Koller and Malhotra, 2004). Hydrodynamic forces developed within the tank may damage the inner columns supporting the roof.

Excessive sloshing of the contained liquid may lead to buckling of the roof or upper portion of the tank wall in fixed roof tanks and failure of the roof seals in floating roof tanks. Uplifting of the tank due to overturning moments generated by the hydrodynamic forces may damage the anchor bolts, mantle-base plate interface and piping connections. Overturning moments may also lead to differential settlement of the tank foundation (Barros,2004).
Post-earthquake field studies in the early 60's revealed that seismic response is particularly influenced by the sloshing effects of the contained liquid and there is a need to develop reliable methods to analyze the hydrodynamic effects. Mechanical analogue systems have been developed to provide simple means to analyze the hydrodynamic forces caused by the complex tank-liquid-soil interaction at a reasonable level of accuracy. Housner developed one of first mechanical analogue systems to model the dynamic response of ground supported rectangular and cylindrical liquid tanks with rigid walls (Housner, 1963). The contained liquid is treated as incompressible and inviscid. Tank wall is considered to be rigid and sloshing displacements are assumed to be small. Two or more discrete masses are used to represent the contained liquid. The first mass known as the "impulsive mass" represents the bottom portion of the contained liquid that moves in unison with the tank wall. Top portion of the contained liquid responsible for sloshing is represented with "convective" masses attached to the tank wall with springs. Properties of the impulsive and convective components are derived using the equation for irrotational flow. For majority of tanks, impulsive component which usually has a vibration period of 0.5 s or less dominates the hydrodynamic pressures exerted on the tank wall while the long period convective modes mainly contribute to free-surface displacements caused by sloshing. Modelling capabilities of mechanical analytical have been extended in the last 40 years to account for tank wall-fluid-soil interaction and uplifting. Yang, presented a comprehensive overview of the hydrodynamic forces on tanks under certain wall deformation patterns and the vibrational response of empty tanks, as well as the application of those results to fluid-tank systems subjected to lateral base excitation (Yang, 1976). Wozniak and Mitchell, adapted Housner's model to oil tank design to be used in API 650 (Wozniak and Mitchell,1978). Housner and Haroun, developed a mechanical analogue system that takes into account the flexibility of the tank wall into consideration (Haroun, 1981). Veletsos also presented a mechanical analogue system for the analysis of flexible cylindrical tanks. Veletsos pointed out that the coupling between liquid sloshing modes and the shell vibrational modes is weak, therefore the convective pressure can be estimated with reasonable accuracy by considering the tank walls to be rigid (Veletsos, 1984). Veletsos and Tang, developed a mechanical analogue system that takes soil flexibility into account (Veletsos and Tang, 1992). Malhotra and Veletsos, developed a mechanical analogue system for the unanchored cylindrical tanks (Malhotra and Veletsos, 1994). Malhotra developed a simplified mechanical analogue system for the analysis of flexible cylindrical tanks (Malhotra, 2000). Ibrahim presented an extensive review of methods used in the analysis of sloshing effects within tanks of various geometries (Ibrahim, 2005).
The mechanical analogue system (Figure 1) proposed by Veletsos, (Veletsos, 1984) was used for calculating the overturning moment and the base shear in tank wall as well as the free surface displacements for this study. Although the naptha tanks in the Tupras tank farm were floating roof tanks, this model is expected to provide reasonably accurate results as the vibration period of the first convective mode which dominates the sloshing action is not significantly affected by the existance of the floating roof (Sakai et al., 1984).

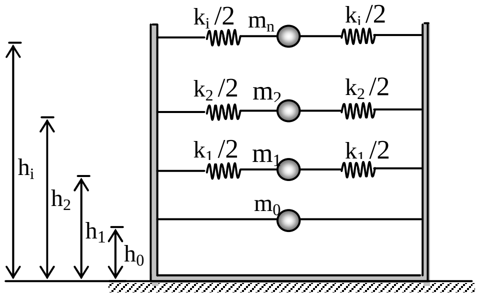

Figure 1 Mechanical analogue system used in the study (Veletsos, 1984)

Model properties of the impulsive and convective components can be extracted from equations derived by

Veletsos (Veletsos, 1984). In these equations, H and R represent the liquid height and the diameter of the tank while m_l represents the total mass of the liquid in the tank. I_1 and I_1' represent the Modified Bessel function of the first kind and first order and its first derivative respectively. Mass of the impulsive component can be calculated from equation (1.1) whereas its height can be calculated by (1.2) and (1.3) (Veletsos,1984).

$$m_0 = m_l \sum_{n=1}^{\infty} \frac{16}{\pi^3} \frac{H}{R} \frac{1}{(2n-1)^3} \frac{I_1\left[(2n-1)\frac{\pi}{2}\frac{R}{H}\right]}{I_1'\left[(2n-1)\frac{\pi}{2}\frac{R}{H}\right]} \tag{1.1}$$

$$h_0 = H \frac{\sum_{n=1}^{\infty}\left[1-\frac{2(-1)^{n+1}}{(2n-1)\pi}\right]\alpha_n}{\sum_{n=1}^{\infty}\alpha_n} \tag{1.2}$$

$$\alpha_n = \frac{16}{\pi^3} \frac{H}{R} \frac{1}{(2n-1)^3} \frac{I_1\left[(2n-1)\frac{\pi}{2}\frac{R}{H}\right]}{I_1'\left[(2n-1)\frac{\pi}{2}\frac{R}{H}\right]} \tag{1.3}$$

Convective masses can be calculated from equation (1.4) where m_j represents the mass of the jth convective mode and λ_j represents the jth root of the equation, $J_1'(\lambda) = 0$. J_1' represents the first derivative of a Bessel function of first type and first order (Veletsos, 1984).

$$m_j = \left[\frac{2}{\lambda_j^2 - 1} \frac{R}{\lambda_j H} \tanh\left(\lambda_j \frac{H}{R}\right)\right] m_l \tag{1.4}$$

Stiffnesses k_j and vibrational frequencies ω_j of the convective oscillators can be obtained from equations (1.5) and (1.6) where g represents the gravitational accelaration (Veletsos, 1984).

$$k_j = m_j \omega_j^2 \tag{1.5}$$

$$\omega_j^2 = \frac{\lambda_j g}{R} \tanh(\lambda_j \frac{H}{R}) \tag{1.6}$$

Heights of the convective masses to be used in the calculation of the overturning moments acting on the tank wall can be obtained from equation (1.7) (Veletsos, 1984).

$$h_j = \left[1 - \frac{R}{\lambda_j H} \tanh\left(\frac{\lambda_j}{2} \frac{H}{R}\right)\right] H \tag{1.7}$$

Base shear acting on the tank wall at an arbitrary time t can be calculated with equation (1.8) where $A_j(t)$ given by equation (1.9) represents the temporal variation of acceleration response of the convective oscillators (Veletsos, 1984).

$$Q(t) = m_0 \ddot{u}_b(t) + \sum_{j=1}^{\infty} m_j A_j(t) \tag{1.8}$$

$$A_j(t) = \omega_j \int_0^t \ddot{u}_b(\tau) \sin[\omega_j (t-\tau)] d\tau \tag{1.9}$$

Maximum value of the base shear acting on the can be estimated by adding the maximum impulsive base shear to SRSS of the maximum convective base shears (1.10). In equation (1.10) $\ddot{u}_{b,\max}$ represents the maximum acceleration of the tank base and A_j represents the maximum acceleration response of the jth convective oscillator (Veletsos, 1984).

$$Q_{\max} = m_0 \ddot{u}_{b,\max} + \sqrt{\sum_{j=1}^{\infty} [m_j A_j]^2} \tag{1.10}$$

Temporal variation of the overturning moment acting on the tank wall and its maximum value can be estimated with (1.11) and (1.12) in a similar fashion.

$$M(t) = m_0 h_0 \ddot{u}_b(t) + \sum_{j=1}^{\infty} m_j h_j A_j(t) \tag{1.11}$$

$$M_{\max} = m_0 h_0 \ddot{u}_{b,\max} + \sqrt{\sum_{j=1}^{\infty} (m_j h_j A_j)^2} \tag{1.12}$$

Maximum value of the free surface liquid displacement is used to estimate the freeboard height and can be estimated with equation (1.13) (Veletsos, 1984).

$$d_{\max} = R \sqrt{\sum_{j=1}^{\infty} \left(\frac{2}{\lambda_j^2 - 1} \frac{A_j}{g} \right)^2} \tag{1.13}$$

2. ANALYSIS

Diameters of the Naphta tanks that were burnt down in the Tupras tank farm varied between 20 m to 25 m. A representative tank with a diameter of 25 m, assumed to be filled upto 12 m with Naptha fuel and having a freeboard height of 80 cm was used in the analysis. Density of the Naptha was taken as 800 kg/m^3 for the calculation of the total liquid mass in the tank. The temporal variation of the sloshing displacement was calculated using the local IZT090, YPT060 and YPT330 base acceleration records and presented in figure 1. Peak values of acceleration, velocity and displacement for these are presented in table 1.

Table 1. Peak values of acceleration, velocity and displacement for IZT090, YPT060 and YPT330 records

Record	PGA (g)	PGV (cm/s)	PGD (cm)
IZT090	0.22	29.8	17.2
YPT060	0.268	65.7	57.01
YPT330	0.349	62.1	50.97

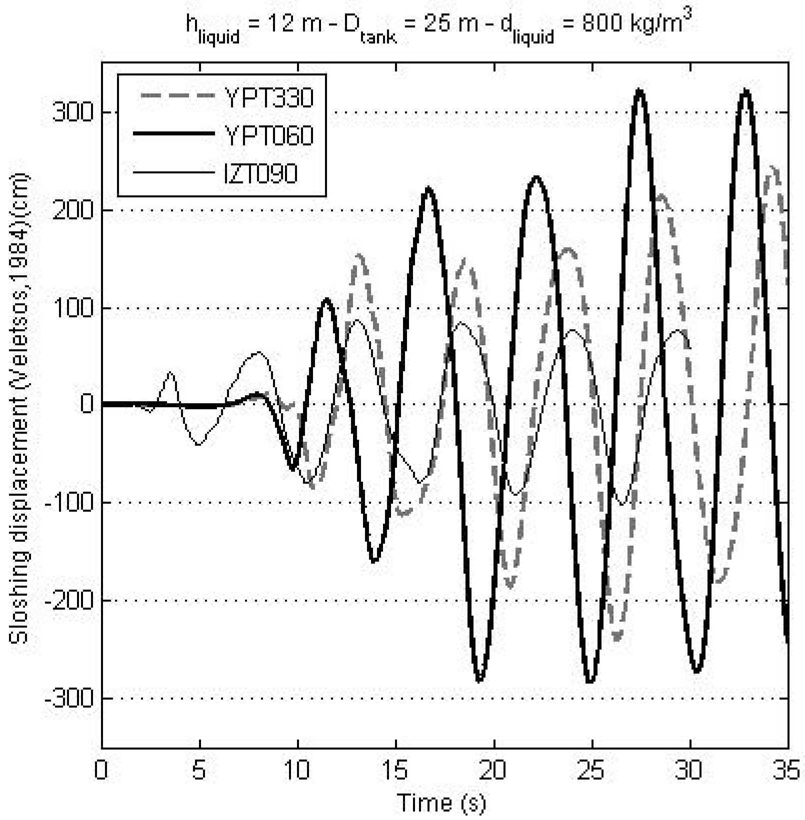

Figure 2 Sloshing displacements for YPT330, YPT060 and IZT090 acceleration records

It is easily observed from Figure 2 that the sloshing displacements are over the normal freeboard height tolerances for the Izmit (IZT) record and quite excessive for the Yarimca (YPT) records. Although the PGA for the YPT060 acceleration record is only 0.268g, sloshing displacements exceeded 300 centimeters.

In order to compare the results from records with the same PGA, the analysis was repeated for the scaled acceleration time-histories (0.40g) using the 1940 Imperial Valley Earthquake (1940) El Centro (EW), 1992 Erzincan earthquake, Erzincan (EW) and 1999 Kocaeli Earthquake, Yarimca, (NS) records. Temporal variation of the sloshing displacements for the scaled base acceleration records are presented in Figure 3. Peak values of acceleration, velocity and displacement for the scaled base acceleration records are presented in table 2.

Table 2. Peak values of acceleration, velocity and displacement for the scaled acceleration records

Scaled Record	PGA (g)	PGV (cm/s)	PGD (cm)
El Centro 1940 EW	0.40	37.96	16.67
Erzincan 1992 EW	0.40	51.89	17.70
Yarimca 1999 NS	0.40	98.24	85.24

Sloshing displacements obtained from the scaled El Centro, Yarimca and Erzincan acceleration records clearly indicate that PGA of an earthquake acceleration record alone is not enough to predict the effects of the sloshing action.

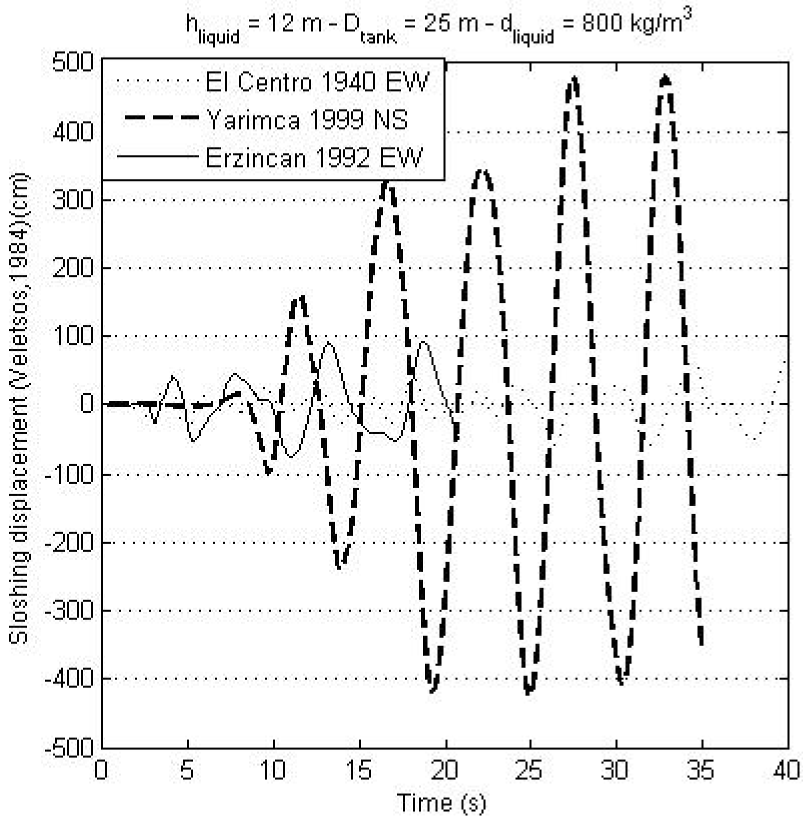

Figure 2 Sloshing displacements for the El Centro, Yarimca and Erzincan acceleration records scaled to 0.40g

3. CONCLUSIONS

Seismic responses of the floating-roof Naphta tanks at the Tupras refinary were analyzed using a Matlab scipt based on the mechanical analogue systems with the acceleration time-histories records collected from the site. Results of these analyses confirmed the excessive sloshing action. It was concluded that the frequency content of the base acceleration has a significant influence on the seismic response and that site-specific time-history records should be utilized in the design of critical tanks. Even with the limited number of records used in the study, it is seen that the PGD and PGV also needs to be taken into account when assessing the sloshing action of liquid storage tanks.

It should be pointed out that the facilities in the Tupras refinary and majority of the industrial facilities in the region were designed and operated according to internationally accepted codes of practice of their time. Therefore, there is a need to check the reliability of existing tank farms, especially those built before the 70s, with the current codes of design.

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