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Seismic Performance Evaluation and Retrofit of Liquid Storage Tanks-Case Study

Bülent ERKMEN*[1]

Abstract

Seismic performance of existing liquid pentane storage tanks located in a tank farm in Turkey Kocaeli region, which is a high seismic region, is studied. The tanks are free-to-slide on their existing reinforced concrete foundation. The tanks seismic performance is evaluated based on the 2018-Turkish Building Seismic Code and API 650 provisions using three-dimensional (3D) finite element methods with nonlinear time-history analysis. The developed FE model for seismic performance assessment of the existing tanks includes tank-foundation dynamic interaction, tank supports uplifting, and sliding over the foundation. The study revealed poor and inadequate seismic performance for the existing tanks due to lack of tank foundation-anchorage. A practical seismic retrofit strategy is developed to anchor the tanks to the existing reinforced concrete foundation. Prefabricated and field-welding free steel split sleeves are developed for the tank anchorage. The retrofitted tank seismic performance is evaluated to verify the proposed retrofit strategy and its effects on tank seismic behavior. The base shear and uplift reactions for the retrofitted tank are monitored for the anchorage design. Tank top drift, which is an important seismic performance parameter for tank piping, and tank steel material yielding are also checked to verify adequacy of the proposed retrofit strategy.

Keywords: Liquid storage tanks, tank sliding, tank uplift, seismic

1. INTRODUCTION

This paper presents seismic performance evaluation of existing liquid pentane storage tanks located in a tank farm in Kocaeli region of Turkey and their seismic retrofit. The tank location is a high seismic region hit by the 1999 Kocaeli earthquake, which caused severe damage to the industrial facilities and liquid storage tanks as well as devastating fires in the region. Liquid-storage tanks are crucial part of the modern industrial facilities. Therefore, liquid-storage tanks filled with hazardous liquids such as oil, oil derived products, chemicals, petrochemical, and food processing liquids are in widespread. Failure of such tanks has frequently resulted in spillage of toxic material with disastrous effects and fires following explosions as occurred following the 1994 Northridge, the 1995 Kobe, 1999 Kocaeli, and the 2011 Eastern Japan earthquakes [1-3]. Therefore, when such tanks are located in earthquake prone regions, they should remain functional, or the damage should be at acceptable levels after earthquakes [4-6].

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Liquid storage tanks seismic design provisions in current design codes such as API 650 [5], Turkish Code [6], and Eurocode 8 [7] are based on a mechanical spring-mass analogy developed by Graham and Rodriguez [8], Jacobsen [9], and Housner [10] for rigid tanks; and modified by Haroun and Housner [11] for flexible tanks. The mechanical model also known as spring-mass model shown in Figure 1 is based on liquid behavior under seismic loads. The part of the liquid located in the lower part of the tank, which is called impulsive component, is assumed to move with the tank under seismic loads. This component typically has natural period of vibration (T_i) in the range of 0.1 to 0.4 seconds [8, 8, 12]. The other part of the liquid located in the upper part of the tank is called convective component, and it is assumed to freely vibrate to form liquid sloshing in the tank during seismic loading. The convective component has longer natural period of vibration (T_c) between 3 and 10 seconds depending on the tank dimensions and liquid level [4, 5, 12].

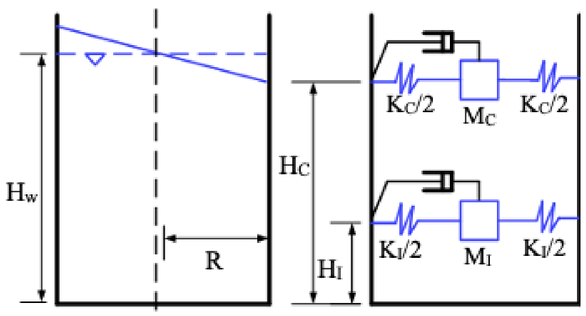

Figure 1 Spring-mass model for liquid storage tanks

Seismic behavior of liquid storage tanks is very complex due to liquid-structure dynamic interaction, liquid sloshing, and tank foundation interaction. The mechanical spring-mass tank model considerably simplifies computation of liquid storage tanks seismic behavior. Although this modelling approach is not sufficient to monitor change in the liquid level and liquid-structure interaction due to liquid sloshing, the approach is computationally cheap, simple to develop, and adequate for the main objective of this study [13-17].

The spring-mass model for the pentane tanks is developed using API 650 seismic provision [5]. The required parameters, which are shown in Figure 1, are the convective (M_C) and impulsive mass (M_I) values of the liquid, the elevations (H_I and H_C) at which they should be connected to the tank walls, and the spring constants for both masses. The damping for tanks has generally been assumed to be at the order of 0.5% for convective and 2-5% for impulsive modes.

This paper discusses seismic performance of liquid pentane tanks located in an industrial facility in Kocaeli region. The region is seismically active with large earthquakes, and the tank farm is in the vicinity of the North Anatolian fault. The tanks were post-installed on an existing concrete mat foundation, which was designed and provided to support various liquid storage tanks. Because the pentane tanks are post-installed, they are not anchored to the existing foundation. In other words, the tanks rest on the foundation, and they are free to slide and uplift. Seismic performance evaluation of the tanks showed that their seismic performance is not adequate due to tank structural damage resulting from tank sliding and uplifting. Therefore, a practical seismic retrofit strategy is developed to anchor the tanks to the existing reinforced concrete foundation. For this, prefabricated and field-welding free steel split sleeves are developed for the tank anchorage due to welding restrictions and explosion/fire risks at the facility. The study compares seismic performance of the tanks before and after the retrofitting. A simple and effective post anchorage detail is presented, which can be employed where such tanks need to be installed on existing foundations.

2. EXISTING AND UPGRADED PENTAN TANKS

A general view and dimensions of the pentane tanks are given in Figure 2. The tanks are vertical cylindrical type with a diameter of 382 cm and a total height of 1195 cm. The tanks are supported with six stand-supports, which are made of 36 cm diameter steel pipe with a wall thickness of 9.5 mm. The tank shell thickness is 10 mm for top end-dome and cylindrical part and 14 mm for the bottom end-dome. The steel grade used for the tanks is S235, which is one of the typical steel grades used for fabrication of liquid storage tanks.

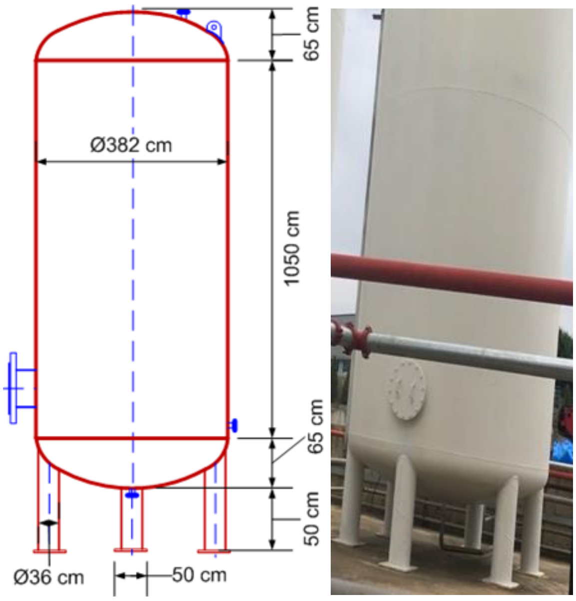

Figure 2 Dimension and overall view of pentane tank

The six stand-supports of the tanks are provided with a 20 mm thick 50 cm by 50 cm square base plate, but these plates are not anchored to the concrete foundation. In other words, the tanks rest on the foundation, and are free to slide and uplift from the foundation. In general, liquid storage tanks located in zones of high seismicity are recommended to be anchored if the ratio of safe operating height (*H*) to tank diameter (*D*) exceeds 2.0 to prevent tank uplift, overturning, and sliding [5, 12]. The pentane tanks are post-installed at the farm on an existing concrete foundation as a part of facility production expansion program. Therefore, anchorage of the tanks to the existing foundation was likely abandoned due to complications involved during expansion program.

Tanks seismic performance, which is discussed in the following sections, was found to be inadequate due to tank damage, large support uplift, sliding on the foundation, and tank overturning. Tank anchorage to the foundation was done through six stand-supports of the tank as shown in Figure 2. Each tank support is provided with a two-piece prefabricated steel split sleeves as shown in Figure 3. The sleeves are easy to fabricate and do field installation without requirement for field welding. The field welding is not permitted since it poses a risk of fire and explosion. Each sleeve is clamped to the tank stand-supports to transfer the shear and axial uplift forces. The split sleeves are connected to the reinforced concrete mat foundation through four Hilti M27 anchors. The anchors are connected to the foundation using Hilti HIT-RE 500 V4 injectable epoxy. The selected epoxy is heavy duty and suitable for seismic applications.

(a)

(b)

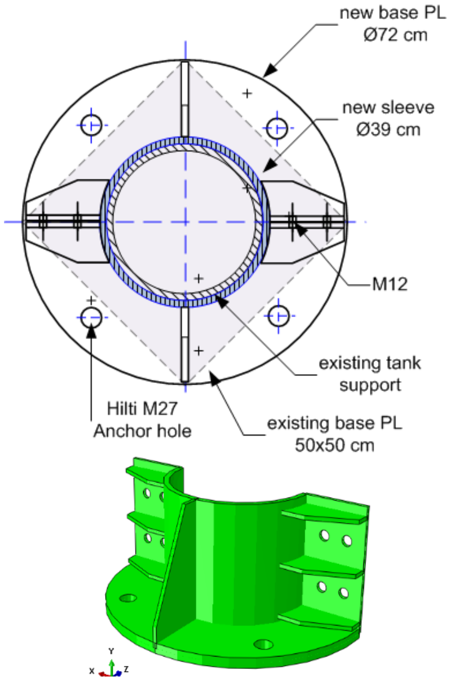

Figure 3 (a) Plane view and (b) 3D view of split sleeve

2.1. Site Seismicity and Selected Ground Motions

The tank farm is located in Kocaeli industrial region, which is a seismically active region with large earthquakes. The tank farm site has very tight layers of sand, gravel and hard clay based on the site soil report. Therefore, it is classified as site class ZC according to the 2018-Turkish Building Seismic Code (TBDY) [18]. The site has peak ground acceleration (PGA) of 0.556*g* and peak ground velocity of 40.7 cm/s per Turkey Earthquake Risk Maps (AFAD) [19] for earthquake level DD2, which has a 10% probability to be exceeded in 50 years. The site 5% damped design spectrum shown in Figure 4 has acceleration parameters for the short period (S_{DS}) equal to 1.614*g* and at period of 1 second (S_{D1}) equal to 0.551*g* per AFAD.

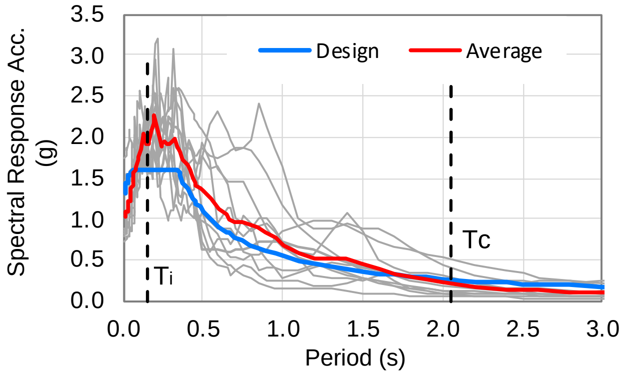

Figure 4 Design and average response spectrum

A set of 12 ground acceleration records given in Table 1 are selected from the Pacific Earthquake Engineering Research (PEER) Center database [20] to be used for nonlinear time history analyses of the tank. The number of records and selection are consistent with TBDY recommendations. The selected earthquake records include data from the tank location as well as other near-fault records since the farm is located in the vicinity of Main Marmara Fault. The selected ground motions are scaled to match the design spectrum for the site as shown in Figure 4. The ground motions are scaled so that their average spectrum will be above the design spectrum for period range between tank impulsive period T_i and liquid convective period T_c.

Table 1 Selected ground motions

Ground motion	Name	Year	Station	Dist.(1)
GM1	Helena Montana	1935	Car. College	2.9
GM2	Victoria Mexico	1980	Cerro Prieto	14.4
GM3	Morgan Hill	1984	Lake Dam	0.5
GM4	Duzce Turkey	1999	Lamont 375	3.9
GM5	Chi-chi Taiwan	1999	CHY074	6.2
GM6	Tottori Japan	2000	TTR007	11.3
GM7	Bam Iran	2003	Bam	1.7
GM8	Parkfield CA	2004	Cholame 4W	4.2
GM9	Big Bear	1992	Fire Sta #36	41.9
GM10	Joushua Tree CA	1992	Fire Sta #36	22.0
GM11	Duzce Turkey	1999	Irigm 498	3.6

(1) closest distance to earthquake generating fault in km.

3. TANK FINITE ELEMENT MODEL

Tank finite element (FE) model is developed using general purpose finite element program ABAQUS [21], which is selected for its computational efficiency for modelling nonlinear contact as well as its stability for nonlinear time history analysis. The FE model includes tank sliding and uplifting (separation) interactions with the foundation under dynamic loading. The model is developed based on the impulsive and convective liquid parameters given in Table 2. The required parameters for the liquid are computed using API 650 guidelines, and include mass, the distance between the bottom of the shell and the center of the lateral seismic forces, and periods of vibration for each liquid component.

Table 2 Tank modelling parameters

Parameter	Value
Operating liquid height	8.5 m
Liquid density	625 kg/m^3
Liquid mass	64366 kg
Impulsive liquid mass (M_I)	58073 kg
Convective liquid mass (M_C)	6293 kg
Impulsive mass height (H_I)	3.8 m
Convective mass height (H_C)	7.5 m
Impulsive liquid period (T_i)	0.15 sec
Convective liquid mass (T_c)	2.05 sec

The developed FE model is shown in Figure 5. The model includes 3D tank model, the six stand-supports and their square base plates, and the foundation to properly model tank-foundation contact interaction. The tank and foundation are modelled using S4R shell element, which is a 4-node general-purpose shell element with reduced integration. The element is suitable for large strain analyses of both thin and thick shells. Typical S235 steel material properties are assumed for the tank. The yield (f_y) and ultimate strengths (f_u) are taken as 235 MPa and 360 MPa, respectively. The Young's modulus and Poisson's ratio are taken as 210000 MPa and 0.3, respectively. The reinforced concrete foundation is assumed to be elastic with typical C30 concrete material properties.

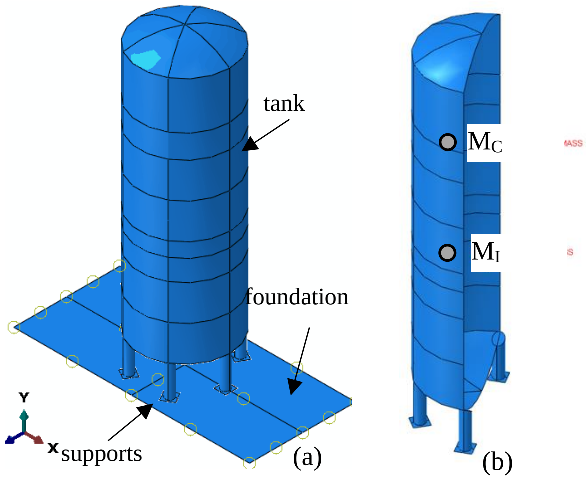

Figure 5 (a) FE model general view and (b) attachment of liquid masses

The impulsive and convective liquid masses are connected to the tank wall through elastic springs and coupling constraint (Figure 5b). For this purpose, two reference points were defined for each mass at the same point (H_I and H_C). The first reference point was connected to the tank shell using coupling constraint while the second reference point was assigned point mass and connected to the first reference point with the elastic spring. The spring stiffness was calculated for each mass to have the corresponding vibration periods T_i and T_c.

For boundary conditions, the reference points are allowed to move only in the direction of applied ground acceleration and restrained for other degrees of freedom. The tank foundation is assumed to be fixed for all displacement degrees of freedom except for the acceleration degree of freedom in the direction of earthquake records (i.e., global X-direction). The earthquake acceleration history is defined as the boundary condition for the tank foundation. The dynamic interaction between the tank base plates and its foundation is defined through contact formulation, which allows contact separation of surfaces. The static and dynamic friction coefficients between the two surfaces are taken as 0.57 [22].

Because tank liquid content is not modelled explicitly, the hydrodynamic pressure on the tank inner surface is modelled as initial pressure-loading as given in Figure 6. The gravity loads due to tanks self-weight and hydrodynamic pressure were applied to the model at a static analysis step, which was followed by the dynamic explicit time-history analysis step for earthquake loading. The vertical component of ground motions is considered as a static load acting in the opposite direction of the gravity. The vertical seismic acceleration is conservatively taken as $0.67S_{DS}$ per TBDY [18] while API 650 recommended acceleration value is $0.47S_{DS}$. The explicit dynamic analysis is selected for high nonlinearity due to tank sliding over the foundation and uplifting of tank supports. The whole model is meshed with shell elements, and a nominal mesh size of 25 cm is used for the tank and its foundation as shown in Figure 6b.

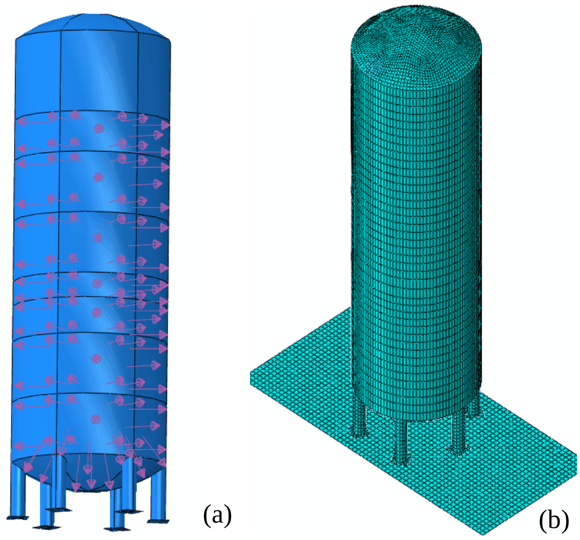

Figure 6 (a) Application of hydrodynamic pressures and (b) FE mesh

The seismic performance of the existing tanks is found to be inadequate mainly due to tank not having any foundation anchorage. Therefore, tank six stand-supports are anchored to the foundation through steel split sleeves as a part of the proposed retrofit scheme. The split-sleeves are fixed to the foundation with four Hilti M27 anchors and HIT-RE 500 V4 injectable epoxy. The same finite element model of the tank is used for the retrofitted tanks. However, the foundation is removed from the model since the retrofitted tanks are anchored to the foundation. In addition, the boundary condition of the tank supports is changed to pin-pin support. The new support condition is defined using a reference point for each support, and tank support base plate bottom surface is coupled to this reference point for all degrees of freedom as shown in Figure 7. The earthquake acceleration history is applied to the six reference points at the same time.

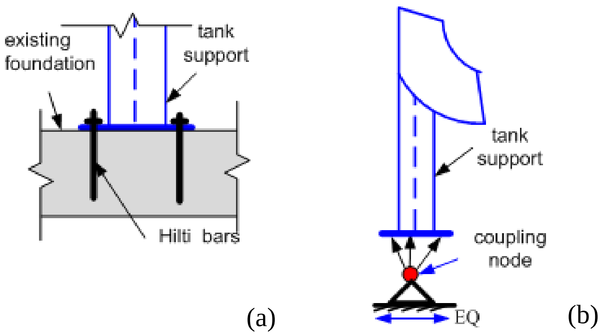

Figure 7 Retrofitted tank (a) foundation anchorage and (b) updated boundary condition

4. RESULTS AND DISCUSSIONS

The seismic performance evaluation of the tanks is based on time-history analyses performed using 12 scaled earthquake records. A summary of both existing and retrofitted tank seismic performance parameters is given in Table 3. The seismic performance of the tank is evaluated based on tank relative roof displacement, support uplift, tank overturning, retrofitted tank support reactions, and tank material damage.

Table 3 Summary of seismic performance

	Existing Tank		Upgraded Tank		
Ground motion	δ_{Roof} (mm)	Δ_{SPRT}[2] (mm)	δ_{Roof} (mm)	Support tension (kN)	Shear (kN)
GM1	263	64	57	331	92
GM2	x[1]	x	137	475	126
GM3	x	x	246	531	140
GM4	121	21	59	348	93
GM5	x	x	182	515	141
GM6	103	22	97	407	118
GM7	244	59	99	464	115
GM8	x	x	252	575	139
GM9	x	x	135	466	132
GM10	258	63	66	362	100
GM11	210	50	79	405	107
AVRG	200	47	128	444	118

(1) x shows tank failure due to tanks overturning.
(2) support maximum uplifting.

Because the existing tank is not anchored to the foundation, tank overturning occurred due to seismic loads for five earthquake records as given in Table 3. The main reason for the tank failure is the fact that tank supports are not anchored to the foundation and tank being free to slide over the foundation. Figure 8 shows tank displacements during earthquake loading. Tank supports uplifted from the foundation due to lateral seismic loads, and tank remained supported only by one or two supports as shown in Figure 8. The total seismic base shear is carried by these few supports, which bended as shown in Figure 8. At the locations where the supports are connected to the tank main body large material yielding and damage are observed as shown by the equivalent plastic strain (PEEQ) contours in Figure 9 due to bending of these supports.

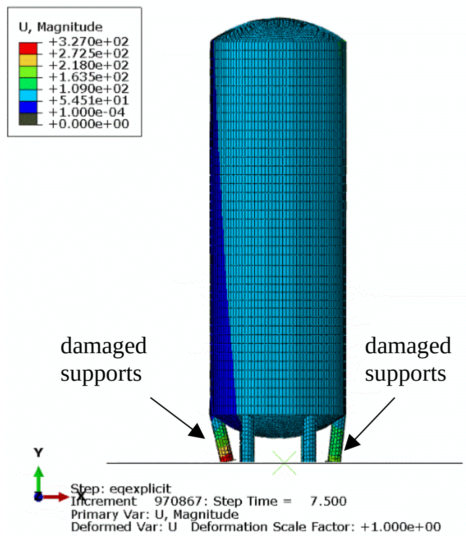

Figure 8 Tank support displacement and damage

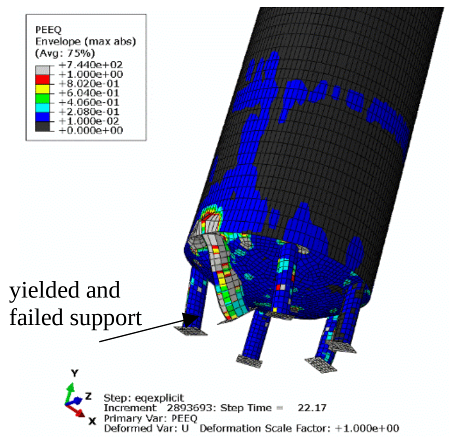

Figure 9 Tank support failure and material yielding

For the earthquake records that do not cause tank overturning failure, tank roof maximum relative displacement (δ_{Roof}) is between 103 mm and 263 mm with an average value of 200 mm. The average relative tank top displacement of 200 mm is still considered to be large to prevent piping damage, which will cause liquid spillage after earthquakes. In addition, tank sliding over the foundation is another important performance criteria for tank piping connected to the foundation. For example, tank sliding over the foundation under GM9 is more than 1 m before its collapse due to overturning. In summary, it is concluded that the existing tanks need to be anchored to the foundation to limit their displacement, damage, and overturning failure.

Seismic evaluation of the tanks shows the need for seismic strengthening for their foundation anchorage. Tanks six stand-supports are anchored to the foundation using two-piece split sleeves and four M27 anchors with injectable epoxy. To determine design requirements for the anchorage system and its effects on tank seismic behavior, the nonlinear time-history analyses of the tank are repeated with the updated boundary conditions. The maximum support tension and shear reaction forces are given in Table 3. The maximum shear and tension reaction forces occurred at different supports. The maximum tension force is between 331 kN and 575 kN with an average value of 444 kN. The maximum shear force is between 92 kN and 141 kN with an average value of 118 kN. The tank anchorage system is designed for these average reaction forces.

The maximum support tension and shear reactions occurred under GM8 and GM5 earthquakes, respectively. Tank support tension and shear reactions time-history curves are given in Figure 10 and Figure 11, respectively. Anchoring the tank to the foundation improved its seismic performance by distributing the shear reaction force to all supports and limiting tank lateral displacements. Tank roof lateral displacement in the earthquake direction decreased significantly due to tank anchorage to the foundation. The displacement is between 57 mm and 252 mm with an average value of 128 mm as given in Table 3. These displacement values are more acceptable for tank piping to prevent piping failure, liquid content spillage, and fire during earthquakes.

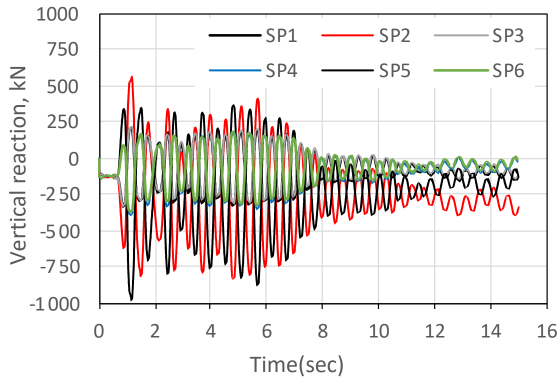

Figure 10 Supports vertical reaction history under GM8

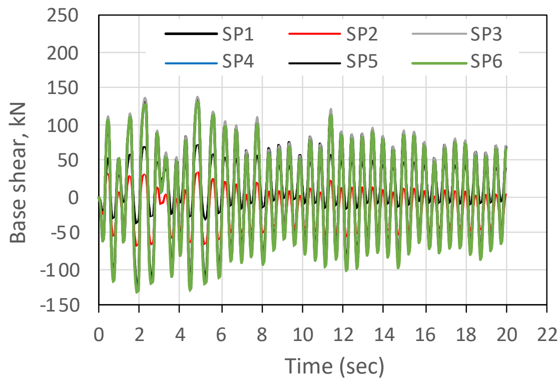

Figure 11 Supports shear reaction history under GM5

Figure 12 shows tank shell material yielding under GM8 earthquake, which creates the largest tension forces for the tank supports. The results show that tank main body and supports remain damage free (elastic) under the given earthquake. Tank bottom end-dome, where the supports are attached to the tank main body, experiences some material yielding. However, the equivalent plastic strain (i.e., PEEQ) values are less than 12%. In addition, the large values of PEEQ are only observed over a small area, where stress concentration occurs due to meshing and modelling in tank support and main body connection regions.

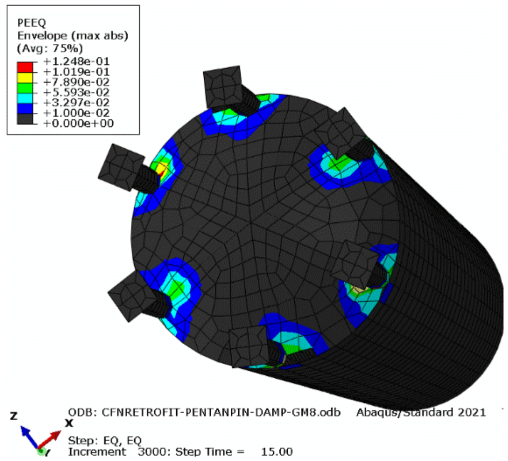

Figure 12 Anchored tank yielding and PEEQ contours

5. CONCLUSIONS

Seismic behavior of liquid pentane tanks located in a high seismic region of Turkey is studied using 3D nonlinear time-history analyses using 12 recorded ground motions. It is demonstrated that not having any tank anchorage-to-foundation has significant effects on tank seismic behavior including support uplift, tank sliding, material damage, and failure due to tank overturning. The tanks failed due to overturning for 5 ground motions out of 12 records selected for time-history analyses. In addition, the tanks experienced significant damage due to supports of the tank uplifting and sliding over the foundation.

A simple two-piece prefabricated steel split sleeve, which is easy to prefabricate and suitable for field installation without any field welding, is developed for tank foundation anchorage. The seismic design for the sleeve connection to the foundation is done by repeating the nonlinear time-history analyses of the tanks. The retrofitted tanks have significantly improved seismic behavior without any tank failure. Tank roof displacement decreased to 128 mm on average, which is tolerable for tank piping to remain intake after potential earthquakes. In addition, tank shell yielding is limited to a small area, where supports are connected to the tank main body. This study highlights the importance of seismic evaluation of existing liquid storage tanks, and presents a practical seismic retrofit strategy developed to anchor such tanks to existing reinforced concrete foundations.

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The Declaration of Conflict of Interest/ Common Interest

No conflict of interest or common interest has been declared by the authors.

Authors' Contribution

The first author B. E. contributed 100%.

The Declaration of Ethics Committee Approval

This study does not require ethics committee permission or any special permission

The Declaration of Research and Publication Ethics

The authors of the paper declare that they comply with the scientific, ethical and quotation rules of SAUJS in all processes of the paper and that they do not make any falsification on the data collected. In addition, they declare that Sakarya University Journal of Science and its editorial board have no responsibility for any ethical violations that may be encountered, and that this study has not been evaluated in any academic publication environment other than Sakarya University Journal of Science.

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