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EVALUATION OF CODE PROVISIONS FOR SEISMIC PERFORMANCE OF UNACHORED LIQUID STORAGE TANKS

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Abstract.

Seismic performance of two unanchored liquid-storage tanks with tank diameter of 24.5 m and 36 m and operating liquid height of 12.2 m and 20.0 m, respectively were investigated using Coupled Eulerian-Lagrangian (CEL) and mechanical spring-mass analogy nonlinear finite element computational methods. The CEL approach includes the effects of higher modes of liquid vibration (sloshing), liquid breaking effects, and liquid-structure interaction during seismic loading. The modern seismic design provisions for liquid-storage tanks, on the other hand, are based on a mechanical spring-mass analogy. This approach neglects the higher vibration modes for the sloshing water, liquid-structure interaction, and effects of tank base uplift on seismic performance. For the tanks, base uplift histories were computed with both modeling approaches through nonlinear time history analysis performed using five recorded earthquake acceleration data. The uplift histories were compared to evaluate the adequacy of code seismic design provisions for unanchored tanks, and to determine whether the mechanical spring-mass analogy can be used to predict seismic performance of unanchored tanks.

Analysis results show that the traditional mechanical spring-mass analogy, which is the basis for the current seismic design provisions, does not capture tank uplift history and its effects on dynamic loads. This approach underpredicts the total numbers of tank uplifts during seismic loading. The maximum tank base uplift computed using mechanical spring-mass analogy had an average error between 22% and 58 % for each tank. The results show that there is a need to developed a modify version of the traditional mechanical spring-mass analogy to be used for predicting seismic performance of unanchored liquid-storage tanks.

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1 INTRODUCTION

At grade liquid-storage tanks are crucial parts of modern industrial facilities and public water supply system. Liquid-storage tanks filled with hazardous liquids such as oil, oil derived products, chemicals and food processing liquids are widespread throughout the world. Failure of at grade liquid-storage tanks has frequently resulted in spillage of toxic materials with disastrous effects and fires following terrifying explosions as occurred, for example, following the 1994 Northridge, the 1995 Hanshin (Kobe), and the 2011 Eastern Japan earthquakes [1]. In addition, such tanks are crucial to provide safe drinking water and reliable water supply for firefighting immediately following destructive earthquakes to limit fire related post-earthquake damage and avoid outbreak of diseases. Therefore, when such tanks are located in earthquake prone regions, they should be designed to survive earthquake effects and remain functional after earthquakes. In other words, seismic performance of liquid storage tanks is a matter of special importance, extending beyond the economic value of the tanks and its contents.

At grade liquid storage tanks depending on their base fixity fall into two categories: (1) anchored and (2) unanchored tanks. A fixed base tank requires a substantial foundation and attachment mechanism in the form of bolts to carry the considerable overturning moment that occurs due to seismic loads. Therefore, because of the cost, large liquid-storage tanks are often not fixed to their foundation even in seismic areas. During earthquakes, all mass of unanchored tanks and its content contribute to the overturning moment while only a small portion of the mass contributes to the overturning resistance. Therefore, unanchored steel tanks are especially susceptible to damage during earthquakes.

The seismic response of unanchored tanks during earthquakes is highly nonlinear and much more complex than that implied in the design standards. Especially tank-base uplift provisions proposed by the current codes such as API 650 [2] and Eurocode 8 [3] are based on a mechanical spring-mass analogy, which has little technical verification for its applicability for unanchored tanks. The tank base-plate uplift is a function of tank size, tank aspect ratio (liquid height to tank dimeter ratio), liquid height, tank foundation, local seismicity, and tank site soil type. However, none of the current tank seismic design provisions reflect the effects of all these parameters in calculation of tank-base uplift and its effects.

The seismic behaviour of anchored liquid-storage tanks is well established [4]. A large number of experimental and theoretical studies have been conducted on dynamic response of liquid-storage tanks. However, most of these studies have focused mainly on the response of anchored tanks [5, 6, 7, 8, 9, 10, 11, 12, 13, and 14], of which no separation of the tank shell base from the foundation is considered. However, the seismic behaviour of unanchored tanks is not truly studied and reliable guidance on predicting tank base uplift, tank behaviour, and water sloshing are not well understood and documented. The dynamic behaviour of unanchored tanks is significantly different from that of anchored tanks since the assumptions of symmetric and asymmetric behaviour of the tank shell are no longer valid due to separation of the tank base from its foundation. In addition, the effect of tank base uplift on liquid-tank integration and seismic performance of the tank is not well documented.

2 LIQUID-STORAGE TANK SEISMIC DESIGN PROVISIONS

Evaluation seismic design provisions for unanchored liquid-storage tanks is challenging because the seismic design provisions (e.g., API 650) either do not include any solid guidelines or just simple equations to predict the effect of tank base-plate uplift on tank seismic performance. The main reason for the absence of detailed provisions is that the codes consider that the uplift causes damage to the tank, and therefore they recommend using anchors in order to avoid any uplift. Therefore, instead of evaluating accuracy of code given equations for effects of uplift, a more comprehensive approach is followed here to properly evaluate adequacy of the provisions. This approach is based on comparing tank base-plate uplift histories computed using two computational models. The first computational model, on which current seismic design provisions are based, is called mechanical spring-mass model. The second computational model, which is called Coupled Eulerian Lagrangian (CEL) model, is a detailed model including liquid-structure interaction explicitly as well as tank foundation interaction.

Seismic design provisions of liquid-storage tanks such as API 650 and Eurocode 8 are based on a mechanical spring-mass analogy developed by Graham and Rodriguez [1952], Jacobsen [1949], and Housner [15] for rigid tanks, and modified by Haroun and Housner [16] for flexible tanks. In the spring-mass analogy, which is shown in *Figure 1*, a portion of the mass of the fluid content (M_i) is considered to act as if it is rigidly connected to the tank walls while the remaining portion of the liquid content (M_c) is flexibly attached to tank walls. The water that synchronizes with the vibration of the tank is called *impulsive* and the sloshing component of the water that generates free surface waves and having its own frequency of vibration is called *convective* component. The free surface sloshing motion has a period of oscillation that is in general much longer than the fundamental period of the liquid-filled tank. In addition, tank foundation is assumed to be rigid in this mechanical spring-mass analogy. It should be noted that the sprig-mass analogy, principal of which are set in tank seismic design provisions assumes both anchored and unanchored tanks have the same properties (e.g., mass and spring stiffness).

For the mechanical spring-mass analogy, the relationships to calculate the mass and spring properties (i.e., mass values, spring stiffness, and mass location along the tank height) for the convective and impulsive components of liquid are given in the related seismic design provisions such as API 650. In this study, the API 650 provisions were used for the developed mechanical spring-mass tank model.

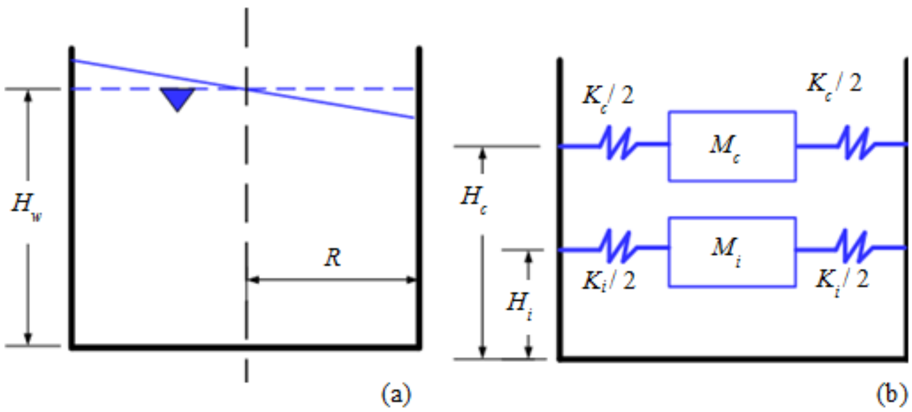

Figure 1: (a) Tank with oscillating water surface and (b) mechanical model (spring-mass analogy)

3 METHODOLOGY

Two unanchored liquid storage tanks were designed using seismic design provision of API 650. The tanks' seismic design parameters were selected to ensure that tank base-plate uplifts for the selected seismic levels. The tanks seismic performance was determined in terms of tank uplift histories, which were computed by performing time-history analysis with five strong ground motion data. Tank uplift histories were computed using two finite element models (i.e., CEL and mechanical spring-mass models). The finite element models of liquid-storage tanks were developed using ABAQUS general-purpose finite element program [17]. The computed uplift histories were compared to determine adequacy of mechanical spring-mass analogy (i.e., code seismic design provisions) to predict tank base uplift.

3.1 Prototype tanks

Two unanchored liquid-storage tanks with tank dimeter of 24.5 m and 36.0 m and design liquid level of 12.2 m and 20.0 m, respectively were designed using seismic design provisions of API 650. The tanks were designed as self-anchored with tank base-plate uplift. Tank roof was assumed to be self-supporting dome. The tanks were assumed to be located at high seismic region with 5% percent damped spectral response acceleration parameter at short period (i.e., S_S) 1.0g and corresponding acceleration parameter at a period of one second (i.e., S_I) equal to 0.4g. The region-dependent transition period for longer period ground motion (T_L) was assumed to be 12 seconds. The tank site class was assumed to be ASCE/SEI 7-10 [18] Site Class D (i.e., stiff soil). The seismic force reduction factors for convective and impulsive vibration modes were taken as 2.0 and 3.5, respectively. Tank shell plate, bottom and annular bottom plates, tank free board requirements were determined using API 650 provisions. The tank dimensions and design liquid levels were determined to ensure tank stability for sliding and overturning. A summary of tank properties is given in *Table 1*.

Design Parameter	Tank-A	Tank-B
Tank diameter (m)	24.4	36.6
Design liquid height (m)	12.2	15.2
Bottom/annular plate thickness (mm)	6	6
Roof plate (mm)	13	25
Equivalent shell plate thickness (mm)	8	14

Table 1: Prototype tanks

3.2 Selection and scaling of strong ground motion records

Five strong ground motion data recorded with stations located on Site Class D were selected to perform tank time history analysis. The ground motion records were obtained from the Pacific Earthquake Engineering Research Center NGA-West2 database, and a summary of their properties is given in *Table 2*. The selected earthquakes had a magnitude range of 6.5 to 7.6 and a rupture distance of 4.4 to 18.2 km. The ground motion records were selected giving preference to site class, spectral shape over the period range of interest, free-field records, and its magnitude.

ID	Earthquake (Year)	Station (1)	Comp.	Mag.(2)	Distance km	Scale Factor
EQ1	Chi-Chi Taiwan (1999)	TCU072	Chichi-Tcu072-N	7.6	7.1	1.0
EQ2	Erzincan (1992)	Erzincan	Erzincan-Erz-EW	6.7	4.4	0.8
EQ3	Imp. Valley-02 (1940)	El Centro, Array #9	Impvall.I-I-Elc270	7.0	6.1	1.6
EQ4	Northridge-01 (1994)	Sun Valley, Roscoe Blvd	North-Ro3090	6.7	10.1	1.0
EQ5	Supers. Hills-02 (1987)	El Centro, Imp. Co. Cent	Super.B-B-Icc000	6.5	18.2	1.2

(1) All stations were located on Site Class D.
(2) Mag. is moment magnitude, distance is to rupture plane.

Table 2: Summary of selected ground motion records

The ground motions were scaled to match the design spectrum for ASCE/SEI 7-10 Site Class D with S_s =1.0, S_1= 0.4, and T_L=12 sec. The scaling of ground motion records to match the design spectrum is of little importance for this study. However, to ensure that tank base uplift occurs, the earthquake records were scaled to match the design spectrum used for the tank design. The scale factors are given in *Table 2*. The selected records had different characteristics in terms of peak acceleration, duration, and distance to the fault. Also it includes near-fault records such as EQ2 with only 4.4 km to the rupture fault. Especially EQ2, EQ4, and EQ5 had large acceleration pulses, which increase their damage potential. The design spectrum and spectral response acceleration for the scaled earthquakes are given in *Figure 2*.

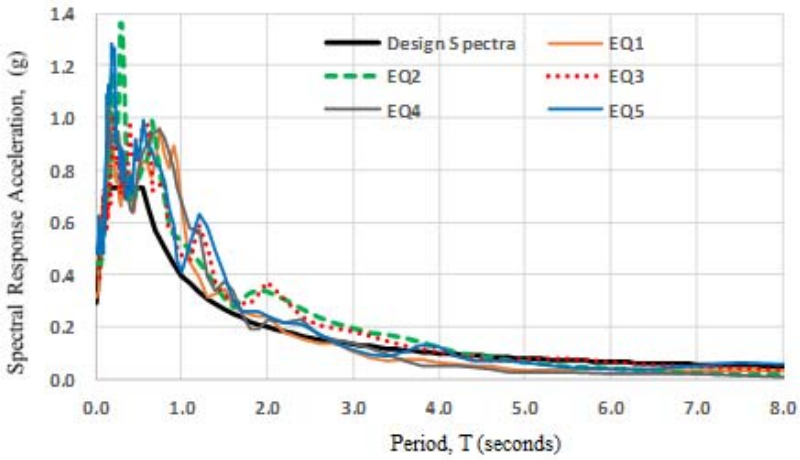

Figure 2: Design spectra and spectral response acceleration curves for the selected ground motions

3.3 CEL modeling of liquid-storage tanks

There are two classical numerical finite element formulations, namely *Lagrangian* and *Eulerian* descriptions. In the Lagrangian formulation, finite element nodes and material points are connected throughout the analysis and they move together. With this numerical formulation since material deforms with nodes that it is connected, it is easy to track material boundary/surfaces. However, under high strains (e.g., fluid flow) the Lagrangian mesh can severely distort, which results in poor quality solution or convergence issues. On the other hand, in the Eulerian finite element formulation, finite element nodes are fixed in the space while the material (e.g., fluid) flows through the mesh. The advantage of Eulerian formulation is that the mesh undergoes no distortion (i.e., strain) and therefore accurate solutions can be obtained for problems involving large deformations or strain gradients. Therefore, Eulerian approach is a suitable numerical method for modelling arbitrarily large deformations, and so it is suitable for studying soft matter and viscoelastic fluids [19]. A third finite element description is one including both Eulerian and Lagrangian formulations in the same model. This modelling approach is called *Coupled Eulerian Lagrangian* (CEL) formulation. In the CEL formulation, the materials with large deformation gradient and distortion such as liquids are modelled as Eulerian material while the other materials are modelled as Lagrangian (e.g., the tank shell).

Time history analysis of liquid-tank structure under selected earthquake records was performed using Coupled Eulerian Lagrangian finite element formulation. The tank and its rigid foundation, which was modelled as a plate, were Lagrangian parts while the water was modelled as Eulerian part. The model was composed of four parts, which were tank, rigid base, water, and Eulerian domain. The Eulerian domain (i.e., 3D mesh fixed in space) is only need-ed in the simulation to compute future location of water during seismic loading. The parts and details of developed CEL tank finite element model are given in *Figure 3*.

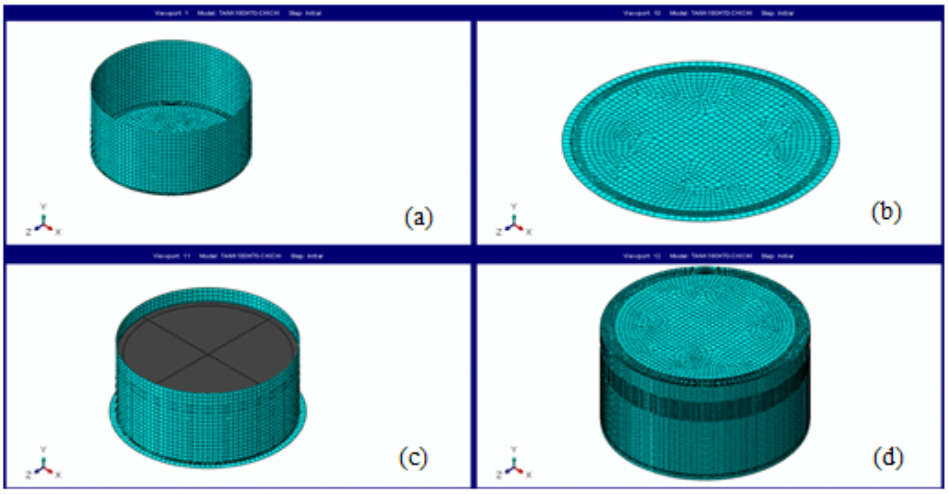

Figure 3: CEL model and mesh (a) tank, (b) rigid base, (c) water in tank, and (d) Eulerian domain

The contact between the tank bottom plate and tank foundation was modelled through contact interaction. The value of friction coefficient between the tank and its foundation was assumed to be high enough (i.e., 0.8) to prevent sliding of the tank over its foundation during seismic loading. In other words, it was assumed that there is no sliding between the tank and its foundation, but vertical separation (i.e., uplift) was allowed when the contact pressure was negative. The contact between the water and tank walls was defined to be frictionless. The water was modelled as a Newtonian fluid in which the viscous stresses are linearly proportional to the local strain rate. Finally, the tank roof and its mass were not included in the developed models explicitly. Tank roof was considered by defining a coupling constraint among the nodes of tank shell course connected to the roof. Not including roof plate mass was found to be conservative for the computed maximum value of tank uplift, therefore it was not included in the simulations.

For the boundary conditions, the rigid tank foundation was assumed to be fixed for all degrees of freedom except for the acceleration degree of freedom in the direction of earthquake records (i.e., global Z-direction). The earthquake acceleration data was defined as boundary condition (i.e., acceleration) for the tank foundation. Other than contact between the tank and its foundation no other boundary condition was defined. Gravity loading was the only loading considered. Gravity loading was applied to the tank and water.

The tank and its foundation were modelled using S4R shell elements. The S4R element is a 4-node general purpose shell element with reduced integration scheme. The effect of shell element membrane action, which is especially important for tank bottom plate membrane action and tank overturning resistance, was included by considering the effects of nonlinear geometry on the analyses. A nominal mesh size of 500 mm was used for the tank and its foundation. However, much finer mesh (a nominal size of 300 mm) was used for the tank and foundation regions, where tank-foundation separation (i.e., uplift) was likely. Finally, all CEL analyses were performed using ABAQUS explicit analysis technique.

3.4 Mechanical spring-mass analogy model

The developed FE model for mechanical spring-mass analogy of the tanks is given in *Figure 4*. The mechanical FE model is the same model used for the CEL analyses. However, the water was removed from the model, and it was replaced with impulsive and convective water masses as recommended by the design provisions. The boundary conditions, loading, and contact between the tank and its foundation were not changed (no sliding and surface-to-surface contact with separation allowed for the uplift). However, because water was not modelled explicitly, the hydrodynamic pressure on bottom plate was modelled as initial pressure loading before earthquake loads were applied. The impulsive and convective water masses were connected to the tank wall through springs and coupling constraints. For this purpose, two reference points were defined for each mass. The first reference point was connected to the tank shell at the level of mass using coupling constraint while the second reference point was assigned point mass (i.e., impulsive or convective water mass) and connected to the first reference point with the spring as shown in *Figure 4*. The springs and the mass reference point were allowed to move only in the direction that ground acceleration was applied.

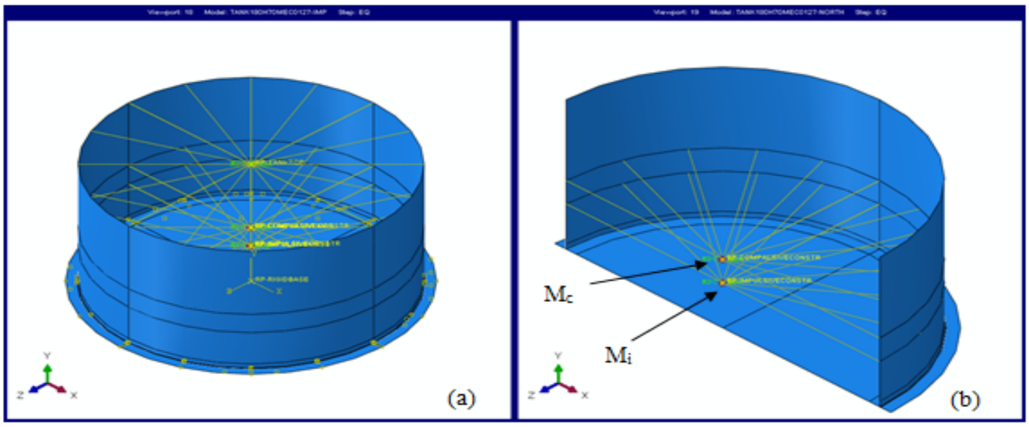

Figure 4: Model with impulsive and convective masses and springs (a) whole and (b) half tank models

For the mechanical spring-mass analogy, the relationships to calculate the mass and spring properties (i.e., mass values, spring stiffness, and mass location along the tank height) of convective and impulsive components are given in API 650. The calculated mechanical spring-mass properties for the tanks are given in *Table 3*.

Parameter	TANK-A	TANK-B
Mass, M_i *(kg)*	3086586	7464282
Spring stiffness, K_i *(N/m)*	2.243E8	3.727E8
Period, T_i *(sec)*	0.74	0.89
Water mass location, H_i *(m)*	4.57	5.72
Mass, M_c *(kg)*	2487999	8043281
Spring stiffness, K_c *(N/m)*	3.494E6	7.215E6
Period, T_c *(sec)*	5.30	6.63
Water mass location, H_c *(m)*	7.38	8.82
Subscript "*i*" and "*c*" stands for impulsive and convective components, respectively.		

Table 3: Summary of spring and mass properties for impulsive and convective components

4 RESULTS AND DISCUSSIONS

The analysis results were compared based on the tank uplift histories computed at the maximum uplift locations. For this purpose, tank base uplift was monitored at two locations. These are "*right*" and "*left*" uplift locations, which are separated by 180 degrees and located on the perimeter of tank shell. These locations are where the maximum base uplift occurs, and they are located along the direction that earthquake accelerations were applied. *Figure 5* shows CEL model with water filled tank and its foundation before seismic loads were applied, water sloshing due to seismic loads, and tank base-plate uplift.

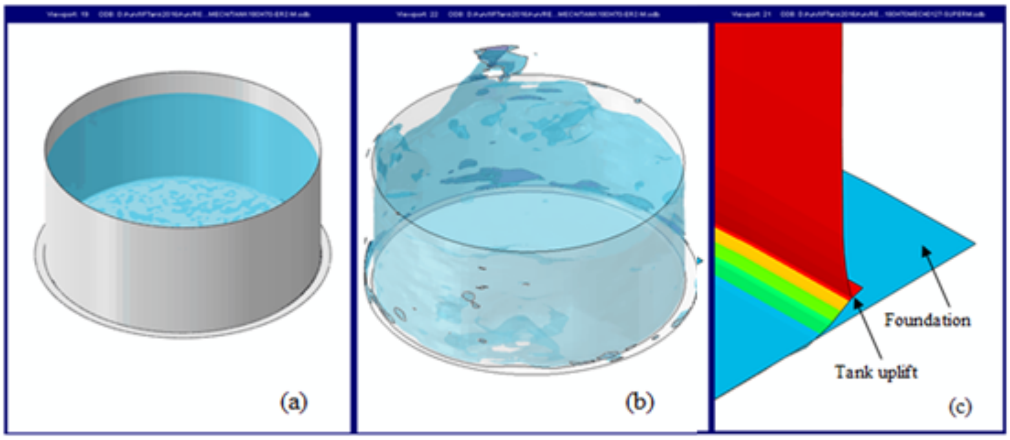

Figure 5: Tank (a) before earthquake loading, (b) water sloshing during loading, and (c) tank-base plate uplift

Figure 6 shows a comparison of computed tank uplift histories at the left and right uplift locations for both CEL and mechanical spring-mass tank models for several earthquake records. The results show that the total number of cases that tank uplift occurred during earthquake duration was underpredicted with the mechanical model for all considered records for both left and right uplift locations. This observation clearly indicates that the mechanical spring-mass analogy does not capture the effect of tank uplift on dynamic loads that unanchored tanks are subjected to. In addition, the results suggest that the tank uplift affects the amount of water behaving as impulsive and convective components. This is likely to be due to vibration period elongation due to tank uplift.

A summary of computed maximum tank uplifts values for each tank and seismic record is given in *Table 4*. In addition, the error for tank uplift computed using mechanical spring-mass analogy was computed relative to those computed using CEL model. The maximum tank base uplift computed using mechanical spring-mass model had errors between -5% and 46% with an average error of 22% for Tank-A, and between -60% and 254% with an average error of 58% for Tank-B. In other words, on average the maximum tank uplift values predicted using the mechanical model were higher than those predicted using the CEL model. This finding indicates that mechanical spring-mass analogy ignores some dynamic loads that provide additional resistance to tank uplift.

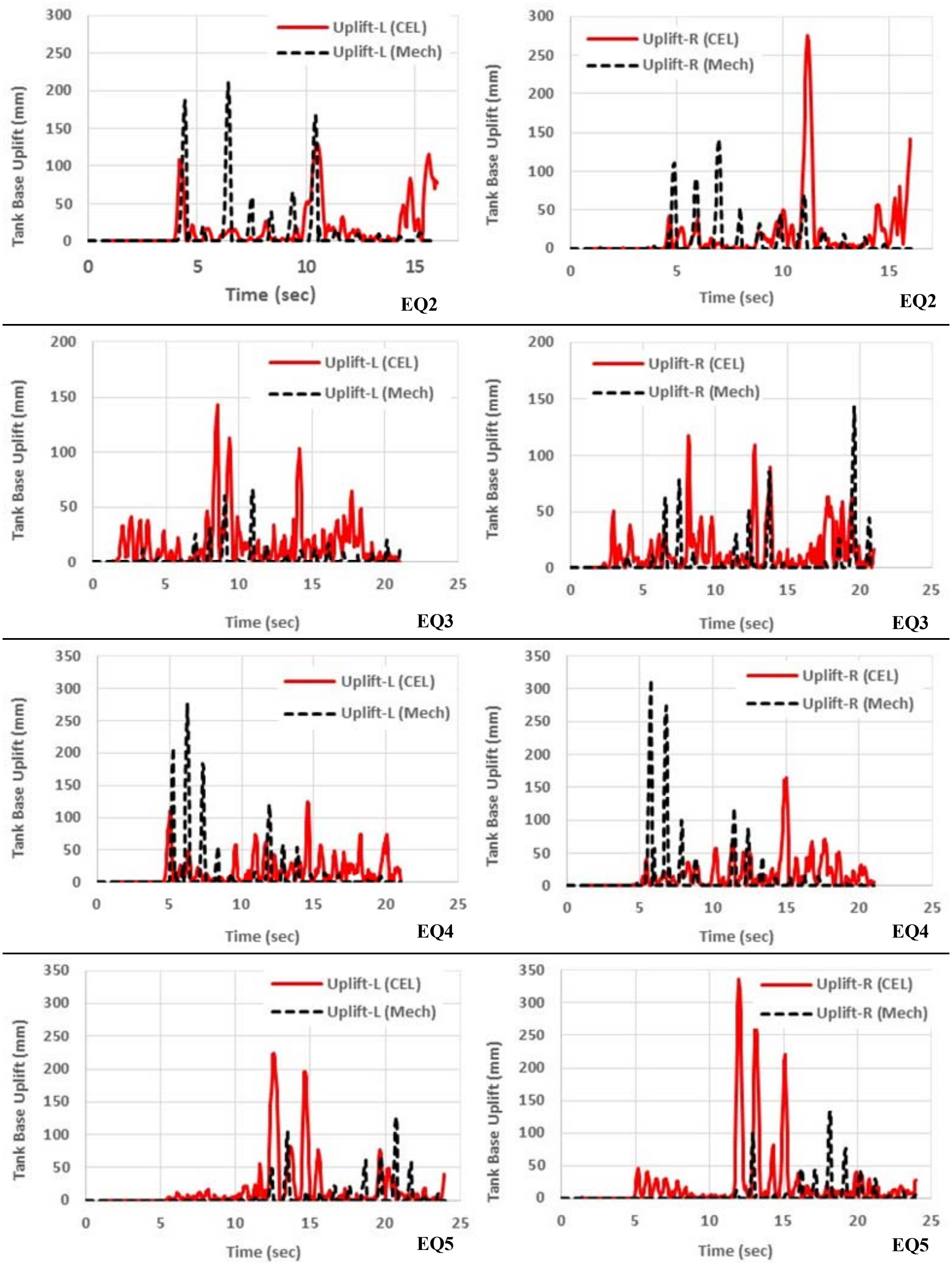

Figure 6: Tank-B base-plate uplift histories for CEL and mechanical spring-mass models

TANK	EQ Record	CEL (mm)	MECH. (mm)	Error (%)
TANK-A	EQ1	222	280	26
	EQ2	189	185	-2
	EQ3	206	196	-5
	EQ4	262	383	46
	EQ5	179	259	45
TANK-B	EQ1	126	446	254
	EQ2	276	210	-24
	EQ3	143	181	27
	EQ4	164	315	92
	EQ5	336	133	-60

Error = (MECH-CEL)/CEL

Table 4: Summary of computed maximum tank uplifts

5 CONCLUSIONS

Seismic performance of two unanchored liquid-storage tanks was investigated using Coupled Eulerian Lagrangian (CEL) and mechanical spring-mass analogy, on which the current seismic design provisions are based. The seismic performance of the tanks was computed using five strong ground motion records. The computed tank base uplift versus time histories were monitored and compared. The results indicate that

- The mechanical spring-mass analogy approach does not capture tank uplift and its effects on dynamic loads that unanchored tanks are subjected to.
- The mechanical spring-mass analogy underpredicts the total number of tank uplift during seismic loading.
- The maximum tank base uplift computed using the mechanical spring-mass analogy had average errors of 22 % and 58 % for Tank-A and Tank-B, respectively for the selected earthquake records.
- The results suggest that mechanical spring-mass analogy is not adequate to capture seismic behaviour of unanchored tanks.
- There is a need to develop a modified version of the traditional mechanical spring-mass analogy to be used for predicting seismic performance of unanchored liquid-storage tanks.

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